Biofouling on structural materials of lock hydraulic structures

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Abstract. This paper addresses issues related to studying the mechanisms of biofouling formation and analyzing methods for their diagnosis and removal. Understudied aspects of this problem are identified and the applicability of existing methods is assessed. A comprehensive analysis of the processes of biofouling occurrence and development on ships is conducted, its biological composition is studied, the formation processes are modeled, countermeasure methods are considered, and the use of modern digital technologies is explored. The importance of research aimed at eliminating biofouling is emphasized, the nature and risks associated with these formations are identified, and the importance of diagnosing their component composition is substantiated. Special attention is given to the potential use of robotic systems with elements of artificial intelligence for monitoring and interfering with biofouling.

1 Introduction

The intensification of anthropogenic impacts on water resources, reflected in the increasing number and variety of underwater engineering structures, has a multifaceted impact on aquatic ecosystems. The nature and extent of this impact, including both positive and negative aspects, remain the subject of scientific debate. Furthermore, underwater structures in coastal zones are subject to complex abiotic factors (hydrodynamic loads, temperature, acidity), which induce significant mechanical stress in materials, determining their strength characteristics and durability, as well as affecting the system reliability, functionality, and environmental safety of the structures.

Any artificial substrate, whether immersed in freshwater or marine environments, is colonized by aquatic organisms, which can lead to the impairment of the functional characteristics of the structures. Structures such as locks, piers, hydroelectric power plant structures, port facilities, canal walls, aquaculture facilities, and ship hulls are susceptible to the growth of benthic flora and fauna, a phenomenon known as biofouling.

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On the one hand, these structures can have a positive impact on the marine environment by serving as additional hard substrate for various taxa (hydroids, polychaetes, amphipods, mollusks) that form communities subject to successional changes. Certain aquatic organisms, such as mussels or amphipod tubes, serve as secondary substrate for new colonizers. On the other hand, a potential negative consequence is the role of artificial structures as vectors and "springboards" for the introduction and subsequent dissemination of invasive species within fouling communities, which can dominate native taxa.

Biofouling communities are recognized as some of the most productive and diverse macrobial communities globally [1–4]. Globally, they are largely represented by similar taxonomic groups: shell-forming foulers (tube worms, bivalves, mussels, oysters) and soft-bodied colonizers (hydroids, algae, kelp), even with species differences. Abiotic factors (hydrodynamics, temperature, nutrient concentration, illumination, tidal phenomena, depth) determine the species composition and structure of fouling communities, causing their significant variability between and within ecoregions. Additional factors influencing fouling dynamics include distance from the shoreline and substrate type and spatial orientation. Epibiotic communities on artificial substrates typically differ taxonomically from those on natural substrates, and spatial differences at the macro- and micro-levels also correlate with the complexity of available ecological niches.

Thus, the underwater surfaces of canal hydraulic structures' metal structures function as a solid vertical substrate colonized by communities of numerous periphyton species—fouling aquatic organisms whose taxonomic range extends from unicellular algae, fungi, and bacteria to mollusks, crustaceans, and sponges. The aquatic community that forms on structures in flowing waters is of significant interest to hydrobiologists as a natural population-species cross-section of the reservoir's flora and fauna. In addition to fouling organisms, it includes planktonic and benthic organisms lacking their own biological anchoring mechanisms but settling on the substrate and fouling organisms from the water flow [5–9].

The vertical stratification, height, and underwater surface area of such structures make it possible to assess the bathymetric distribution of species, quantitative abundance, and biomass of fouling aquatic organisms, as well as determine the quantitative and mass proportion of invasive species in the ecosystem. Furthermore, certain periphyton species serve as bioindicators of aquatic environmental quality, while others, being active filter feeders, contribute to its self-purification. The dominant fouling organisms—mollusks and crustaceans—also form a significant portion of the food supply for the reservoir's ichthyofauna.

