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Use of an ROV with Modulated Lighting for Diagnosing the Technical Condition of Submerged Port Wharf Structures

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ABSTRACT: The technical condition of underwater port structures is critical to the safety and longevity of maritime infrastructure. Traditional inspection techniques, such as diver-assisted surveys, are constrained by safety risks, limited duration, and reduced efficiency in turbid waters. This study explores the application of a remotely operated vehicle (ROV) equipped with modulated lighting systems to enhance visibility and facilitate high-resolution imaging in optically complex underwater environments. The experiment employed a CHASING M2 ROV, modified with red, green, and white lighting configurations, to inspect the quay wall of a port. The impact of lighting color on image quality was evaluated. Results indicate that modulated lighting tailored to the optical properties of turbid coastal waters can improve image contrast and facilitate defect detection. The findings highlight the potential for advanced ROV systems to augment underwater inspection protocols in challenging optical environments.

1 INTRODUCTION

Remotely Operated Vehicles (ROVs) are tethered to and controlled from surface vessels, enabling the exploration and monitoring of underwater environments without the physical presence of human operators within the vehicle [13]. The application of ROVs in the technical inspection of submerged components of marine and coastal infrastructure is of significant importance. By means of video recording, digital imaging, technical data acquisition, and seabed topographic surveys, ROVs facilitate the collection of critical information necessary for the design, construction, maintenance, and rehabilitation of these structures. Routine inspections are essential to ensuring the operational integrity and longevity of any underwater infrastructure [12]. In particular, the inspection of port infrastructure plays a pivotal role in maintaining safe, efficient, and sustainable port operations.

In the context of Polish seaports, the frequency and scope of quay inspections are governed by port regulations established by the directors of maritime offices with jurisdiction over specific coastal areas. These regulations stipulate the obligations of quay operators regarding the upkeep and monitoring of port infrastructure. Specifically, operators are required to conduct periodic hydrographic soundings and seabed cleanliness assessments in the zones adjacent to quays and port basins.

The utilization of ROVs in underwater surveying and inspection is a relatively recent advancement, which contributes to the limited volume of academic and technical literature addressing this methodology [18]. The most pertinent publication in this domain is [19], originating from Lithuania, which details the deployment of a domestically developed ROV comparable to the one employed in the present study. However, the Lithuanian research primarily focused on the inspection of a vessel's submerged hull and the development of a related database. A comprehensive review of existing literature indicates that future port infrastructures are expected to integrate advanced automation technologies, electrification, and intelligent energy management systems [7].

The deployment of Remotely Operated Vehicles (ROVs) for the technical inspection of underwater port infrastructure represents a promising and increasingly viable alternative to traditional diver-based methods. This approach offers the potential to substantially reduce operational costs, inspection timeframes, and risks to human safety. As diagnostic platforms, ROVs can be outfitted with a range of sensor systems and imaging technologies, facilitating the collection of high-resolution visual data and comprehensive technical information.

The objective of the present study is to assess the feasibility of utilizing ROVs equipped with modulated lighting systems for the visualization and diagnostics of the technical condition of submerged components of port wharfs. The goal is to determine whether this approach can serve as a cost-effective yet equally reliable alternative to conventional underwater inspection techniques.

The successful planning and execution of underwater engineering, inspection, and maintenance activities depend critically on the optical characteristics of the aquatic environment. In particular, two key parameters—remote sensing reflectance (Rrs) and turbidity—are instrumental in characterizing water clarity, light propagation conditions, and the overall suitability of a given water body for vision-based operations. These parameters are especially pertinent in port environments, where the presence of suspended particulate matter (SPM), dissolved organic and inorganic substances, and hydrocarbon-based pollutants such as oil significantly affects underwater visibility and image quality [9].

Among these factors, high turbidity constitutes the most prominent challenge to effective underwater imaging. Turbidity results primarily from elevated concentrations of suspended particulate matter, which scatter incident light and thereby impair visibility and reduce the quality of acquired imagery. This scattering is quantitatively described by the Volume Scattering Function (VSF) (Formula 1), which represents the angular distribution of scattered light intensity dI per unit incident irradiance E in a given volume dV.

$$VSF(\theta,\lambda) = \frac{dI(\theta,\lambda)}{E(\lambda)\cdot dV}\left[m^{-1}sr^{-1}\right] \quad (1)$$

This formulation accurately characterizes the phenomenon of single scattering. In marine environments, the Volume Scattering Function (VSF) is known to exhibit significant asymmetry. Specifically, forward scattering may exceed backscattering by up to six orders of magnitude [15], a disparity that substantially degrades the clarity of images acquired in turbid waters. This pronounced anisotropy in scattering behavior has been confirmed by the pioneering measurements conducted by Petzold [14], as well as by subsequent studies carried out in the Baltic Sea [3, 4].

