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DRONES AND REMOTE SENSING FOR NON-DESTRUCTIVE TESTING OF MARINE CONCRETE STRUCTURES IN THE BALTIC SEA

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Abstract

Marine concrete structures in the Baltic Sea—including breakwaters, piers, and historic fortifications—play a vital role in coastal protection, navigation, and cultural heritage. Now exceeding their design lives, these assets are increasingly threatened by harsh brackish conditions, freeze–thaw cycles, and environmental contamination. Traditional diver-based inspections are hazardous and offer limited insight into hidden or internal degradation. Recent advances in non-destructive testing (NDT) and remote-sensing platforms—particularly those using remotely operated underwater vehicles (ROVs)—enable safer, more comprehensive monitoring. This paper synthesizes current NDT methods (ultrasonic, radiographic, electromagnetic, thermographic), complementary remote sensing (sonar, photogrammetry, satellite), and highlights recent Baltic Sea case studies. Environmental and operational challenges (e.g., biofouling, low visibility, signal attenuation) are discussed, synthesised from field experience, and the possibilities of AI-assisted analysis, digital twins, and next-generation autonomous platforms proposed. Integrated, data-driven diagnostics conclude to extend asset service life and protect underwater cultural heritage across the Baltic.

Keywords: Baltic Sea, marine concrete, non-destructive testing, remote sensing, underwater drones.

1. Introduction

The Baltic Sea coastline is a special example of how engineering, economy, and history come together. Along this coast, reinforced concrete structures such as breakwaters, harbour piers, and World War II-era fortifications are very common [1, 2]. These constructions are extremely important—they protect from storms, ensure safe shipping, support industry, and act as historical monuments. Places like the Gdynia Babie Doły Torpedo Depot or Kiel's naval forts give direct links to Europe's twentieth-century past.

Most of these concrete structures were built between the 1930s and 1970s. Today, they are much older than planned and show clear signs of serious deterioration. Problems range from surface-level cracks and salt deposits to deeper issues such as corrosion of steel reinforcement, large empty spaces (voids) inside the concrete, and layers separating from one another (delamination) [3]. As shown in Figure 1, these types of damage have been found in many different locations on the Baltic Sea.

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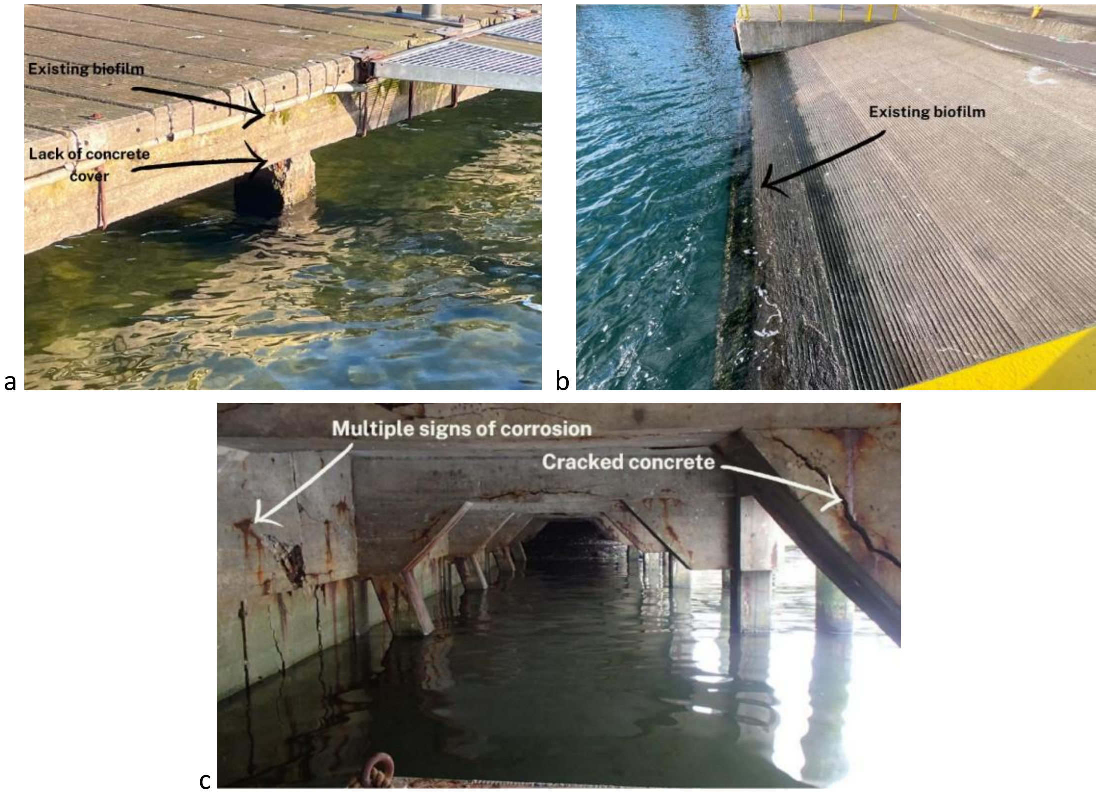

