BULLETIN of Cherkasy State Technological University

Journal homepage: https://bulletin-chstu.com.ua/en Vol. 30 No. 1. 2025

UDC 004.056.55:004.75
DOI: 10.62660/bcstu/1.2025.21

Sonar image processing for improved underwater environment modelling

Oleksandr Katrusha*
Master
National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"
03056, 37 Beresteiskyi Ave., Kyiv, Ukraine
https://orcid.org/0009-0008-7097-4843

Artem Burdeinyi
Master
National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"
03056, 37 Beresteiskyi Ave., Kyiv, Ukraine
https://orcid.org/0009-0009-3113-2149

Abstract. The purpose of the study was to present a sequence of development of an algorithm for improving the quality of images obtained using side-scan sonar. Mathematical image processing techniques such as contrast enhancement, edge processing, and colorimetric techniques were used to achieve this goal. Steps to improve image contrast included normalising signal intensity, adaptive contrast enhancement using limited contrast alignment of histograms, and correction of uneven lighting. The sonar radiation pattern and image intensity normalisation scheme were demonstrated. The contrast limited adaptive histogram equalisation filter showed higher values of the peak signal-to-noise ratio and structural similarity index compared to conventional histogram alignment, indicating better preservation of detail, image structure, and noise reduction. Analysis of edge processing, in particular by Canny and Sobel, has shown their potential effectiveness in improving the detail of underwater structures. In addition, the use of Gaussian smoothing allowed reducing the level of high-frequency noise and make textures smoother. As a result, there was a decrease in graininess, softness of object contours, and overall smoothing of the scene. In addition, cubic spline regression showed normalised image data. In turn, colorimetric analysis focused on converting images between greyscale and colour spaces, which made it easier to identify underwater objects and structures. An example of Hue-Saturation-Value components was given, which demonstrated different effects on the quality of sonar image visualisation. The Value component provided the most expressive distinction between the object and the background, while the Hue component was ineffective for structure analysis. The combination of Value and Saturation allowed for improved contour detail. Optimisation of the pseudo-colour gamut allowed adapting the image to different tasks, contributing to more accurate object recognition. The results obtained confirm the feasibility of using the presented methods in a wide range of applied tasks related to visualisation and analysis of underwater environments

Keywords: contrast adjustment; edge selection; colourimetric analysis; distortion elimination; adaptive anti-aliasing

Article's History: Received: 18.09.2024; Revised: 20.02.2025; Accepted: 17.03.2025.

Suggested Citation:
Katrusha, O., & Burdeinyi, A. (2025). Sonar image processing for improved underwater environment modelling. *Bulletin of Cherkasy State Technological University*, 30(1), 21-34. doi: 10.62660/bcstu/1.2025.21.

*Corresponding author

Copyright © The Author(s). This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/)

INTRODUCTION

Sonar is one of the main technologies for studying the underwater environment, in particular, for detecting and mapping objects on the sea floor. This is the process of using sound waves to determine the location and characteristics of underwater objects, where sonar is the main element. A sonar is a device that sends and receives acoustic signals, and a sonogram is an image that is obtained as a result of sonar operation. One of the most common types of sonar is side-scan sonar (SSS), which is used to create detailed images of the underwater surface by sequentially scanning it using narrow-band ultrasonic waves. The SSS system operates on the principle of emitting sound waves reflected from objects on the sea floor and receiving reflected signals, which allows creating a clear image with high resolution. The use of this type of sonar is important in research where accurate visualisation of underwater structures and objects is required. One of the main problems in using sonar is the relatively poor quality of the resulting images, often due to factors such as poor contrast, noise, and distortion that make it difficult to interpret the data. A significant obstacle is that the appearance of band noise from roll variations negatively affects image clarity, particularly making object recognition and seabed segmentation difficult (Katrusha, 2024). In addition, existing image processing methods do not always effectively cope with the correction of uneven lighting and image detail, which creates difficulties in accurately detecting underwater objects and structures.