The integral of the VSF over the full solid angle domain yields the scattering coefficient $b(\lambda)$, which quantifies the total amount of light scattered per unit length and is expressed in units of m^{-1}:

$$b(\lambda) = 2\pi\int_0^{\pi} VSF(\theta,\lambda)\cdot sin\theta d\theta\left[m^{-1}\right] \quad (2)$$

In axially symmetric systems, where particle orientation is random, the scattering phase function—defined as the Volume Scattering Function (VSF) normalized by the scattering coefficient $b(\lambda)$—describes the angular probability distribution of scattered light. In highly turbid waters, where the mean free path of photons is reduced to the order of centimeters, multiple scattering effects become predominant. Under such conditions, the single-scattering approximation is no longer valid, resulting in glare and diminished image contrast, particularly when conventional, non-collimated lighting is employed.

Turbidity represents a direct measure of water clarity, quantifying the cloudiness or haziness caused by the presence of numerous light-scattering and light-absorbing particles. It is typically expressed in Nephelometric Turbidity Units (NTU) and shows a strong positive correlation with the scattering coefficient $b(\lambda)$, while correlating inversely with underwater visibility [5]. Beyond its influence on light propagation, turbidity imposes a fundamental limit on the effective imaging range of optical sensors. Turbidity levels are typically elevated in coastal and port environments due to anthropogenic activities such as dredging, vessel movement, and industrial discharges.

In oligotrophic oceanic waters, turbidity is minimal, allowing light penetration depths to exceed 30 meters. Conversely, in turbid port environments, visibility may be restricted to less than 1 meter due to high concentrations of suspended particulate matter (SPM). The particle size distribution (PSD), refractive index, and angular scattering properties of the water are strongly influenced by the composition and origin of the particulates, all of which modulate light–matter interactions within the medium.

SPM in port waters is predominantly generated by sediment resuspension processes and typically consists of silts, clays, and other mineral particles. These particulates are highly efficient at scattering light, particularly in the forward direction. In port areas, sediment resuspension is frequently induced by vessel propeller wash, cargo handling operations, and construction-related activities. The backscattering coefficient $b_b(\lambda)$ increases proportionally with mineral content, contributing to elevated remote sensing reflectance (R_{rs}) values, especially within the green and red spectral bands.

Absorption is another critical factor affecting underwater visibility. In clear, oligotrophic waters, blue light exhibits the greatest penetration depth, owing to minimal absorption by both water molecules and colored dissolved organic matter (CDOM). In contrast, turbid coastal waters—characterized by elevated concentrations of CDOM and SPM—exhibit absorption minima in the mid-visible range (500–600 nm), resulting in the characteristic green coloration of such waters [6; 8; 17].

Remote Sensing Reflectance (R_{rs}) (Formula 3) describes the spectral ratio of water-leaving radiance (L_w) to downwelling irradiance (Ed).

$$R_{rs} = \frac{L_w(\lambda)}{E_d(\lambda)} \quad (3)$$

Remote sensing reflectance (R_{rs}) is significantly influenced by both the absorption and backscattering coefficients, which are themselves governed by the concentration, size distribution, and composition of suspended particulate matter. In underwater environments where visual tasks such as crack detection, biofouling assessment, and infrastructure mapping are of critical importance, R_{rs} functions as a real-time, non-invasive indicator of water clarity. As such, it can inform both lighting modulation strategies and image post-processing techniques employed by Remotely Operated Vehicles (ROVs). R_{rs} typically exhibits peak values at wavelengths where absorption is minimal and backscattering is relatively high. This spectral behavior has direct implications for the design of ROV lighting systems: rather than relying on broadband white light, the use of spectrally optimized light sources—particularly within the green region (500–600 nm)—can enhance image contrast and depth perception under turbid conditions.

In addition to particulate-induced turbidity, the presence of oil and hydrocarbon derivatives introduces further complexity to underwater optical assessments. This is particularly relevant in port and harbor environments, especially those in proximity to petrochemical terminals, where surface oil films, dispersed oil droplets, and emulsified hydrocarbons are frequently observed. These substances induce nonlinear optical effects due to their complex refractive indices and strong wavelength-dependent absorption and reflection properties [9; 11].

Oil contamination in water typically leads to increased absorption at shorter wavelengths (blue–violet) and generates specular reflections at air–oil–water interfaces. Furthermore, emulsified oil droplets can modify the scattering phase function by enhancing mid-angle and backscattering components. This optical alteration results in elevated Rrs values in the red and near-infrared spectral regions, while simultaneously diminishing spectral contrast. The resulting flattening of the reflectance spectrum reduces the effectiveness of color-based segmentation and object detection algorithms commonly used in underwater computer vision systems.

