Remote Vessel Inspections with an ROV using Livestreaming

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Abstract

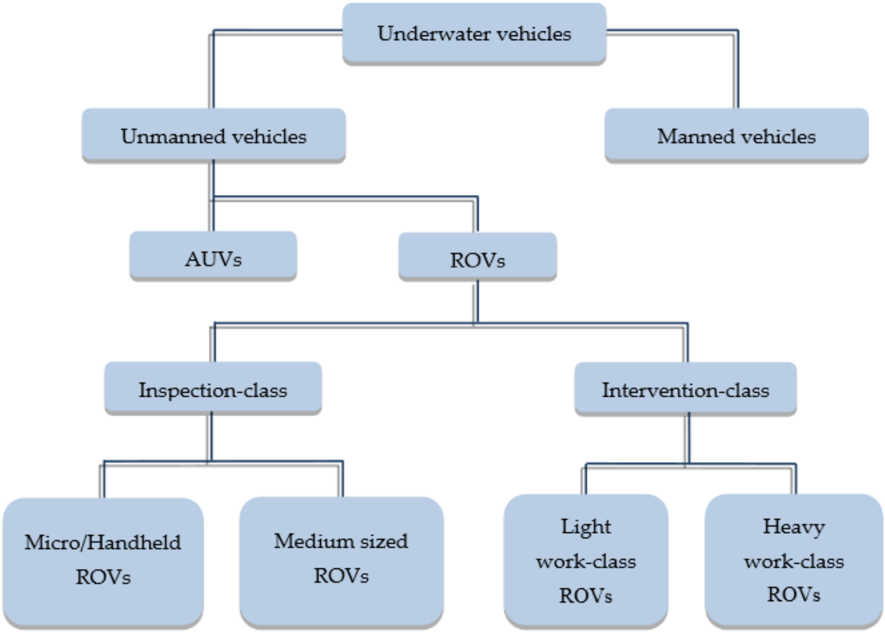
This paper describes the possibility of conducting in-water surveys with ROV (remotely operated vehicles) as part of a risk management approach for maritime and port operations. The risk management approach will be evaluated using a qualitative mixed-method analysis of literature analysis, a well-accepted risk management model being the Swiss Cheese Model and a connected Bow Tie Analysis. Furthermore, the practicability of commercially available small-size ROV is being displayed in this paper based on operational examples and frameworks. This paper furthermore introduces the concept of remote streaming as part of an unmanned inspection to enhance operational qualities through remotely adding competencies to the operation.

1. Introduction of small-size ROV (remotely operated vehicles)

Remotely operated vehicles have been in operation for decades, mainly in deep-sea and offshore operations. Over the past years, technology evolved and a number of small-size ROV (remotely operated vehicles) systems have entered the commercial market. The comparable low price of small-size ROV of about 15.000 EUR compared to former ROV prices of several hundred thousand EUR as well as the technological abilities of this new ROV class have caused a shift in ROV operability. Affordable prices and operational technology have shifted ROV operation from offshore to the ports and allow for a whole new dimension of unmanned inspection as part of risk management. With affordable and reliable technology at hand, port operators, authorities as well as ship owner and – charterer are able to conduct inspection of underwater structures at almost any time without expensive diver operations.
Increasing demand on efficiency of global transportation results in increasingly complex supply chains for producers of goods, retailers and transportation service provider. This leads to firms becoming extremely vulnerable to the consequences of a disruption in the transportations system (Hecker, 2002; Flynn, 2006). In the context of maritime operations this factor is crucial because ports and ship operating services are very price sensitive and are confronted by national and international competition. Any mean to uphold legal requirements in terms of inspection or other danger prevention and/or to even enhance service quality while reducing operation costs at the same time are perceived as highly welcome in the maritime business both from academia and from business operations. This paper argues that enhancing service quality while reducing costs can to a large part be achieved through innovative technology where ROV are seen as such a mean. The main areas of service are seen to be on the safety and the security side or maritime operations.
On the safety side, ROV represent an innovative technology assisting and or replacing conventional diving operations that are often expensive and not without danger for the diver. Sone ports don't even allow manned diving operations, while evidence rises, that unmanned diving operations are not affected by these safety regulations. The argument of providing safe inspection services can even be integrated in the concept of corporate social responsibility (CSR) where it is shown, that "*responsible firms are better positioned to grow in terms of reputation and revenues*" (Drobetz et al. 2014).
From a security side, ROV provide advantages in preventions of smuggling of contraband and other illegal substances through ports. After the 9/11 attacks in the US, maritime operation security is legally regulated by the ISPS code (International Ship and Port Facility Security). Stein (2018) introduced the concept of ROVs to assist ISPS operations in ports. Studies already revealed a connection between transport service security and customer satisfaction (see for example Hu and Lee, 2011; Chang and Thai, 2016). It is inevitably agreed that security is to be embedded into daily operations processes (Frittelli, 2003) and in collaboration among different stakeholders (Bichou, 2005) in order to be successful. Costs of security, however, are crucial with regard to competition.
This paper follows the ROV classification scheme by Capocci et al. (2017) displayed in figure 1.