Fig. 1. Examples of damaged marine concrete structures – (a) Old Pier in Puck, Poland; (b) Seaport in Władysławowo, Poland; (c) Fur Harbour, Denmark.

One reason for such fast damage is the unique Baltic environment. The sea has brackish water—less salty than an ocean, but still salty enough to quickly corrode steel bars and anchors inside the concrete [3]. In winter, very cold temperatures mean constant cycles of freezing and thawing, which causes cracks to start or get bigger [2]. Ice pushes and scrapes against concrete, damaging edges, while in summer, rapid growth of algae, barnacles, and mussels not only weakens the concrete but also hides damage from inspectors and their sensors [4].

Human actions have made the situation worse. After World War II, nearly 32,000 tonnes of chemical weapons—including containers filled with mustard gas and arsenic—were thrown into the Baltic Sea, mainly near the Bornholm and Gotland basins and some Polish and Danish coastal areas [5]. Studies over many years have shown that these dangerous chemicals remain in the water. They have caused higher arsenic in fish, polluted beaches and sea beds, and sometimes led to poisoning in fishermen or local residents [3]. This means that working near or on these underwater structures, in the area of contamination, can be dangerous for both divers and robotic equipment.

Figure 2 below, based on several studies [3, 5, 6], shows the main environmental challenges that exist in the Baltic Sea.

