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Application of Virtual Reality for Remote Ship Inspections and Surveys – A Systematic Review

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ABSTRACT: The use of virtual reality for the establishment of compliance is a potential game-changer in enabling real-time remote inspections/ surveys of vessels. When provided with high-speed internet access, robots or remote-controlled inspection vehicles such as drones, crawlers, unmanned aerial vehicles (UAVs), and so on, may be equipped with remote inspection technologies (RITs), and smart optical cameras and sensor suites in conjunction with wearable technologies, and smart/ mobile devices, to carry out an aerial and underwater virtual assessment of the coating condition of the steel structural members of the vessel while transmitting the data in real-time or near real-time, via collaborative software. To ease the travel restrictions and border closures prompted by the Coronavirus (COVID-19), these novel technologies have been introduced by some flag states and classification as alternatives to traditional in-person statutory inspections/ class surveys. This study aims to employ a systematic literature review (SLR) approach to (1) classify the profiles of existing publications related to remote inspections/ surveys, (2) highlight the key thematic areas being discussed within the domain of remote inspections/ surveys and identify tasks and processes that may require virtual reality application. To the best of our knowledge, the findings have revealed that there is no existing SLR paper related to the application of remote inspection techniques in ship inspections/ surveys. However, the review retrieved 28 primary studies from the following databases: Scopus, Web of Science, Science Direct, and Google Scholar. Based on the results, various studies have proposed multifarious solutions to overcoming the existing technical and regulatory barriers to the mass deployment of these cutting-edge technologies.

1 INTRODUCTION

Maritime transport has weathered the whirlwind of the deadly COVID-19 pandemic amidst a myriad of challenges which have prompted significant disruptions in seaborne trade. For example, to avert the impacts of border closures and travel restrictions on the performance of routine statutory inspections and classification surveys, some flag states and classification societies have resorted to the application of remote inspection techniques in lieu of traditional in-person inspections/ surveys to establish compliance while easing the knock-on effects of the lockdown [1-6]. However, the use of remote inspection techniques had been introduced by a few classification societies prior to the global outbreak of the COVID-19 pandemic, as an alternative means of crediting statutory inspections/ class surveys thereby aiming to optimise and automate existing inspection/ survey-related tasks and processes [7]. As a result, the number of inspections/ surveys credited by remote techniques has increased sharply since 2016, especially among members of the International Association of Classification Societies (IACS) [8, 9].

Conventionally, seagoing vessels are operated within the hostile ocean environment which poses threats to the structural integrity of the hull and other steel structural members on board [10]. In accordance with the relevant IMO conventions and regulations, vessels engaged in international voyages are required to maintain seaworthiness. As such, the IMO has made it mandatory for ships to undergo periodic inspections to satisfy compliance in addition to those carried by the classification societies [11].

As such, the introduction of remote inspection techniques serves as a possible proxy which may or may not require surveyors' access on board the vessel. Moreover, the introduction of remote inspection techniques has the potential to mitigate inspection-related risks while improving efficiency and lowering cost and required time. [12]. To this objective, RITs have been deployed to assess the structural integrity of the hull and other steel structural members both below the waterline and in hard-to-access zones.

Hence, this review seeks to contribute to the wider academic discourse in the following ways. First, conduct a thematic review of remote ship inspection/ survey to identify and classify current publications available within the broader literature, as well as to appreciate the trends in remote inspection techniques. Second, highlight the main thematic areas to identify the progress and potential gaps. Lastly, identify activities and processes that require the use of virtual reality in remote inspections/ surveys.

Furthermore, this study has been undertaken in accordance with the guidelines established by [13] to answer the research questions. Though originally intended for the field of software engineering, this guideline highlights a gradual approach to thoroughly understanding the trends based on primary studies while publishing the findings appropriately.

Therefore, the remainder of this SLR paper has been structured into the following sections. In section two, a background to remote surveys is briefly discussed. In section three, the research method and the approach to data collection and synthesis are described. Section four summarises the key findings, along with the discussions provided. Last of all, in section five, the conclusion and future research work are briefly summarised.

2 BACKGROUND

The term remote inspection/ survey refers to the examination undertaken or partially carried out by an attending surveyor without access on board, to establish whether the ship and its equipment comply with applicable conventions and regulations of the IMO, statutory requirements of the Flag State administration, and the minimum standards established by the classification society [14].

According to [15, 16], remote surveys can be integrated with RITs such as drones, remotely operated vehicles (ROVs), aerial robots or robotic crawlers, that are specifically designed with multifarious features to obtain desired capabilities such as capturing still images and live-streamed videos. Also, RITs can be combined with mobile and wearable devices to enable the collection, transmission, and processing of high-quality and elaborate inspection data in real-time or offline [17].