According to them, micro or handheld inspection ROVs weigh between 3 kg and 20 kg and can be deployed and recovered using manpower alone. They state that "*a significant aim in using micro ROVs is to reduce operational costs and system complexity, allowing the user to complete the job in an efficient manner*". The depth rating of this ROV category is generally less than 300 m

Figure 1: Outline of underwater vehicles



Source: Capocci et al. (2017)

2. Methodology

This paper introduces the concept of ROV based vessel inspection using livestreaming technology. Livestreaming is particularly suitable because it allows for different stakeholders to join and spectate the inspection remotely. This paper argues that the availability of small-size ROV brings significant advantages to underwater inspection operations as part of a general risk management. After introducing the concept of ROV and underwater inspections in form of a literature analysis, the paper introduces the concept of ROV based under inspection based on well accepted risk-management frameworks. Furthermore, the concept and advantages of livestreaming are being introduced in this context and finally results and evaluations are being discussed towards the end of this contribution.

This paper choses a qualitative mixed-method analysis of qualitative evaluations and a case study analysis. The literature review follows a systematic approach as presented in Tranfield et al., 2003; Denyer and Transfield, 2009). The risk management analysis follows well accepted frameworks of the Swiss Cheese Modelling (following Reason, 1990; 2006) and the Bow Tie Analysis (following Nielsen, 1971). The combination of qualitative methods is regarded to be particular suitable for innovation research in transport logistics. Voss et al. (2002) state that "*case research reflects one of the most powerful research methods in operations management, particularly in the development of new theory*".
In line with this argument, Näslund (2002) also states the importance of qualitative research to enhance logistics research quality. Studies already addressed the importance of structured frameworks as a basis for future research for academic areas with limited existing literature (Miles and Hubermann, 1994; Shields and Rangarajan, 2013). Academic contributions on ROV operations are indeed limited to this time, with leads to the conclusion that the above introduced methods appear very suitable for this paper's innovation research.

2.1 ROV literature analysis

Following the classification of Capocci et al. (2017), this paper focusses on the Micro or handheld ROVs of the inspection class as displayed in figure 1. While the amount of literature in the context of deep-sea ROV operations of medium sized ROV systems and above given, contributions of micro-sized ROV operations are limited. This can nonetheless be explained by the relatively novelty of this ROV class entering the industrial markets less than a decade ago. Furthermore, the aspect of remote and unmanned inspection using drones, also called UAS (unmanned aerial systems) or UAV (unmanned aerial vehicles) is well evaluated while underwater remote inspections is a novelty within the literature to the best of the author's knowledge. Following the explained structured literature approaches, two main areas of micro ROV studies were identified among the literature being ROV development and ROV operation. While quite some contributions focus on developmental systems and introductory tests, the operational contributions of industrially available case studies remain scarce.