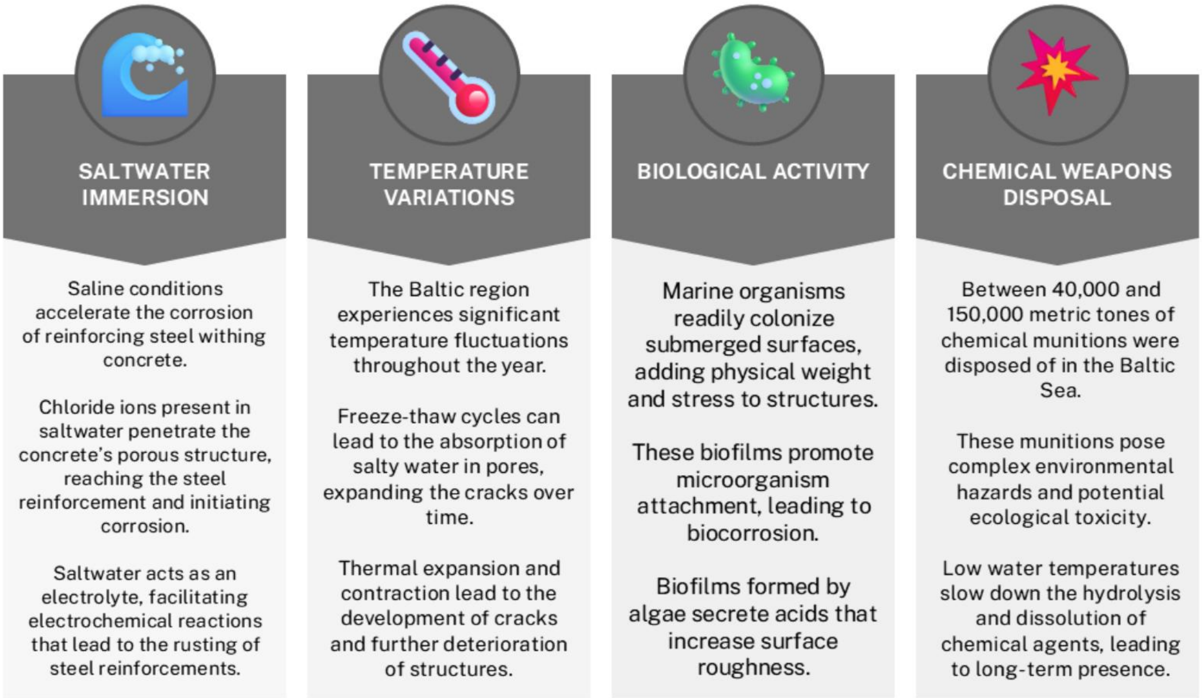

Fig. 2. Environmental challenges scheme (References: Greenberg et al., 2016; Polak-Juszczak & Richert, 2021; Achterberg et al., 2024)

Until recently, most underwater inspection depended on sending divers to check the condition of the concrete. But this is expensive, risky, and gives a rough idea about the actual state of the structure, eg. because of poor visibility or strong currents [7]. It forced engineers and authorities to look for new solutions. In the last few years, modern non-destructive testing (NDT) and remote sensing methods have been developed. These techniques, when used with underwater drones (ROVs) or autonomous robots, can test the concrete deeply, often without needing divers at all. The use of miniaturized and more durable sensors, as well as new ways of analysing data—like artificial intelligence (AI), real-time 3D modelling (so-called "digital twins"), and better communications—now allow much more reliable and safer assessment of old concrete structures [7, 8].

This paper describes the current research and real-world examples from the Baltic Sea. It explains existing technologies, shows their strengths and weaknesses, and highlights the integration of different sensors. The paper also points out the main problems—such as turbidity, fouling, and difficult weather—and looks towards future solutions like artificial intelligence for automatic crack detection and digital twins for real-time monitoring.

2. Methodology

The methodological framework of this review was intentionally designed to bridge scientific research and field-tested practice. The core aim was to evaluate the applicability, effectiveness, and limitations of non-destructive testing (NDT) and remote sensing methods—as well as their deployment via underwater drones (ROVs)—with a direct focus on the environmental and operational challenges specific to the Baltic Sea region.

2.1. Systematic review insights

A systematic review was performed to identify the main trends, content gaps, and areas of active innovation in the inspection of marine concrete structures in the Baltic Sea. The approach was based on bibliometric methods, using the PRISMA protocol, and included academic databases such as Scopus and Google Scholar. Search queries combined terms like "Baltic Sea," "concrete," "non-destructive testing," "remote sensing," "underwater drone," and "ROV." The review covered literature published up to November 2024.

There is a noticeable lack of research directly focused on the intersection of advanced NDT, remote sensing, and the practical challenges faced by Baltic marine infrastructure. The leading contributors to the field are institutions from China, the USA, and the UK, although Poland, Sweden, and Germany are also significant due to their Baltic coastline and direct regional interests. Most publications focus on general NDT, corrosion and durability of marine concrete, and broad SHM [1, 4, 7]. There has been a recent increase in studies leveraging artificial intelligence and machine learning to process large volumes of inspection data, identify cracks, or classify defects [9].