Consequently, the impact of biofouling on artificial structures, which reduces their operational efficiency and reliability, has economic consequences for industries such as energy and aquaculture, necessitating fundamental research into the development and composition of these communities. Scientific research in the field of biofouling is of fundamental importance for developing economic sectors and regions. Previous studies have demonstrated that micro- and macrofouling organisms (bacteria, oysters, mussels) initiate localized corrosion processes in metal structures; these effects are classified as highly destructive, as they lead to damage to metal surfaces, the material itself, or its protective coatings.

2 Materials and Methods

The primary mechanism of biofouling is the formation of biofilms on the surfaces of structures. These biofilms act as a link between aquatic organisms and the substrate. The process begins with the formation of biofilms, after which macrofoulers colonize all underwater surfaces. According to literature [4], mechanical cleaning, application of antifouling coatings, and regular underwater cleaning are used to remove biofouling. The effectiveness of waterjet machining has also been demonstrated.

When using antifouling paints [10], ship hulls and structural elements are coated with compounds containing biocidal components that either inhibit the growth of organisms or cause their death.

As our research has shown, understanding the spatial organization of biofouling layers is fundamental to the development of effective control strategies. This task is particularly relevant in light of the emergence of new physical control methods based on ultrasound and laser irradiation, which have demonstrated high efficiency. Therefore, the development of reliable methods for biofouling diagnostics appears essential for progress in this field.

In scientific practice, it is common to classify biofoulings taxonomically. Biofouling organisms include both prokaryotic and simple eukaryotic organisms (bacteria, algae), as well as complex macroorganisms (mollusks, polychaetes, and some fish species). An additional criterion for classification is colonization rate, which allows for the distinction between rapidly forming biofilms and slowly growing colonial organisms.

2.1 Study of the structure of biofouling

Our study attempted to identify plant organisms within a homogeneous biofouling layer. To this end, we conducted a photoluminescence study of green plants and algae. The experiment revealed that intense red photoluminescence was observed when excited by radiation of specific energies. The photoluminescence spectra of green plants in all cases exhibited two closely spaced peaks. Significantly, the energy characteristics of both peaks remained virtually identical for different plant species.

These results suggest that modern technological solutions, such as underwater unmanned vehicles equipped with high-resolution cameras or mobile photoluminescence systems, offer new opportunities for real-time monitoring of underwater objects, as previously demonstrated using the hulls of sea vessels [5].

Images obtained by such drones can be processed using deep learning methods, which successfully handle large volumes of visual data. Algorithms based on neural networks are capable of detecting and classifying various types of biofouling by training on pre-labeled data. Convolutional neural networks (CNNs) are particularly effective in visual classification tasks because they are able to identify informative features in images, increasing the reliability of identification.

3 Result and Discussions

Significant potential in biofouling classification lies in the use of real-time artificial intelligence systems. Equipping underwater unmanned vehicles with video data transmission systems enables monitoring of ship hulls and hydraulic structures without decommissioning. Integrating machine learning algorithms into diagnostic systems enables rapid analysis of incoming data and the generation of practical recommendations. This approach enables timely identification of changes in surface condition and the initiation of appropriate preventative or remedial measures, thereby optimizing operating costs and increasing shipping efficiency. However, the successful implementation of such systems requires consideration of a number of critical parameters, among which the representativeness and volume of training data are fundamental. Generating diversified sets of biofouling images in combination with data augmentation methods can significantly improve classification accuracy. Particular attention should be paid to studying the impact of variable lighting conditions and the optical characteristics of the aquatic environment on the reliability of the algorithms. The implementation of standardized validation protocols [11] ensures verification of the effectiveness of developed solutions and guarantees their operational reliability during industrial operation.

In the context of the rapid development of robotics and artificial intelligence, there is growing scientific and practical interest in the development of automated ship hull cleaning systems (Fig. 1). Modern robotic platforms are characterized by the ability to perform effective and safe cleaning in a variety of environmental conditions, which determines their significant economic potential and practical value for the maritime industry.