The **development** of micro-class or "low-cost" ROV systems is covered by the literature to some extent, however, its contribution to science remains questionable as many developments lack behind already industrially produced ROV at the time of research.
Battle et al. (2003) have experimented with a low-cost ROV system called URIS based on a Pentium III system. They can be referenced among the pioneers of experimenting with low-cost micro-class ROV systems prior to the widespread availability of sophisticated micro-processors and industrially constructed ROVs or its spare parts. Over a decade later several research designed ROV studies were introduced but apart from their new design form, their operational ability was already behind market standard of low-cost micro ROVs commercially available. Zain et al. (2016) describes a 4 thruster torpedo form ROV based on the open source platform open ROV using an ATMega2560 microcontroller. The innovation of this design lies in its streamline form that makes it potentially suitable for long distance operations with minimum power demand. Vukšić et al. (2017) developed a ROV based on an already existing Blue Robotics system rebuild in steel using single board microcomputers (2549Q–AVR–02/2014). Apart from the increased robustness using steel instead of plastics, depth of 150m were not exceeded so that the prototype is not exceeding any comparable industrially produced ROVs from that time. Wiryadinata et al. (2017) designed a 3 degrees of freedom ROV system in 4-inch PVC pipe form using an AVR microcontroller (ATMega32). Kungwani and Misal (2017) used a PVC pipe form with a PIC16F877A microcontroller that in line with Wiryadinata et al. (2017) provide 3 degrees of freedom and no significant advantage to market ready ROV systems at that time. At the same time, Osen et al. (2017) developed a PE plastic and Plexiglas ROV for Aquaculture inspection based on Raspberry Pi and Arduino microcontroller and were able to provide a prototype for an investment of 1.500€ that is basically 1/10 of the market price of comparable cow-cost ROV systems at that time. Hartono et al. (2020) introduce a research design ROV using an Arduino microcontroller, however, despite making reference to an industrially produced ROV system in one figure (a Deep Trekker DTG-2) the prototype offers no advantage compared to current ROV systems already widely available on the market. Siregar et al. (2020) introduces a Fitoplankton SAS ROV with 3 degrees of freedom based on a Raspberry Pi type B+ microcomputer and a PIXHAWK flight controller, both state-of-the-art technologies that are also operated in industrially produced ROVs such as the BlueROV-2. The advantage of this micro class ROV is provided by the ability to maintain depth with a single camera using the triangle similarity algorithm

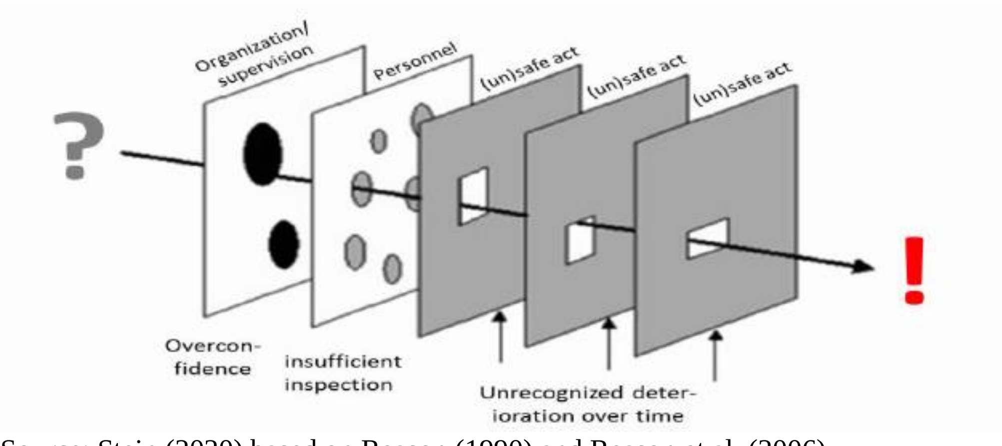
On the **operations** side only few contributions provide case study analysis and even fewer using industrially produced ROV systems. Pacunski and Palsson (2008) used an industrial ROV (DOE Phantom HD2+2) to collect quantitative data for analyzing marine communities of fish. The ROV of the study ranged around 100.000$ which was a low-cost investment at that time. Alotta et al. (2012) introduce Nemo, a metal frame ROV that conducted inspections at the wreck of the Costa Concordia Ship off the coast of Tuscany. The ROV, however, is only a prototype and no market ready low-cost system. D'Alessando et al. (2016), Heisinger et al. (2017) as well as Costa et al. (2018) operated a self-assembled open source ROV first generation that was later in 2018 succeed by the second generation ROV called Trident. The cost of this self-assembled ROV kit ranged around 1.000$ and is based on Beaglebone Black and Arduino MEGA microprocessors. Teague et al. (2018) operated a