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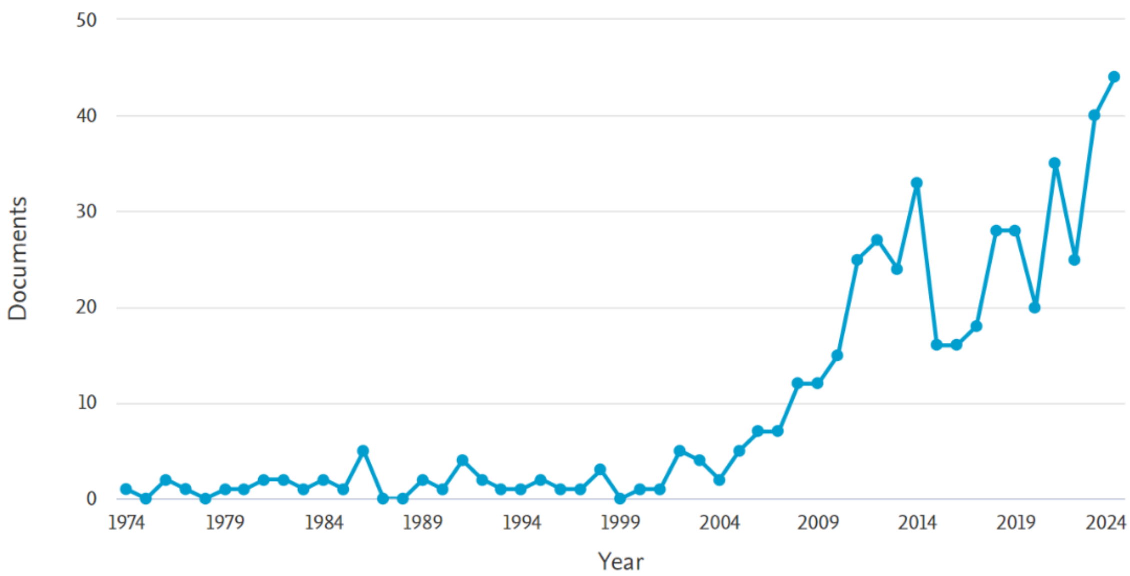

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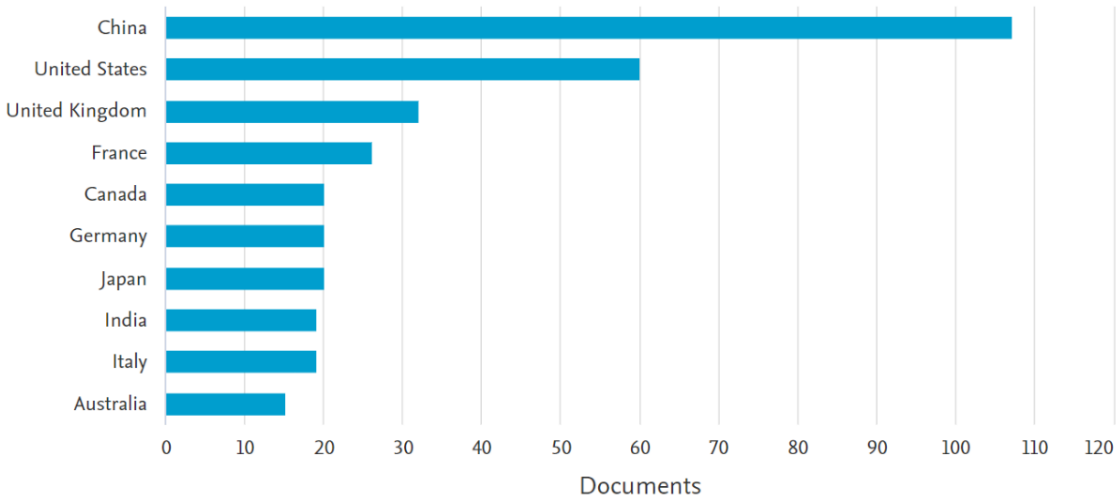

Fig. 3. (a) Annual frequency of research article publications; (b) Documents by country or territory.

These insights highlight a need for more focused studies and technology applications tailored to the specific environmental and operational realities of the Baltic Sea.

Bibliometric analysis was performed to map research trends, subject area clustering, and country or institutional productivity, further guiding the manual selection of pivotal works.

2.2. Overview of Non-Destructive Testing (NDT) methods

Non-destructive testing (NDT) methods enable the assessment of concrete structure integrity and deterioration without causing any harm to the material or requiring extensive intervention. These techniques are important for the periodic evaluation and maintenance of marine structures, especially in challenging environments.