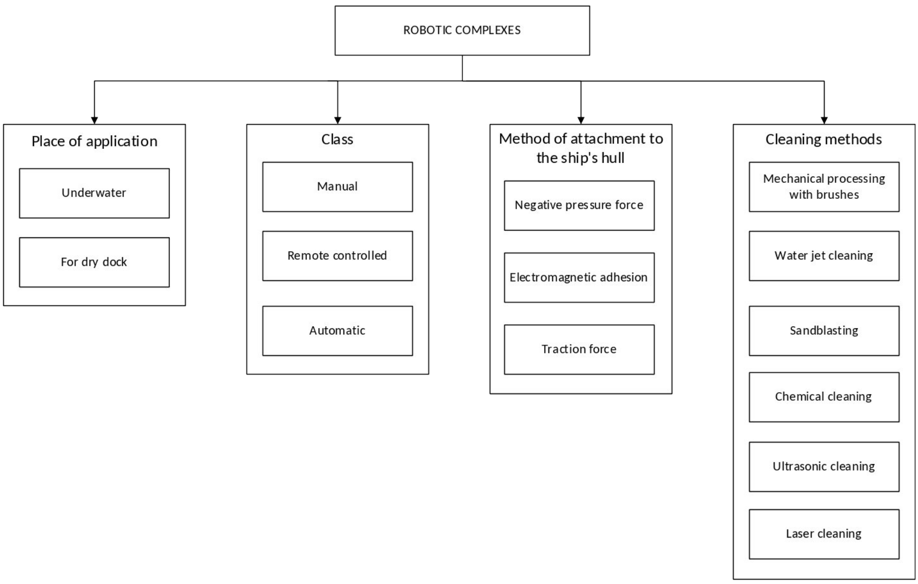

Fig. 1. Classification of robotic systems used for cleaning ship hulls from biofouling.

The underwater robotic cleaning system's architecture is divided into above-water and underwater components. The above-water segment includes the operator console, the lowering and recovery winch, and the communications system. The underwater module integrates the control computer, adhesive system, propulsion units, cleaning tool, navigation sensors, hydroacoustic equipment, and a machine vision system. A schematic diagram of the robotic system for cleaning hull structures is shown in Figure 2.

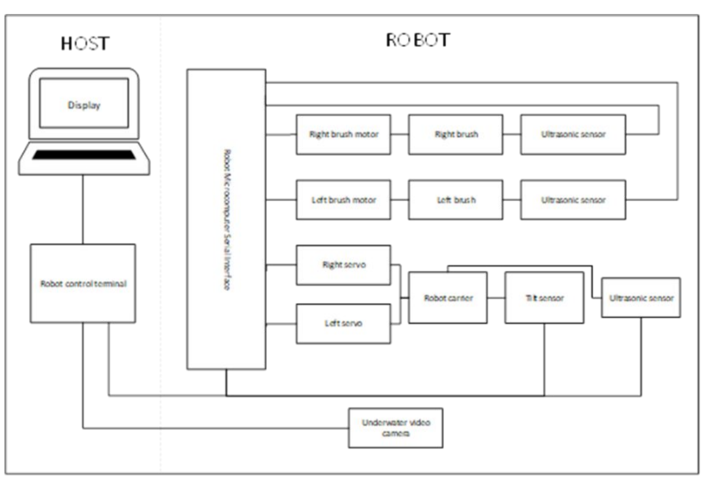

Fig. 2. Robot diagram scheme.

The robot moves along the surfaces of underwater structural elements using a propulsion system. Directional control is provided by differential adjustment of the angular velocities of two independent drives. A permanent magnet system is used to ensure adhesion to vertical and inclined surfaces. Surface cleaning is performed by brush mechanisms as the robot moves along a predetermined trajectory. The cleaning device consists of rotor brushes, an actuator module, and a supporting frame. Two electric motors, which drive the brush elements, operate in opposite directions [12]. The cleaning process is continuous as the robot advances until the operation is completed.