BlueROV2 (company Blue Robotics) of about 10.000€ exploring hydrothermal venting using photogrammetric analysis. Lund-Hansen et al (2018) operated a low-cost ROV of 15.000€ as blend of polycarbonate and aluminum parts being tested for maneuvering under ice covered waters. The paper provides novel insights as it is the first contribution operating a low-cost ROV under technical challenges of working in the Arctic at water and air temperatures well below zero °C. Busher et al. (2020) operated an industrially manufactured second generation open ROR trident system (company Sofar Ocean) of about 2.000$ to asses ecological baselines of an indigenous seascape.

2.2 Risk management analysis introduction on underwater inspections

Stein (2020) introduced the concept of risk management of unmanned inspection among maritime infrastructures, which is also the basis for this paper's qualitative analysis. The evaluation and recognition of accidents as a chain of subsequent events has a history in risk management theory. Over time and as a reaction to major disasters, risk analysis focused more on the organization and their internal factors of inabilities to prevent accidents. Theory claims that organizations tend to a certain degree of uncertainty, leading to "*ill-defined or competing preferences, ambiguous goals, unclear technology and fluid patterns of stakeholders' involvement in the decision-making process*" (Moura et al. 2017).
The aspect of different subsequent effects in environments of rising complexity was evaluated by Reason (1990) and his "Swiss cheese model" (SCM) that shaped risk management orientation for many years. It's orientation based on mayor disasters in the late 1970s and 1980s including Flixborough, Challenger, Three Mile Island, Bhopal, Chernobyl, the Herald of Free Enterprise and the King's Cross Underground fire (Reason et al. 2006). Since maritime disasters were regarded among complex system failures in the SMC, this model is particularly suitable for this paper's research. Reason et al. (2006) later described the model as "explanatory device for communicating the interactions that occur when a complex well-defended system suffers a catastrophic breakdown". The defense within a system and their associated inadequacies are graphically represented by layers of and holes in Swiss cheese. When the 'holes' in a system's defense align, an accident trajectory can pass through the defensive layers and result in a hazard causing harm to people, assets and the environment (Reason, 1990).

Figure 2: The Swiss cheese model

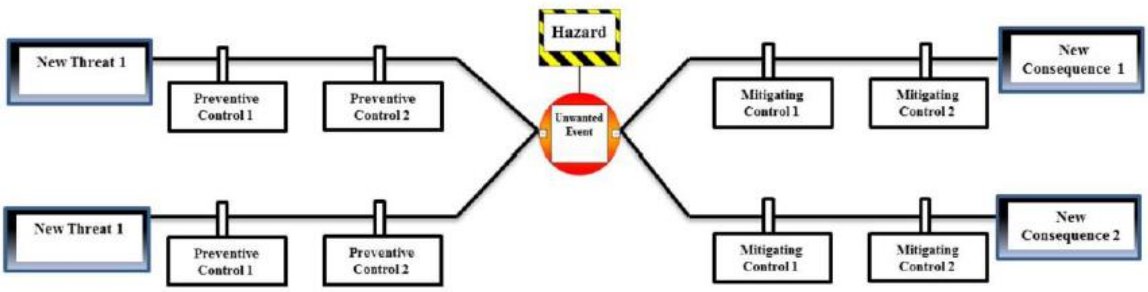


Source: Stein (2020) based on Reason (1990) and Reason et al. (2006)