For a better understanding of this topic, it is necessary to consider other papers. For example, V.I. Ivaniuk *et al.* (2024) proposed the integration of colour reconstruction and deep learning (DL) on board autonomous unmanned underwater vehicles to improve the accuracy and speed of underwater object detection, considering the complexity of the environment. For its part, N.F. Bogomolov *et al.* (2021) analysed speckle interferogram and computer-generated optical image processing based on a model in Matlab. The results showed the effectiveness of an approach for optical diagnostics of biological micro-objects using cross-correlation analysis. Moreover, O. Klein *et al.* (2023) developed the architecture of a cyberphysical computer vision system for detecting anomalies in images, especially for objects in motion. They proposed a hybrid approach that involves centralised management of the system with the ability to scale the level of autonomy for each task. Sonar devices use different frequencies-from 6.5 kHz to 1 MHz, which provides a sonogram resolution of 60 m to 1 cm. T. Fletcher *et al.* (2024) found that recreational sonars, such as Lowrance, provide sufficient resolution and accuracy in classifying environments at a lower cost and with less data processing time compared to professional systems, making them an effective tool for mapping littoral areas of water bodies. Y. Zhang *et al.* (2021) analysed five image enhancement algorithms: histogram equalisation (HE), greyscale stretching (GS), mean filter (MF), Multi Scale Retinex (MSR), and wavelet transform (WT), and HE, GS, and MSR provided the best results. However, traditional optical computer vision techniques such as MSR inspired S. Li *et al.* (2022) and Y. Liu & X. Ye (2023) to develop specific enhancement methods for sonar imaging. Y. Liu & X. Ye presented a greyscale correction method for SSS images with complex terrain, based on acoustic attenuation compensation and improving the bottom relief display and mosaic quality of SSS images. S. Li *et al.* proposed a new method of radiometric correction that considers the features of SSS image formation and uses low-angle and anisotropic variational constraints for lighting and albedo components, effectively solving the distortion problem.

Regarding the evaluation of the results of methods, it can be noted that there is no universal approach to evaluation. V.D. Nguyen *et al.* (2023) provided an empirical method for estimating the radiation pattern for processed images based on acoustic transducers using geometric backscattering model for SSS. Advances in machine learning (ML) and artificial intelligence (AI) should be considered, which open up new opportunities for improving intensity correction, in particular, for automating the identification and correction of complex distortion patterns. For example, K. Sivachandra & R. Kumudham (2024) conducted a review of research on object detection and classification in SSS images using deep and ML techniques, and image processing, analysing the use of convolutional neural network (CNN), data sets, detection accuracy, and classification. Similarly, Y. Steiniger *et al.* (2022) provided an overview of studies using DL for sonar image analysis, in particular, for feature detection, classification, detection, and image segmentation of SSS synthetic aperture sonars, with a focus on CNN, including the creation of an open dataset and comparative studies of DL methods. Such approaches are widely used and popular in sonar image processing and computer vision technologies. In the considered studies, there is no comprehensive algorithm for improving the quality of sonar images, which would include simultaneously improving contrast, edge processing, and colour interpretation. The purpose of the study was to develop an algorithm that combines these methods to improve the information content and accuracy of sonar images. The task was to analyse improved image quality, apply edge processing techniques to improve sonar image detail, and explore colorimetric techniques to improve image interpretation.