Moreover, among the criticisms include the lack of a standard to establish equivalency between remote-assisted surveys and those undertaken with surveyors' access on board [7], the absence of a harmonized code of conduct to guide ethical practices, as well as the nonexistence of a robust regulatory framework to build trust among stakeholders, while providing a safety net for shipowners, especially in terms of liability, data management, governance, and protection, among others [15, 18-20].

In addition, the International Transport Workers' Federation (ITF) has raised the alarm about the use of the seafarers in collaboration with the attending surveyor to carry remote inspections/ surveys on board the vessel, thereby terming it as imposing an additional burden on the crew who have no relevant training in that regard [21]. Therefore, these barriers need to be addressed by the relevant stakeholders.

Apart, different RITs have been used mainly to visually assess the coating condition of structural steel members on board the vessel. For example, remotely operated vehicles (ROVs) can be deployed to visually inspect the hull's condition below the waterline [22], UAVs or drones, fitted with cameras, are more suitable for collecting still images or live-streamed footage, especially from hard-to-access zones of the vessel such as places located at heights, enclosed spaces, cargo holds, tanks, and so on [12, 23, 24], robotic crawlers can be deployed to inspect the hull condition both underwater and above the waterline [25], and autonomous underwater vehicles (AUVs) can be deployed to minimise hull fouling and energy consumption while enhancing safety [16, 26, 27]. Unlike ROVs and crawlers, UAVs lack the capabilities to conduct non-destructive testing and thickness gauging [25]. Still, when equipped with localisation and vision-based sensing devices, UAVs can operate autonomously in environments where there is limited Global Positioning System (GPS) signals [28]. So, the use of remote-assisted surveys has the potential to optimise maintenance and inspection-related tasks and save time and cost while minimising risks to surveyors.

3 METHODOLOGY

This section presents the methods adopted in this SLR paper. Using a step-by-step approach, the review seeks to identify the profiles of publications focused on the use of remote inspection techniques to credit ship inspections/ surveys, and related processes and tasks that require the application of virtual reality, as well as to identify the direction of future research. The study is undertaken in accordance with the guidelines proposed by [29].

3.1 *Research Questions*

As part of the review protocol, we initially carried out some preliminary searches from previous studies. relevant to the topic, to identify the most used terminologies and synonyms in remote inspection techniques and properly formulate our research questions. Based on these searches, we have refined our research questions to mainly address the following.

RQ1: How are publications focusing on the use of remote inspection/ survey of ships organised?

3.2 *RQ2: What are the key thematic areas being discussed?*

RQ3: Which related tasks/ processes require the application of virtual reality?

3.3 *Search Strategy*

To define our search string, we started by reviewing several related studies [7, 15, 18-20, 25] and combine different keywords to refine our search strings.

To avoid the omission of important publications, we started off by using the synonyms of the keywords to formulate our research questions. Next, we defined our search query for virtual reality and remote surveys/ inspections as illustrated in Table 1.

3.4 *Inclusion and Exclusion Criteria*

As illustrated in Table 1, the criteria for the inclusion and exclusion of papers restrict the selection process to consider studies that have been peer-reviewed within the context of vessel inspection/ survey. Also, we set our exclusion criteria to restrict the following types of studies: papers that are not peer-reviewed, primary studies that are not available in English, as well as papers that were published prior to 2016.

Table 1. Inclusion and exclusion criteria

Inclusion Criteria	Description
I1	Primary studies that are peer-reviewed.
I2	Papers that are published in English.
I3	Papers that are published from 2016-2023
Exclusion Criteria	**Description**
E1	Papers that are not related to the topic.
E2	Papers are not available in full text.
E3	Papers that are not presenting remote inspection. techniques.

3.5 Selection Process

As shown in Figure 1, we have filtered the selected studies in the following steps based on the inclusion and exclusion criteria (shown in Table 1).

3.6 *Quality Assessment*

During the selection, we tried to minimise the risks of bias due to human errors prior to reviewing and validating the primary studies. Also, by considering the quality of the selected publications, the research questions have been formulated to ensure validity while adhering to the guidelines adopted by [29]. To evaluate the quality of the selected papers, we consulted methods adopted by [30-32].

3.7 *Threats to Validity*

To validate and understand the review process, this SLR paper follows the guidelines adopted by [13, 29]. First, searches were randomly conducted in order to refine the keywords while defining the inclusion and exclusion criteria. To this aim, the primary author conducted the aforementioned tasks while the review protocol was validated by the secondary authors.