The initial Swiss Cheese Model (SCM) based on Reason (1990) differentiated accident causation among one of four domains, being organizational influences, supervision, preconditions, and specific acts. With regard to port inspection as basis for risk management, the model exhibits a certain necessity for modification with regard to the underlying accident domains as displayed in figure 1. Basically, every accident caused by deterioration is based on the absence of information mainly of structural damages caused by long-term corrosion. The barriers preventing such an accident are three-fold starting with the organization, over personnel and finally to the act itself. The basic decision to prevent breakdowns due to material fatigue is the decision of the organization to invest into inspection mechanisms such as industrial climbers, divers, drone operators etc.. Supervision for the sake of this argument is included into this barrier because one can only surveil, if means to do so are integrated in the organization. Main reasons for port facilities and ship operators to fail this preventative barrier are cost savings due to the already stated competition and price sensitivity of the maritime domain. Risk management literature describes organizational failure associated with a status of overconfidence in the own risk management (see Årstad and Aven, 2017). Such overconfidence in risk management often ends at the edge of regulatory compliance compared with a failure to learn from prior major accidents. The personnel level of accident prevention is then faced with insufficient inspection means as a consequence of the organization's overconfidence. From a model perspective, the unknown deterioration is then (worst case) brought to the operational level of (un)safe acts. Unlike in other regards of the SCM such as the airline industry, a personnel and organizational failure is no guarantee for an unsafe act, although it increases the chance of an accident to occur. The act itself is the handling of port operations such as loading of containers using gantry cranes, or the berth of a ship at a quay facility or other daily maritime transport operations. Such acts per se are not unsafe even if structures are deteriorated. Over time, however, and under the absence of knowledge that reveals structural damages, a former safe act becomes unsafe because structures cannot withstand the force caused by such operation, which then leads to the accident. In order to address general criticism on the SCM (e.g. Hollnagel et al., 2012) for oversimplification, this paper addresses the specific hole in the model using bow tie analysis (BTA).

Among the most reliable structured approaches to identify accident causations is the bow tie analysis (BTA), which was developed by connecting an event tree and a fault tree analysis connected to an unwanted event (e.g. accident) by Nielsen (1971). The method visualizes of the relationships between the causes of undesired events, the escalation of such events, the controls preventing such event from occurring and the measures in place to limit the impact. BTA has been extensively used in safety critical domains such as the petrochemical and chemical industry and mining industry, which makes it particularly suitable for application in complex maritime settings. The technique does not only assist in effective analysis of incidents and risks but can also be utilized as an effective tool for communicating safety issues (Stemn et al., 2018). The structure of the bow tie focusses on the undesired event in the centre, as a knot point, that leads to a certain hazard in the operation. A hazard often refers to a safety incident where, loss of control of the hazard directly gives rise to the unwanted event e.g. the accident. Threats are located on the left side of the model that passes preventive barriers of preventative control measurements before leading to the knot point. The right side of the model reflects the consequences of an undesired event that are often associated with loss/damage of people, material or operations. From the centre to the consequences, the severity of an event can be controlled by mitigation barriers that reduce or hinder the consequence after an event.