MATERIALS AND METHODS

This study consisted of three subsections that considered methods to improve image contrast, edge processing to improve detail, and colorimetric methods to simplify data interpretation. In the first section, which was devoted to improving image contrast, an example of a sonar radiation pattern was given, where for port, the main lobe had a frequency of 32.15 kHz (kilohertz), and the first side lobe – 30.37 kHz, while for starboard, the first side lobe corresponded to a frequency of 32.15 kHz, and the main lobe – 30.37 kHz. The importance of the SSS radiation pattern was to explain possible variations in signal intensity that affect the contrast and uniformity of illumination on the sonogram. Since uneven exposure can make visual interpretation difficult, consideration of these features helped to better assess the sources of reduced image quality. The method for improving image contrast included the following steps: intensity normalisation, adaptive contrast enhancement, and correction of uneven lighting. Normalisation of intensity took into account the features of the sonar signal, which was reflected in the scheme of the stage of normalisation of the intensity of the sonar image. The contrast limited adaptive histogram equalisation (CLAHE) approach was considered for adaptive contrast improvement. To evaluate its effectiveness, an example of SSS image processing using HE and CLAHE filters was provided. The quality of processed images was evaluated using metrics such as peak signal-to-noise ratio (PSNR), structural similarity index (SSIM), and mean squared error (MSE). The last step was the correction of uneven lighting, where examples of eliminating striped noise and excessive illumination were considered. All three stages are summarised in a Table that contains the purpose of each stage, its description, and usage examples.

For its part, the second section of the study focused on edge processing to improve detail. In the first stage (image pre-processing), the application of cubic spline regression was analysed, which allowed the data to be normalised. This example showed data normalisation with the original image before image processing and the result after normalisation and filtering were applied. The results of using Gaussian blur (GB) to eliminate noise were also demonstrated. For this purpose, a sonar image of the sunken ship obtained using SSS was used. Image processing was performed in the Pixlr Editor Image Editor, where GB with a radius of 15 was applied. In general, the edge selection step was performed using techniques such as Canny and Sobel, which were compared by their advantages and limitations. Morphological operations (dilation, erosion) and high-pass filters (Laplace, Gauss) were considered for the edge amplification stage. In addition, a diagram of this stage was developed, demonstrating the choice of optimal approaches depending on the type of image. Similar to the first subsection, a Table was created to summarise the results with a description of all the stages of the subsection, their purpose, and examples.

In turn, the third section focused on applying colorimetric techniques to improve image interpretation. This included the following steps: converting images between greyscale and colour spaces, using colorimetric models to analyse structures, and optimising the pseudo-colour gamut. For the first stage, an example of the Hue, Saturation, and Value (HSV) colour model components was given, which helped to more accurately identify underwater objects. Using the GNU Image Manipulation Programme (GIMP), the underwater vessel image was divided into separate HSV components to assess their impact on contrast and detail. The application of colorimetric models was described in the form of a diagram that demonstrates the analysis of structures and details. Pseudo-colour gamut optimisation was aimed at adapting images to specific tasks and simplifying their interpretation. All stages of this division were also summarised in the corresponding table, which contained a description, goal, and examples of results.

RESULTS

Contrast enhancement methods for the image processing quality improvement algorithm

Sonar image processing is a key method in modelling the underwater environment. Based on SSS capabilities, it is possible to create detailed maps of the sea floor, identify objects on its surface, and analyse ecosystems. However, there is a need to develop an algorithm for improving the quality of image processing obtained using sonar, using modern mathematical methods. Contrast enhancement should be highlighted as one of the methods of such an algorithm, since low contrast is one of the main obstacles to accurate analysis of underwater structures and objects. This problem is caused by several factors, in particular, the attenuation of the signal intensity due to the distance of the object from the radiation source, the influence of the sonar radiation pattern (Fig. 1), and uneven lighting near the nadir zone. All of these factors create variations in intensity that make it difficult to automatically detect and identify objects.

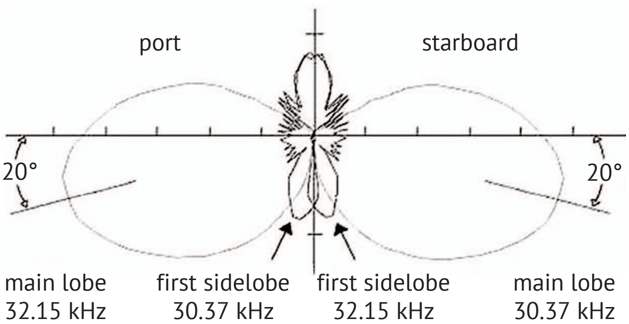

Figure 1. Example of a sonar radiation pattern
Source: compiled by the authors based on P. Blondel (2009)

The sonar radiation pattern causes changes in intensity on the sonogram, which can cause uneven lighting and striped noise. In addition, steps to improve the contrast of sonar images should be considered, considering the specifics of sonogram processing and typical distortions characteristic of this type of data. The first step is to normalise the intensity, which eliminates global lighting variations and equalises the brightness by scaling the pixel values to the specified range (Fig. 2). This allows preparing the data for further processing.