Furthermore, during the search process, we noted the following observations. First, we noticed that there is no existing systematic literature review paper available within the domain of remote ship inspection and surveys. Also, we noticed that there is only one extant primary study [25] that focuses on the use of virtual reality in remote inspections/ surveys. However, other application areas of virtual reality mentioned in the indexed databases selected for this review are mostly focused on ship design and offshore engineering [33-35].

4 RESULTS AND DISCUSSION

In this section, the findings of this SLR paper have been briefly summarised. In line with the approach adopted by [29], 23 publications out of the total of 28 primary studies have been reviewed and analysed. For each question, we have presented the important findings, discussed them, and summarized the most relevant points. Thus, these results imply that there is an increasing interest in remote inspection techniques.

In accordance with our selection criteria and based on the method proposed by [13], we restricted our search to include only peer-reviewed papers available in journals and conferences. Notwithstanding, only one of the primary studies focused on the application of virtual reality in remote surveys (QR2). This lack of primary studies can be partly attributed to the novelty of this research field.

Figure 1. Selection process

4.1 *RQ1: How are the publications focused on the remote inspection/ survey of ships distributed?*

We intend to answer this research question by identifying the selected publications based on the year, types, top peer-reviewed journals, and the most active researchers with their affiliated institutions and countries. By investigating the involvement of individual researchers and their affiliated institutions, we aimed to identify which researchers and countries have more interest in remote inspection techniques. Research interest in remote inspection techniques has increased sharply during the last few years, particularly among researchers who are affiliated with European and Asian institutions. In Figures 5-6, the geographic distribution of the selected primary studies is presented.

4.1.1 *Profiles and Distribution of primary publications*

The selected publications have been summarised in the following figures. Figures 1-4 illustrate the distribution of primary studies by year, type, and peer-reviewed journal/ conference. Results indicate that research interest in remote inspection techniques has increased sharply during the last few years, particularly among researchers who are affiliated with European and Asian institutions. In Figures 5-6, the geographic distribution of primary studies is presented.

Based on our findings, remote inspection techniques are gaining significant popularity in academia and industry. For example, 16 of the 28 selected primary studies (57%) related to remote inspections/ surveys have been published from 2016 onwards. Also, we found that 64 per cent (%) of the selected publications have been peer-reviewed in journals while 36 per cent (%) of published. Moreover, it is worth noting that the most active researchers within the domain of remote ship inspection are mostly affiliated with European institutions followed, by Asian institutions.