Figure 3: The bow tie model



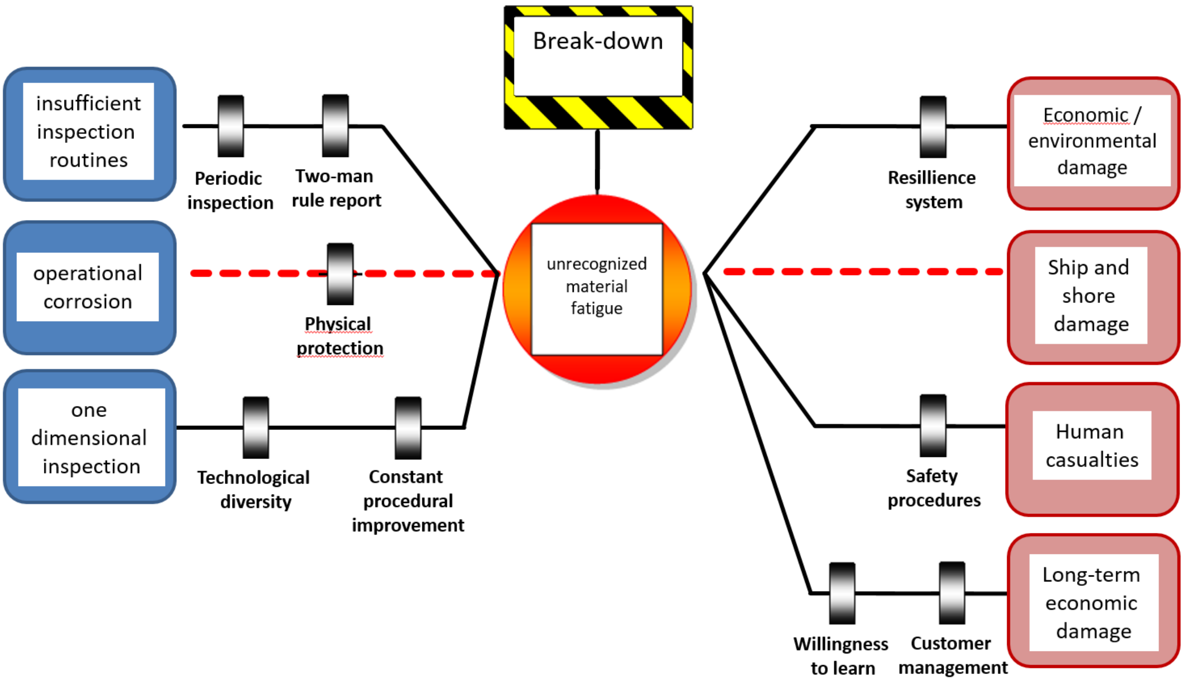
Source: Stein (2020) based on Nielsen (1971)

In order to learn from accidents, one must understand the effects that lead to the accident and the consequences these effects have hand on the overall severity of the accident. Stemn et al. (2018) contributed to this area by connecting BTA to learning effects. Risk analysis models such as the SCM and the BTA provide powerful methods to simplify complex structures in order to communicate them properly in organizations.

2.3 Applying BTA analysis to underwater inspections

The BTA application on ROV inspections on underwater structures bases on the aspect that unrecognized material fatigue will over time lead to a breakdown of the structure. The breakdown represents a tremendous safety incident in a port or ship structure with immediate short- and long term effects. Threats arise in forms of insufficient inspection routines or limited inspection capabilities such as the absence of divers and other underwater inspection mechanisms like ROVs.
Preventive barriers account for the human factor and the quality of the inspection and the speed and quality of an incident report may be influenced by preventative measurements such as awareness, error handling strategies and code of conducts. Inspection quality can be raised through the use new and diversified technology (such as ROVs), procedural improvements or tighter inspection periods and two factor report checks. Using the remote streaming option of this paper's case study, the quality of the inspection can also be enhanced because more spectators with different competencies can join and comment on the very same operation that without online streaming would be limited to physically attending personnel only. Physical protection measurements can to some extent prevent damages in marine port structures as for example introduced by Gang and Yong (2007). Such structures, however, come at high costs and orient towards flood protection of the hinterland rather than reducing deterioration of port structures in practice.
The consequences of a breakdown range from immediate shore and possible ship damage, environmental damage (in case dangerous material from containers is exposed to the sea), economic damage (due to operational stops) to human casualties and severe long-term economic damages. The economic and environmental damages can be condemned through existing resilience strategies. The likelihood of human damage and casualties can be reduced through operational safety procedures. Long-term economic damage in form of lost customer trust or service quality can be reduced by a company's willingness to learn as well as customer management.