Table 1 presents the principal NDT methods, their typical measurement outputs, and their adaptation for use on submerged structures.

Table 1. Comparison of non-destructive methods (References: Pezeshki et al. 2023; Wang et al. 2018; Bourreau et al. 2020)

NDT method	Measurements
Ultrasonic testing (UT)	Internal cracks, voids, honeycombing; approximate concrete strength; surface-crack depth
Radiographic testing (RT)	Rebar position & diameter; large voids or cracks; grout defects in post-tension ducts
Electromagnetic methods (cover-meter, GPR)	Rebar cover and spacing; element thickness; large voids or delaminations; low-resistivity zones hinting at chloride ingress
Infra-red thermography (IR)	Near-surface delaminations, voids, moisture pathways / leaks
Magnetic particle & Eddy-current (MT/ET)	Surface-breaking cracks and corrosion loss in exposed steel

Ultrasonic testing (UT) is already used underwater—especially with ROVs—due to its effectiveness at identifying internal defects and adaptability to robotic deployment [1]. Electromagnetic methods such as ground-penetrating radar are valuable near the surface but have reduced performance in brackish water due to signal attenuation [7]. Infrared thermography is practical mainly above water or in shallow applications, as its effectiveness decreases rapidly with immersion and turbidity. Radiographic and eddy-current methods are limited to special cases, given their logistical complexity and in-water technical constraints.

Continuous innovation—such as integrating sensors into ROVs and developing AI-supported signal processing—enables more regular, objective, and high-resolution assessment of these assets, which is increasingly expected in safety-critical marine environments [9].

2.3. Remote sensing for non-destructive testing

Remote sensing plays a role in the inspection and monitoring of marine concrete. It allows for non-invasive data collection from distances or difficult-to-access areas. These technologies are especially valuable where diver operations are not feasible due to low visibility, strong currents, ice cover, or chemical hazards from dumped munitions [1, 4].

Remote sensing techniques can be grouped into three main categories, each with unique strengths for marine NDT applications:

Table 2: Comparison of remote sensing technology (References: Grządziel et al. 2022; Nilsson et al. 2023; Ravnås et al. 2023; Wang et al. 2018; Pezeshki et al. 2023)

Remote sensing technology	Main principle & Data acquired	Application examples in marine NDT
Sonar (MBES, SSS, SBP, SAS)	Acoustic imaging / sub-bottom profiling	Mapping sea bottom, detecting wrecks, assessing erosion
Optical (Photogrammetry, SfM, LiDAR)	Visual/laser 3D mapping, high-res surface imagery	Surface crack detection, 3D models of piers/sea walls
Satellite/Aerial Sensing	Broad-area environmental and thermal imaging	Monitoring coastal changes, environmental assessment

Side-scan sonar and multibeam echo sounders are vital for quickly scanning large areas and creating detailed maps of seafloor conditions, sediment movement, and the positioning of submerged hazards or wrecks. These technologies are less affected by turbidity and visibility problems than optical methods

[1, 10]. Optical methods can be use where water clarity allows, photogrammetry and LiDAR (light detection and ranging) generate high-resolution 3D models, enabling precise measurement of cracks, spalling, or concrete deformation [4]. Satellite and aerial sensing provides wide-area, integrated views of environmental changes (e.g., shoreline retreat, thermal anomalies), which are especially valuable for planning large-scale maintenance or disaster response [1, 11]. Combining these technologies within advanced inspection campaigns—often supported by automatic data fusion and AI—increases both coverage and reliability, and supports the move toward predictive maintenance and digital twin integration for complex marine assets [8, 9].

3. Results

3.1. Drones in NDT methods application

The use of underwater drones, especially remotely operated vehicles (ROVs), can transform the way marine concrete structures are inspected in the Baltic region. These platforms improve safety, enable access to hazardous or hard-to-reach areas, and allow regular, high-quality data collection for the assessment of structural condition [1, 12].