4.1.2 *Number of Publications*

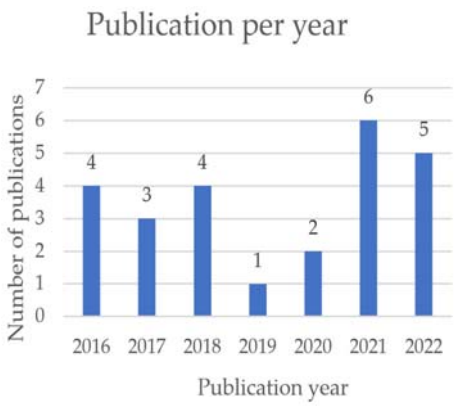

Figure 1. Publication per year

4.1.3 *Types of Publication*

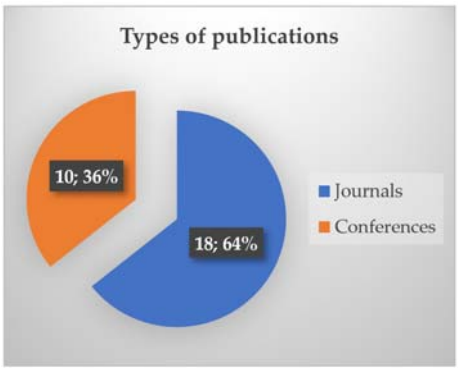

Figure 2. Publication per type

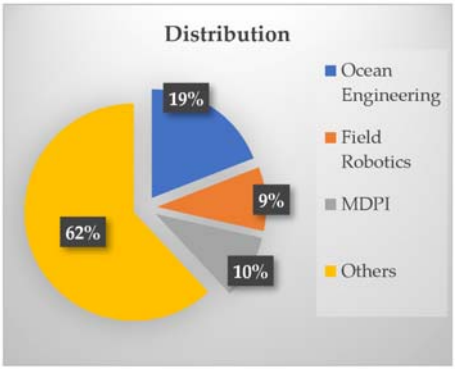

Figure 3. Publication per journal contribution

4.1.4 *Researchers' Affiliations*

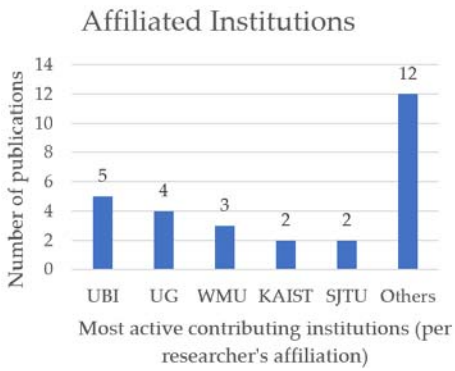

Figure 4. Publication per institutional affiliation

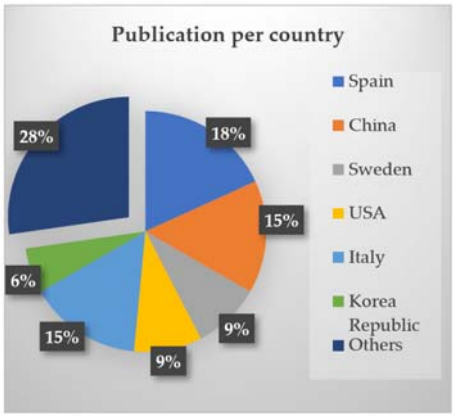

Figure 5. Publication per geographic affiliation

4.2 *RQ2: What are the key thematic areas being discussed?*

In this section, we aim to identify and summarise the most important themes regarding remote inspection techniques. The general information about the key thematic areas has been summarized in Figure 6. As a result, only 23 out of the 28 primary studies have been considered for further discussion.

4.3 *RQ3: Which related tasks/ processes require the application of virtual reality?*

In this section, the application areas of virtual realization have been reviewed and summarized. Based on our findings, there are fewer publications related to this topic. Out of the 28 primary studies reviewed, only one paper has focused on it. However, the few primary studies on the use of virtual reality are within the domain of ship design.

Overall, as illustrated in Figure 6, of the selected 25 publications, 30 per cent (30%) are mainly focused on the design of remote inspection vehicles, 20 per cent (20%) are focused on the related challenges and drawbacks, followed by 18 per cent (18%) are focused on the optimization of robotic platform/ detection tool, 16 per cent (16%) are focused on control software, 13 per cent (13%) are focused on the detection algorithm, while only 3 per cent (3%) are focused on the application areas of virtual reality, smart devices, wearable tools and mobile devices. In general, results from these studies have revealed the growing interest among researchers within the domain of remote inspection techniques which demonstrates the direction of future research.

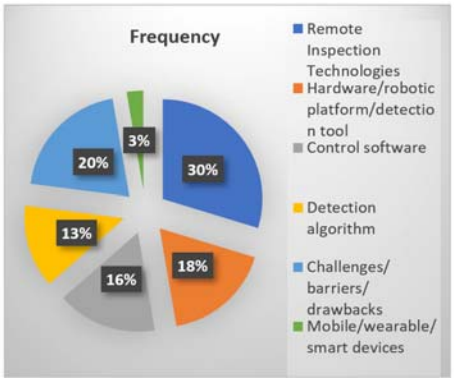

Figure 6. Thematic areas

Based on the findings from the selected publications [10-12,15-20,22,23,25,37-50], the use of remote inspection techniques to credit inspections/ surveys of vessels is an emerging research domain. As such, existing primary studies related to remote inspection techniques are mostly focused on the design and optimization of the current detection hardware of remote inspection vehicles proposing various optical devices such as high-definition cameras and sensor suits such as ultrawide-band (UWB), aimed at enhancing their capabilities to navigate, localise and manoeuvre robustly, especially when entering or exiting hard-to-access and GPS-denied areas of the vessel.

Moreover, to improve the quality of the images captured from the defective steel structural members of the hull and other parts of the vessels, the modification of the control software, the reconstruction of the hull into a three-dimensional view (3D), the reconfiguration of the detection algorithms using multifarious programming languages, machine learning, and deep learning concepts have been extensively highlighted in some of the papers. Hence, most of the primary studies selected for this review have proposed different detection hardware, control software and detection algorithms, as well as various concepts and approaches aimed at reducing inspection/ survey-related hazards, cost, and time while improving the scope and quality of the images and live-streamed videos collected during visual inspections of the coating condition of the vessel.