Figure 4: Applying BTA to unrecognized underwater material fatigue



Soure: Authors

3. The ROV System

The system operated in this study is a Blueye Pro ROV of the company Blueye Robotics A/S from Trondheim, Norway. The measurements of the ROV are 485x257x354mm (LxWxH) and the system weights 8.6kg and consists of a ABS and Aluminum enclosure with Polycarbonate windows. The maximum depth rate is 305m thus exceeding the definition by Capocci et al. (2017) and being the most robust and deep-sea operative low-cost ROV system at the market (at the time of this study). The system consist of an Exmor R CMOS, 1/2.8 inch with maximal image size of 1920 x 1080 and full HD video resolution of 1920 x 1080 25/30 Fp. The integrated LED provides a maximum of 3.300 lumen and can be dimmed. The IMU consists of a 3 axis gyro/accelerometer/ magnetometer with depth sensor resolution of 0.2 bar and maximum operating range of 30 bar.

Figure 5: The Blueye Pro ROV system

Source: Blueye Robotics

3.1 Introducing livestreaming to underwater inspections

Introducing the concept of Livestreaming of an unmanned ROV inspection is a novelty among academic contributions. The literature analysis of this paper revealed past and recent studies on low-cost ROV

Figure 6: ROV operation framework including streaming via Wi-Fi or internet

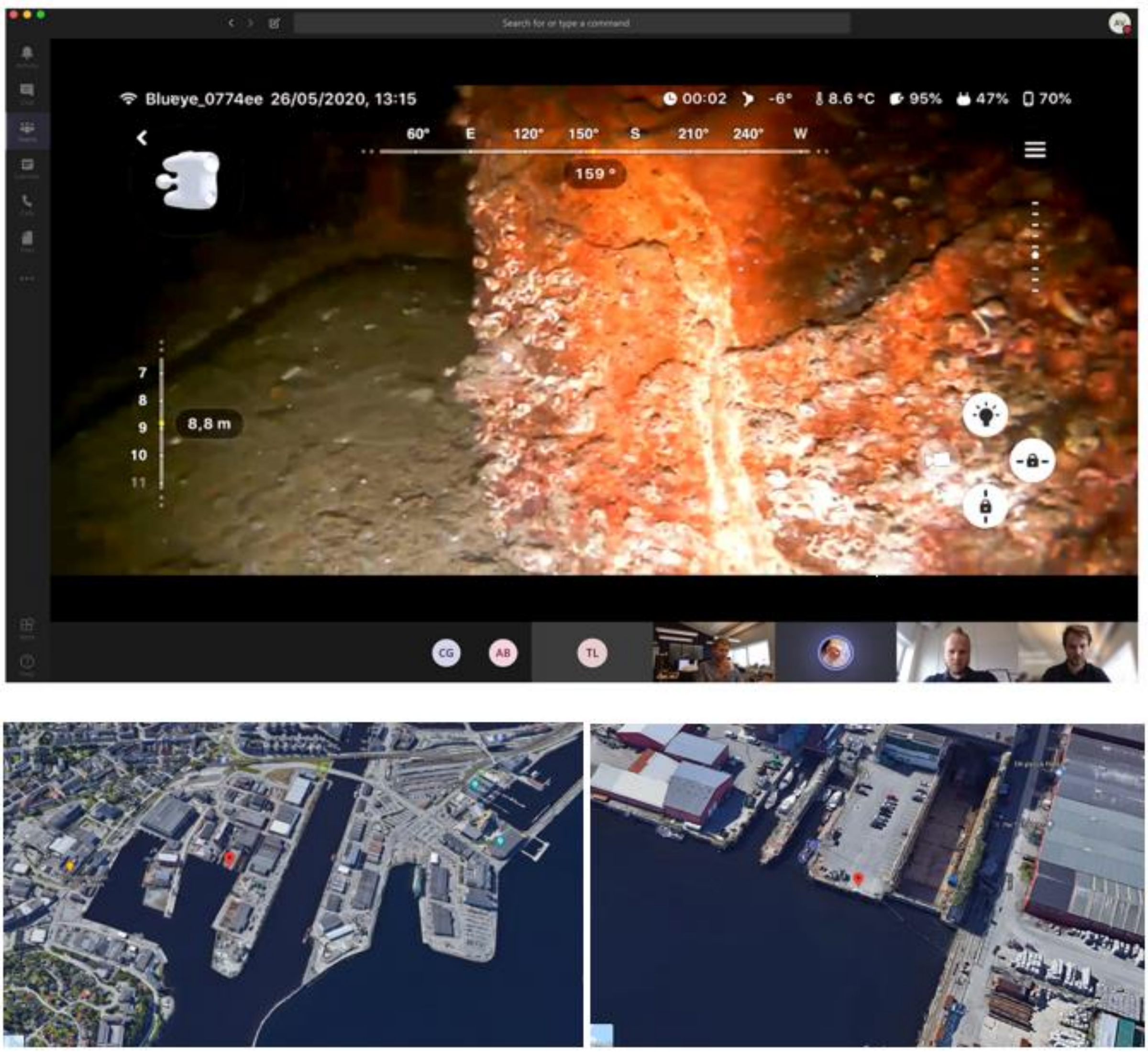
Soure: Authors

systems with a focus on hardware. This case study goes further by evaluating also the software aspect of ROV inspections introducing remote spectating via livestreaming as shown in figure 6. In this case study setting, the ROV is connected via tether with a surface unit that transmits video and control signals over Wi-Fi to a controlling unit with smartphone. A mobile app specifically designed by the ROV manufacture allows to stream the diving operation over Wi-Fi to additional devices in the vicinity of the operation or to stream it globally over the internet. A web application allows for streaming on conventional computers with latency times of less than one second from the ROV to the spectator.

3.2 The Case Study

The case study was conducted in May 2020 using a Blueye Pro ROV in the port of Trondheim, Norway. The aim of the operation was to inspect a damaged part of a steel reinforced concrete dock front, where sediments below were suspected to flow away over time. The structure belongs to a former WW2 submarine base that is partially damaged and requires an increased demand of inspection and monitoring. Figure 7 displays the area of operation as well as the remote streaming of the inspection.

Figure 7: Case Study operation



Source: Authors referring to Blueye Robotics and Google Maps