The versatility of modern ROVs allows integration of different sensors for a single mission. Ultrasonic probes are the most common choice for structural assessment underwater [12, 13]. Visual inspection (HD/4K cameras) is routine, though its utility may be reduced by water turbidity and fouling [1].

A major practical obstacle is biofouling—the buildup of algae, barnacles, and mussels—which obstructs both sensors and the features they're meant to detect. This is illustrated in Figure 4.

Fig. 4. Biofouling (growths and barnacles) visible on the surface of a submerged concrete pile.

Image processing algorithms and machine learning (including AI-based crack recognition) are increasingly used to compensate for fouling and poor visibility [8, 9]. ROVs can access entire breakwater or pier sections, record standardized measurements, and support ongoing trend analysis, setting a new standard for marine concrete inspection [7].

Table 3: Application of non-destructive methods (References: Lousada et al. 2021; Venkatesh et al. 2022; Pezeshki et al. 2023; Chasing-Innovation Technology Co. 2022; Meng et al. 2018; Lambertini et al. 2022)

NDT method	Compatibility with Drones/ROVs	Application
Ultrasonic testing (UT)	✓	Detecting internal cracks; thickness gauging of concrete/steel
Optical / Visual Inspection* (Cameras)	✓/x	Real-time HD video; surface defect and crack detection; AI detection potential; * Biofouling limits the method !
Electromagnetic methods (cover-meter, GPR)	?	Experimental underwater; possible future mapping of rebars/corrosion
Infra-red thermography (IR)	?	Feasible mainly for UAVs above water or very shallow, clear water with ROVs
Magnetic particle & Eddy-current (MT/ET)	x	Not used underwater with ROVs due to technical limitations

Radiographic testing (RT)	x	Not feasible for underwater drones/ROVs due to safety and logistical reasons

Note: ✓ – Widely used/feasible; ? – Limited/experimental/in development; x – Not feasible or not in practical underwater use

3.2. Challenges

Despite the many benefits brought by underwater drones and advanced NDT, inspections continue to face important challenges. Biofouling is a persistent problem, as marine organisms quickly cover both concrete surfaces and sensors, making crack detection and measurements much harder [4, 12]. Fine cracks and corrosion are often hidden under thick layers of algae, barnacles, and mussels (see Fig. 4 in previous section).

Poor visibility due to suspended sediments or plankton blooms regularly reduces the effectiveness of optical inspection and image-based analysis [1]. Even the best cameras often cannot compete with sonar or ultrasonic sensors when the water is murky.

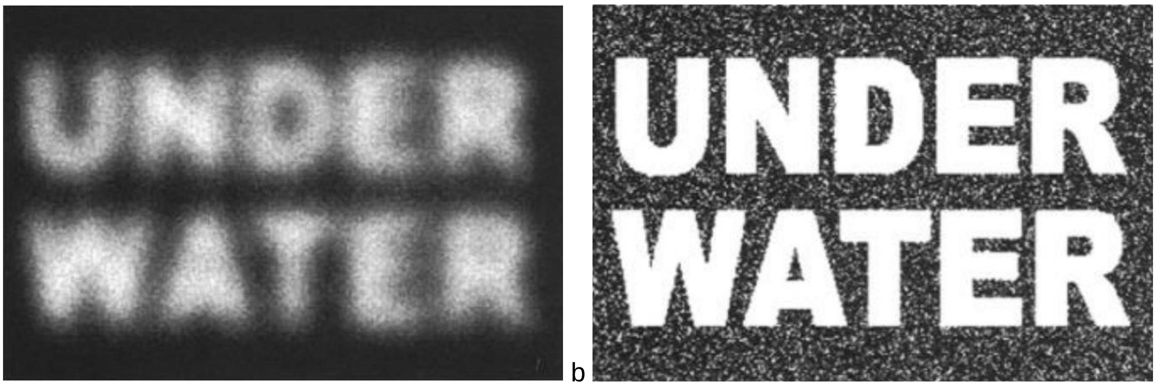

Fig. 5. Sample of underwater image restoration using Wiener filter: (a) blurred; (b) restored (Reference: [16])

Environmental hazards such as strong currents, ice cover, and rapid temperature changes limit the windows for safe ROV deployment. In winter, ice can make launching or recovering ROVs impossible for months [1].