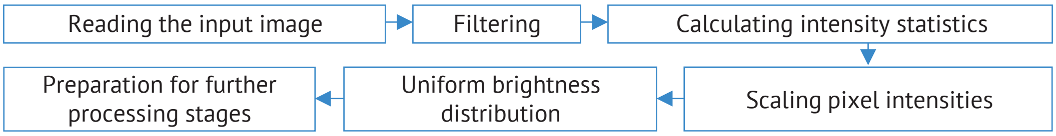

Figure 2. Diagram of the sonar image intensity normalisation stage
Source: compiled by the authors

After normalising the intensity, the next step is to apply an adaptive approach to contrast enhancement, such as CLAHE (Fig. 3). This step is an improvement on conventional histogram alignment, as it works locally within small blocks of the image, while maintaining the naturalness of textures and preventing excessive noise amplification. CLAHE also uses a limit on the contrast level, which allows avoiding overexposure in certain areas.

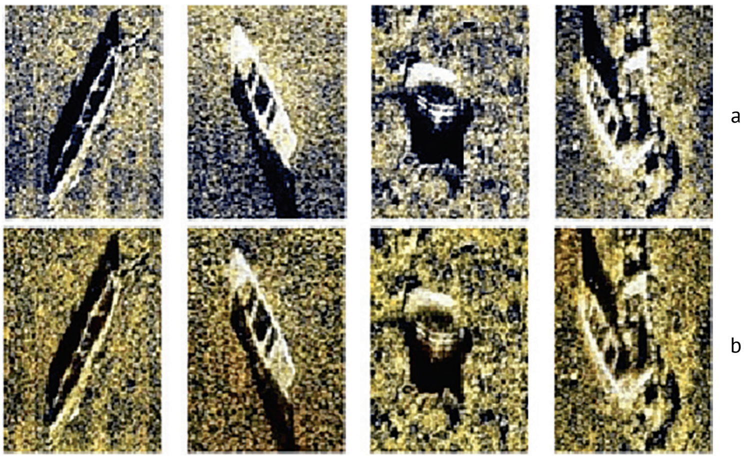

Figure 3. Example of using the usual HE (a) and CLAHE (b) for SSS images
Source: compiled by the authors

In Figure 3 (b), the contrast with CLAHE is noticeably more evenly improved compared to HE (a), without the excessive noise gain observed in HE. CLAHE preserves the details of objects better, especially in shady areas and on borders, providing a more natural look to the image. The analysis shows that CLAHE performs better than HE in most image quality indicators (Table 1).

Table 1. Metrics for evaluating image quality

Image	Method	Entropy	PSNR	SSIM	MSE
Image 1	HE	7.847	12.943	0.698	3,301.756
	CLAHE	7.767	16.345	0.779	1,508.438
Image 2	HE	7.945	12.613	0.697	3,562.527
	CLAHE	7.968	15.893	0.764	1,674.00
Image 3	HE	7.953	11.237	0.610	4,890.696
	CLAHE	7.915	15.479	0.713	1,841.199
Image 4	HE	7.939	11.639	0.637	4,457.708
	CLAHE	7.949	15.670	0.733	1,762.108

Source: compiled by the authors based on Z. Lu et al. (2023)