Figure 7 reveals that apart from the ROV pilot at the port, two service technicians and five spectators followed the operation using Microsoft Teams video capture function. As mentioned, the ability to remotely follow and spectate the operations allows for enhancing the inspection competency because several spectators with additional knowledget can now be part of the very same operation. This aspect represents a new milestone in unmanned inspections using low-costs ROV systems and further enhances inspection quality for ports and shipping companies.

Figure 8: Inspection Pictures from the operation

Source: Blueye Robotics

Figure 8 reveals that sediments were indeed floating away as a result of structural damages in the concrete structure of the harbor front. In total, the diving operation took 10 Minutes preparation, 8 minutes diving time and additional 5 minutes to pack up, while stakeholder and other inspection personnel was able to follow the operation remotely and discuss the findings and plan future repair operations.

4. Conclusion

Micro or handheld ROV systems according to the definition of Capocci et al. (2017) provide significant advantages for underwater inspections. Formerly expensive deep-sea hardware evolved to small systems of a few kg and with investments of less than 15.000€ making this technology available to a wide range of user. The applied risk analysis of this paper argues that inspection quality and procedural improvements of inspection operations are to a large extent accountable for structural information qualities to counteract unrecognized material fatigue of underwater structures. The structured literature analysis of this contribution revealed fragmented experiments on ROV designs that often lack behind already existing industrial systems thus providing limited novelty. Operations of low-cost micro ROV among the literature is scars but grew among the past years as a result of widespread availabilities of cheap ROV and computer hardware.

This study is the first of its kind to introduce a case study using a Blueye Pro system and also introducing the aspect of remote surveillance using software streaming. The aspect of remotely collaboration and adding of competent personnel to an diving operation increases the inspection quality while reducing costs in form of man hours, travelling etc. at the same time. The introduced case study revealed operational results for a remote audience of inspection stakeholders in less than 30 minutes and is far more attractive to operators of any marine infrastructure than conventional diving operations.

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