The operation of the underwater unmanned vehicle for inspecting and cleaning hydraulic structures from biofouling begins with its immersion in the aquatic environment. The first stage involves examining the underwater structures or localized areas, including the bottom and side surfaces. To obtain high-quality images of the propulsion system, the propulsion system must be stopped, eliminating vibration interference and ensuring highly detailed images (Fig. 3). After completing the comprehensive survey, a convolutional neural network analyzes the resulting images, identifies biofouling zones, and classifies them based on pre-trained models. Based on the analysis results, a decision is made on the type of apparatus and the cleaning equipment configuration appropriate to the nature of the detected fouling. Drones with a low-pressure adhesion system, which ensures stable attachment to surfaces and high maneuverability in underwater conditions, appear particularly promising.

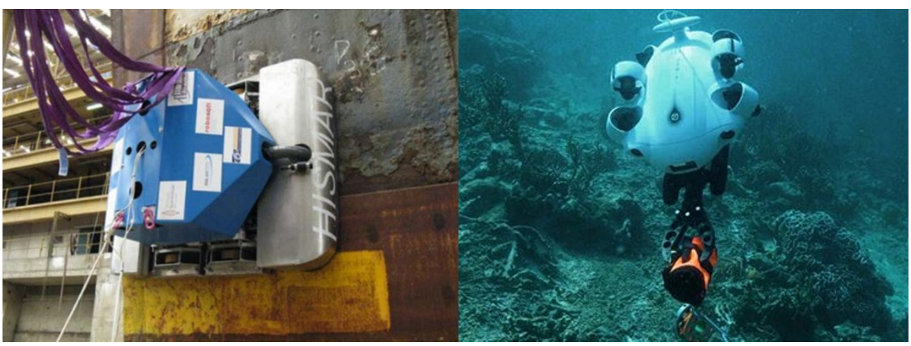

Fig. 3. An example of drones operating in dry dock and underwater mode to combat biofouling.

3.1 Design of underwater cleaning device

The underwater cleaning unit is the drive module of a robotic system for cleaning hydraulic structures. The unit's design includes brush elements, a drive motor, and a supporting structure. The brush assembly consists of a cleaning disc made of stainless steel with a semi-clutch and steel bristles. To achieve maximum cleaning efficiency, wire with an optimal combination of hardness and elastic properties is used.

The cleaning disc is made of aluminum alloy and secured to a separate coupling kinematically linked to the drive motor. The supporting structure is made of aluminum alloy and uses sealed bearing assemblies. Two cleaning units, mounted in the bow of the unit, operate in opposite directions, which compensates for torque and improves system stability.

3.2 Development of a remote floating energy conversion device

Fixing errors in algorithms is a key part of current monitoring systems. The Kalman filter is often used for state guess in moving systems, but it uses linear models and Gaussian noise—ideas that are often not true in real situations with non-linear sensor behavior or complex environmental disturbance.

It is seen as useful to fit an underwater vehicle with an external floating device for turning sunlight into electricity. This will allow for a lighter underwater vehicle design by splitting it into two parts: the working part and the power-making part.

How well solar energy is turned into electrical energy depends on two things: how well the sun's optical rays are physically turned into electrical energy, and keeping the right angles so that direct sunlight hits the solar cells correctly. The panels we use show an efficiency of 24-26% at an optical air mass of 1.5, a solar optical flux of 1000 W/m^2^, and a temperature of 25°C. Highly efficient silicon structures are being made for use as solar cells.

(μcxa1−x)-Si:H films were grown by plasma assisted growth using hydrogen-diluted silane (SiH4). Light on all the resulting heterostructures caused a photovoltaic effect. The sign of this effect did not depend on where the light probe (diameter about 0.2 mm) was on the structure surface or the energy of the incoming photons. So, it can be thought that the photovoltaic effect in these cases is set by a single energy barrier that comes from depositing thin films on a single-crystal c-Si substrate. Usually, the photosensitivity of such heterostructures is stronger when light detection is done with light coming from the thin film side.