The results of metrics (PSNR, SSIM, MSE) confirmed the superiority of CLAHE over HE in preserving structural information and reducing distortion. Overall, CLAHE provides a more balanced quality improvement, reducing noise and artefacts while preserving details and structures in sonar images. At the final stage of sonar image processing, uneven lighting is corrected, which is one of the main problems in sonography. This step is based on the analysis of intensity histograms for each local area of the image. First, a separate histogram is created for each local area (subzone of the image), which reflects the distribution of pixel intensity in this part of the image. Then, based on this histogram, the average intensity value for each region is determined. To compensate for uneven lighting, the approach of adapting local intensity to global image parameters is used. This means that the average intensity value of each local area is adjusted so that it corresponds to the average or specified global intensity level of the entire image. Thus, local brightness variations that can be caused by lighting distortions are reduced, in particular, in the nadir zone. It is necessary to demonstrate an example of excessive illumination in such an area, where bright areas in the centre of the image are detected, and striped noise in the form of horizontal lines of varying intensity and length (Fig. 4). This example is a typical problem to consider when correcting sonar images. In general, the analysed stages of image processing allow achieving improvements in the accuracy and clarity of images, which increases the efficiency of further analysis of underwater objects. Table 2 summarises these steps, their goals, and application examples.

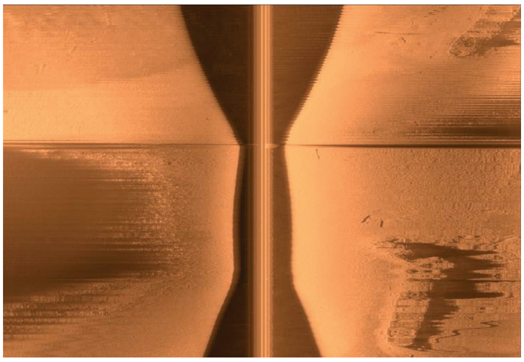

Figure 4. Example of excessive light and striped noise
Source: compiled by the authors

Table 2. Steps to improve the contrast of sonar images

Processing stage	Stage goal	Examples
Normalisation of intensity	Eliminate global lighting variations and equalise brightness across the entire image plane	Eliminate dark spots or bright areas that occur due to uneven lighting in the sonar image
CLAHE filter	Improve local contrast without increasing noise and distortion	Improve contrast in an area with low visibility against the background, for example, increase the clarity of small objects on the sea floor without oversaturating the brightness
Correction of uneven lighting	Reduction of local brightness variations caused by lighting distortions, in particular, in the nadir zone	Compensation for excessive illumination in the central part of the image, where intense signal reflection is observed, or correction of striped noise in the form of horizontal lines

Source: compiled by the authors

Therefore, using the considered steps to improve contrast allows reducing the impact of global and local brightness variations, reduce noise levels, and increase image detail. Metric analysis (PSNR, SSIM, MSE) confirmed that CLAHE provides better image quality compared to conventional histogram alignment, and correction of uneven lighting helps eliminate artefacts in the nadir zone. Thus, the proposed approach improves the quality of sonograms, which increases the accuracy of their subsequent analysis.

Overview of edge processing steps to improve image detail

Detailed sonar images are an important aspect for ensuring accurate analysis of underwater objects and structures. Problems associated with distortion (blurred contours, reduced contrast, and abnormal reflections) or blurring can significantly complicate the process of automatically detecting and classifying objects on the sea floor. To eliminate these problems, edge processing should be used, which is based on image preprocessing, edge detection and edge enhancement. The main task of the preprocessing stage is to reduce noise, in particular, signal reflection, electronic interference, and high-frequency components that degrade the detail of objects. To illustrate this process, an example of data normalisation is given, which shows the original image with noise and distortion, and the result after normalisation and filtering, showing a uniform distribution of intensity and noise reduction (Fig. 5).