Consequently, ROVs operating in port environments must be capable of adapting to dynamically variable optical conditions, which may arise from fluctuating concentrations of suspended particles, oil contamination, and inputs from urban runoff.

2 METHODOLOGY

The ROV used in this experiment is CHASING M2 (figure 1), which is a compact-sized, professional underwater ROV designed for professional users and industrial applications. Its compact aluminium alloy body allows for single-person operation and quick deployment. The M2 features omni-movement in all directions, and thanks to its depth-lock function, it can hover precisely in any position. This enables underwater photography, observation, and manipulation at any angle. The ROV is compatible with various attachments such as a Robot Claw, GoPro camera, external LED lights, and a laser scaler, with a maximum mounting payload of 1.5 kg. The default battery provides up to 4 hours of continuous operation. CHASING M2 is capable of recording underwater temperature and depth, providing professional underwater data support. Its maximum working depth is 100 meters, and the operating temperature ranges from -10 ℃ to 45 ℃. The device achieves a maximum speed of 1.5 m/s (3 knots). Additionally, the M2 is equipped with two LED lights with a total brightness of 4000 lumens (three gears), which compensate for the darkness of deep water.

They improve underwater distance and visibility clarity, significantly restoring natural underwater colors. It is also equipped with a 4K video resolution camera and the ability to observe during investigation by connecting a phone to the remote controller [2]. A GoPro camera was used, which was mounted on the vehicle.

Figure 1. Chasing M2 - ROV with GoPro camera used in experiment

In the conducted experiment, white, red, and green light were used to investigate how the colour of light affects the image observed beneath the water's surface (figure 2,3,4).

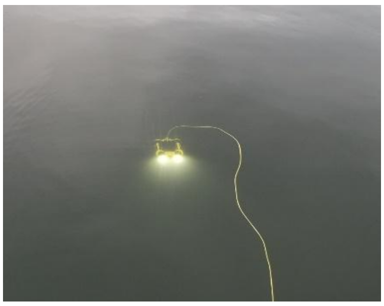

Figure 2. White light

Figure 3. Red light

Figure 4. Green light

3 RESULTS

The technical condition survey of the port's quay wall was conducted using an ROV. The inspection work commenced with scanning the vertical face of the quay wall along the entire length of the examined section (figure 5,6).

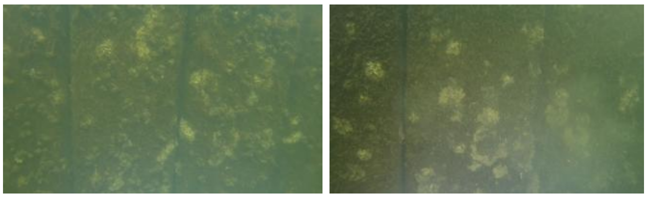

Figure 5,6. Visibility of quay wall with daylight

The ROV, equipped with a high-resolution video camera and LED lighting, moved along the structure, recording real-time imagery. The first series of observations was conducted using standard white light (figure 7,8), which served as a baseline for assessing overall visibility and the characteristics of the underwater image. Subsequently, red (figure 9,10) and green (figure 11,12)light were used.

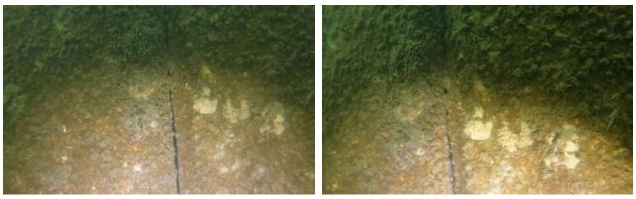

Figure 7,8. Visibility near the quay wall with white light

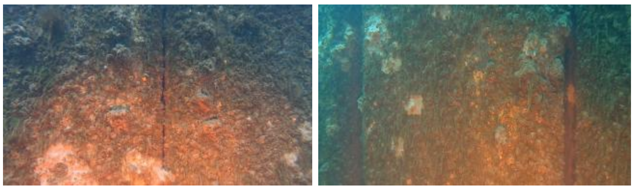

Figure 9,10. Visibility near the quay wall with red light

Figure 11,12. Visibility near the quay wall with green light

Under daylight conditions, visibility was low due to ambient light scattering and absorption (Figures 5, 6). Switching to ROV-mounted illumination improved image acquisition. For white light (Figures 7 and 8) it provided balanced spectral coverage, but succumbed from glare and low contrast in turbid water due to multi-wavelength backscatter.