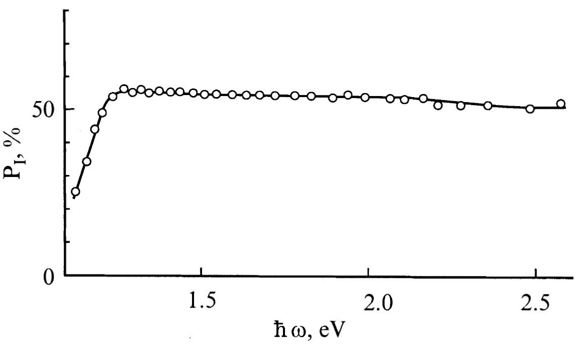

Fig. 4. Spectral dependences of the induced photopleochroism coefficient of the PI heterostructure (μcxa1−x)-Si : H / c-Si, T = 300 K (θ = 75^0)

Polarization photosensitive spectroscopy methods were used to study the photosensitivity of photovoltaic cells. For this, linearly polarized radiation (LPR) was aimed at the receiving plane of (μcxa1−x)-Si:H/c-Si heterostructures. It was found that the angular dependences of the photocurrents i~P~ and i~S~ in these heterostructures match the Fresnel relations for the amplitude transmission coefficients of LPR at different azimuths of the air/film (μcxa1−x)-Si:H/c-Si interface. Across the whole photosensitivity range of the studied heterostructures, the photocurrent i~P~ first goes up with increasing θ and reaches a highest point, i~P~^m^, after which it goes down. The coefficient of photopleochroism caused by slanted incidence of LPI for the obtained (μcxa1−x)-Si:H/c-Si heterostructures follows a θ^2^ relationship as the angle of incidence grows across the whole photosensitivity area. The size of the coefficient of caused photopleochroism in these heterostructures at θ = constant stays almost the same within their photosensitivity area (Fig. 4), as it does for surface-barrier structures. It is important to note that the value of P~I~ in these heterostructures agrees with the refractive index for bulk c-Si, which is also typical for surface-barrier structures. This also shows the high manufacturing quality of the photovoltaic structures used.

3.3 Development of a control system

The control system for the underwater robotic system for cleaning hydraulic structures is implemented using a two-tier architecture. The upper tier, represented by the main computing station located in a protected container on the deck, processes the user interface, initializes initial environmental parameters, assigns tasks, plans trajectories, and visualizes telemetry data. The lower tier, implemented on the slave computing module mounted on the robot carrier, executes commands from the central processor, controlling the vehicle's movement and the operation of the cleaning unit [13, 14].

Data exchange and power supply are provided via a combined cable input. Spatial position and motion parameters are determined using an inclinometer and an ultrasonic sensor system, which correct and program the trajectory of the brush mechanisms. An underwater television system provides visual monitoring of the robot's condition and diagnostics of the surfaces being treated.

4 Conclusion

Conducted studies demonstrate that identifying the species composition of biofouling on underwater structures of energy facilities is a critical element in developing effective diagnostic and monitoring methods. The use of artificial intelligence technologies to classify biofouling based on remote sensing data obtained by underwater unmanned vehicles offers potential for optimizing operational processes in the agricultural sector.

The proposed concept of using autonomous vehicles with integrated AI systems offers significant potential for efficiency. Implementation of this approach enables the creation of a comprehensive system in which underwater drones not only monitor the condition of structures but also maintain their operational performance, ensuring a high level of automation of technological processes and minimizing human error.

The implementation of such a system will improve the efficiency and effectiveness of biofouling prevention and removal measures. This will result in an increase in the service life of energy facilities and a reduction in operating costs, which is essential for the sustainable development of the agricultural sector.

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