Technical and operational issues include the need for frequent sensor cleaning and calibration (to maintain reliability), the limited endurance of drone batteries for long missions, and the complexity of processing large volumes of noisy data [7, 8]. Maintaining consistent data quality in these conditions requires both technological and strategic improvements—such as regular cleaning, advanced image processing, and good mission planning.

In summary, underwater inspections must manage a mix of environmental, technical, and logistical barriers. Overcoming them depends on further sensor innovation, robust AI for data filtering, and coordinated multidisciplinary project teams.

3.3. Opportunities

Recent advances in sensor technology, data processing, and robotics are opening up exciting possibilities for the inspection and protection of Baltic marine concrete infrastructure. One major opportunity is the use of artificial intelligence (AI) in image analysis. Deep neural networks, such as convolutional neural networks (CNN), can quickly and accurately identify cracks and distinguish between biofouling and real structural damage on ROV video feeds [9]. This greatly improves the speed and objectivity of inspections.

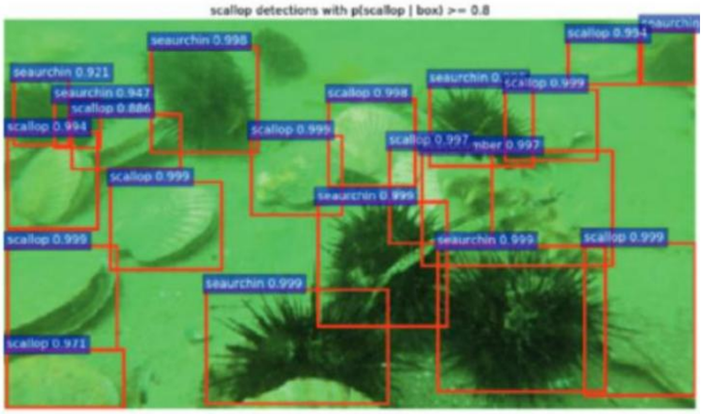

Fig. 6. Detection results of marine organisms using Deep CNN (Reference: Han et al. 2020)

In addition, the creation of digital twins—detailed, virtual 3D models of real-world structures that are kept up-to-date with live sensor data—makes it possible to visualize changes, predict maintenance needs, and manage assets more efficiently [8]. These digital systems can integrate results from periodic drone inspections, sensor networks, and even remote sensing (such as sonar or aerial surveys).

Modern ROVs/AUVs are also becoming smarter and more versatile. Thanks to improved navigation, longer battery life, and the ability to carry multiple sensors or cameras at once, they can collect vast amounts of high-quality data in a single mission [8, 12]. This means even difficult-to-reach or risky locations can now be monitored safely and regularly.

Finally, these technological innovations benefit not only operational assets but also heritage and environmental sites: non-invasive, data-rich survey techniques make it possible to protect both cultural landmarks and valuable ecosystems with minimal disturbance [8].

4. Conclusions

The integration of non-destructive testing (NDT) and remote sensing with underwater drones is revolutionizing the way marine concrete structures are monitored and managed. These advanced technologies make it possible to perform safer, more detailed, and more regular inspections than traditional diver-based methods [1].

Modern ROVs equipped with ultrasonic, optical, and environmental sensors allow for early detection of cracks, corrosion, and other signs of structural degradation—even in low-visibility, hazardous, or contaminated environments. The development of artificial intelligence and digital twins further enhances the value of these inspections, enabling automatic data analysis and predictive maintenance [8, 9].

Despite ongoing challenges—including turbidity, biofouling, limited battery life, and chemical hazards—continued research and interdisciplinary collaboration will improve the preservation of both infrastructure and heritage sites. Adoption of these innovations not only increases safety but also boosts the cost-effectiveness of maintaining critical underwater structures [7].

The experience gained in the Baltic Sea can set an example for other regions, showing how intelligent asset management—combining robotics, NDT, and advanced analytics—can extend the lifetime and safety of marine concrete assets.

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