Furthermore, of the selected publications for this review, fewer studies (only 3 %) have mentioned the related tasks/ processes that require the application of virtual reality in crediting remote inspections/ surveys in real-time or near real-time. Thus, based on the results of the reviewed publications, the use of remote inspection techniques on board the vessel, to credit inspections/ surveys in real-time via collaborative software is yet to become reality due to underlying technical challenges such as low internet connectivity.

Notwithstanding, several of the studies cited in this SLR have highlighted the enormous benefits associated with the deployment of remote inspection techniques and their overlying challenges. For

example, some papers have mainly highlighted the existing technical and regulatory gaps and have proposed methods to overcome them. Among the benefits emphasised include the use of remote inspection techniques as a possible replacement for conventional in-person inspections/ surveys to improve inspection outcomes while mitigating inspection-related hazards and lowering the required timing and associated costs.

Contrastingly, none of the publications selected for this review has mentioned the prospects and challenges involving the use of seafarers to carry out survey/ inspection-related tasks. As such, one of the key issues being discussed in the existing literature is played by the seafarers as representatives of the shipowners during remote inspections/ surveys. By dint of the novelty of the topic, the role of the seafarers is yet to be clearly defined. Regarding performing remote inspections/ surveys on board the vessel in conjunction with the attending surveyor without access on board the vessel, it is critical to define the role and training needs of seafarers, who are integral team players, to prevent fatigue due to additional workload, thereby leading to precarious working conditions. Lastly, based on the results of the reviewed papers, another major challenge that has not received coverage is the lack of procedure and mechanism to ensure trust and transparency, especially during the inspection and transmission of data between the crew and the shore-based personnel.

5 CONCLUSIONS AND FUTURE WORK

In this SLR paper, the use of remote inspection techniques and the application of virtual reality to related tasks/ processes have been presented. To this objective, we identified the most relevant primary studies using four digital databases. Beforehand, we started by defining the research goal, formulating the research questions, and defining keywords and search strings, as well as specifying the inclusion and exclusion criteria.

Based on the search strategy used within the chosen indexed databases, the findings have revealed that up to date, there is no existing SLR paper related to the use of remote inspection techniques to credit vessels' inspections/ surveys or the application of virtual reality in related activities/ procedures. In other words, these results suggest that this specific research area has not gained much attention from the wider literature. Presumably, being the first SLR study to be conducted within this field, we aimed to collate and synthesize the relevant primary studies in a meaningful way to guide the direction of future research. As indicated in Section 4.1, the results show that this field is increasingly becoming popular among researchers in recent years.

Moreover, a decisive point in Section 4.2 is the integration of remote inspection technologies in conjunction with high-resolution optics, wearable tools, smart technologies, and mobile devices to improve existing inspection activities and tasks. In addition to optimising the designs of the detection platforms, existing studies are mostly focused on improving the quality of still images captured and live videos streamed, as well as those of the control software. Thus, future research efforts must focus more on overcoming the existing techno-regulatory barriers to accelerate the mass adoption of these nascent technologies.

Notwithstanding, another conclusive point in Section 4.3 is the use of virtual reality to enable real-time remote inspection/ survey without the attending surveyor accessing the vessel. As such, the lack of standards to establish equivalence between traditional and remote-assisted inspections/ surveys, and the underlying technical and technological constraints are potential barriers. Also, as mentioned in section 4.3, only 3 per cent of the 23 publications collated and synthesized mentioned tasks/ processes that require the use of virtual reality within the realm of remote ship inspection/ survey. Therefore, future research and development efforts must be directed to bridge these gaps, something that is highly recommended in various primary studies.

Lastly, the use of the ship crew to proxy on the shipowner's behalf during remote inspections/ surveys has been extensively highlighted in some of the studies including peer-reviewed articles and the grey literature. For example, in section 4.2, some papers have emphasized the need for closing the existing techno-regulatory gaps related to the adoption of remote inspection technologies in crediting statutory inspections/ classification surveys using harmonised and standardized protocols to guide the inspection tasks and processes, developing and test the performance of RITs, establish training centres for the qualification and competency of the relevant stakeholders. Nonetheless, none of the studies cited in this SLR has made mentioned the training and competency levels required by seafarers in carrying out remote inspections/ surveys on board the vessel. Furthermore, when using the seafarers to represent the owners, there is a need to define their role and training needs properly while ensuring that the collection and transmission of data remain transparent particularly when undertaking statutory inspections to validate compliance. Therefore, future research must be focused on defining the roles and training requirements for seafarers to partake in the implementation of remote inspections/ surveys on board the vessels, backed by a regulatory framework to ensure transparent inspection and data-sharing practices between seafarers and shore-based staff are conducted appropriately.

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