In case of red light (Figures 9 and 10) scattering was minimized but was rapidly absorbed, limiting visibility to a short range. Figures 11 and 12 show that for green light optimal visibility has been delivered. The wavelength (~550 nm) aligns with the absorption minimum in CDOM-rich waters, improving depth penetration and structural detail clarity.

4 DISCUSSION

Quantitative image analysis revealed that green light increased the signal-to-noise ratio (SNR) of structural features by approximately 25% compared to white light and 40% compared to red light. Metrics such as edge contrast (Ce), grayscale variance (σ2), and histogram entropy (H) were computed to evaluate image quality under each spectral condition (Table 1). Edge detection was first performed using a Sobel filter [1], and then average contrast was computed across a representative sample of edge segments. Moreover grayscale variance was calculated for each image after converting to grayscale. Histogram entropy H was calculated using the Shannon entropy formula [16]. In table 1 summarizes the results of image quality assessment for three spectral lighting conditions (white, red, and green) used during ROV inspections.

Table 1. The quantitative evaluation of image quality under different lighting conditions

light	C_e (mean)	σ^2	H
white	0.42	1056	6.72
red	0.31	678	5.88
green	0.54	1420	7.12

where edge contrast was calculated using the difference in pixel intensity across detected edges:

$$C_e = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \tag{4}$$

where:

– I_{max} - maximum pixel intensity on one side of an edge.
– I_{min} - minimum pixel intensity on the other side.

Whereas grayscale variance was computed using:

$$\sigma^2 = \frac{1}{N}\sum_{i=1}^{N}\left(I_i - \bar{I}\right)^2 \quad (5)$$

where:
– I_i - intensity of the i-th pixel,
– $\bar{I}$ - intensity of the image,
– N - number of pixels.

The histogram entropy H was calculated using formula:

$$H = -\sum_{i=1}^{L} p_i log_2 p_i \quad (6)$$

where:
– p_i - probability of the i-th grayscale level.
– L - total number of intensity levels.

Figures from 5 to 12 show that it is the green light that consistently produced images with higher contrast and lower noise levels. Green lighting outperformed red and white in all three metrics, indicating better contrast, structural detail, and texture preservation. Red lighting, while reducing glare, low in entropy and variance due to loss of detail. White lighting offered balanced performance but introduced substantial backscatter, diminishing edge clarity. Red lighting, while effective at minimizing glare, was found insufficient for identifying fine surface features beyond 1 meter of standoff. This is attributed to high absorption of red wavelengths in water. Conversely, white light produced adequate results at close range but was impaired by multi-directional scattering artifacts.

The use of modulated lighting markedly improved the ability to discern surface textures, cracks, and biofouling on the quay wall. These study's findings align with established principles of underwater optics, where water's absorption and scattering characteristics vary across different wavelengths. Green light's optimal balance between absorption and scattering makes it particularly effective for underwater imaging in turbid conditions. The rapid absorption of red light and the high scattering associated with white light limit their utility in such environments.

The integration of modulated lighting systems, particularly those utilizing green LEDs, can significantly enhance the capabilities of ROVs in conducting underwater inspections. By improving visibility and image clarity, these systems enable more accurate assessments of structural conditions, facilitating timely maintenance and repair interventions. The findings underscore the importance of tailoring ROV lighting configurations to the specific optical properties of the inspection environment (local approach).

Advancements in adaptive lighting technologies and real-time image processing algorithms hold promise for further enhancing ROV-based inspections. The development of systems capable of dynamically adjusting lighting parameters in response to environmental conditions could optimize image quality across a range of turbidity levels. Additionally, integrating machine learning techniques for automated defect detection could streamline the inspection process and reduce reliance on manual analysis.

5 CONCLUSIONS

The results presented in this work may be used in the future to provide a quantitative foundation for selecting the optimal lighting spectrum for underwater ROV inspections. It has been shown that modulated lighting, particularly green light at approximately 550 nm, significantly improves image clarity and defect detection during ROV-based underwater inspections in turbid water conditions. Moreover red light's rapid absorption and white light's high scattering limit their effectiveness in enhancing visibility in such environments. Therefore, tailoring ROV lighting configurations to the specific optical properties of the inspection environment is crucial for optimizing image quality and inspection accuracy. Future research should focus on the development of dynamic lighting control systems and the incorporation of automated image analysis tools to streamline the inspection process and improve the reliability of defect detection. The integration of advanced lighting systems and adaptive technologies can further enhance the capabilities of ROVs, enabling more efficient and effective underwater inspections. Moreover, without real-time knowledge of R_{rs} and turbidity, visual navigation and inspection become compromised, leading to false negatives in defect detection or navigation errors. Therefore, deploying in situ sensors capable of measuring R_{rs} and turbidity profiles at multiple depths can inform lighting configuration (e.g., selecting appropriate LED spectra) and camera exposure settings.

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