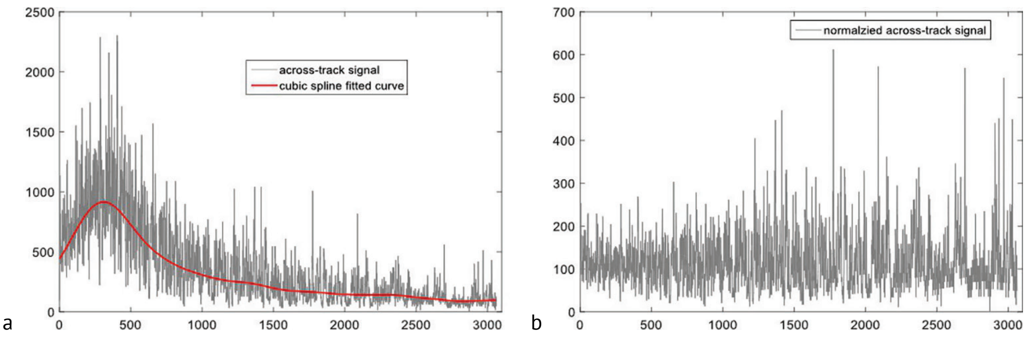

Figure 5. Example of data preprocessing by cubic spline regression
Notes: a – original image before processing; b – result after normalisation and filtering are applied
Source: compiled by the authors based on M. Al-Rawi *et al.* (2017)

This step applies filters to smooth out images and reduce random interference. One effective approach is to use GB to filter images. It is based on convolution of the image with a Gaussian core, which suppresses high-frequency interference, in particular, small chaotic details that look like noise. It is worth demonstrating a sonar image of the sunken ship obtained using the Side Scan Sonar survey (n.d.), which was processed in the Pixlr Editor (n.d.) (Fig. 6).

As a result of applying GB with a radius of 15, a noticeable reduction in grain size was achieved, which made the textures smoother (Fig. 7). The edges of objects have become softer, which reduces the likelihood of false detections in subsequent processing, but at the same time can lead to the loss of some parts. The overall appearance of the scene has become more smoothed out, which can be useful for further segmentation or automatic detection of underwater structures.

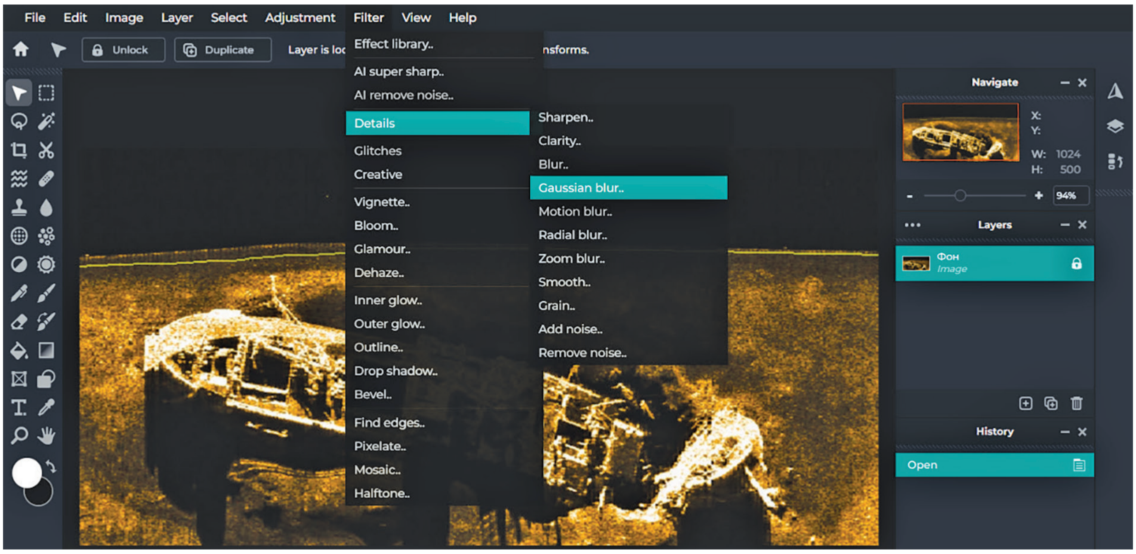

Figure 6. Configuring parameters for GB image processing
Source: compiled by the authors based on Side Scan Sonar survey (n.d.), Pixlr Editor (n.d.)

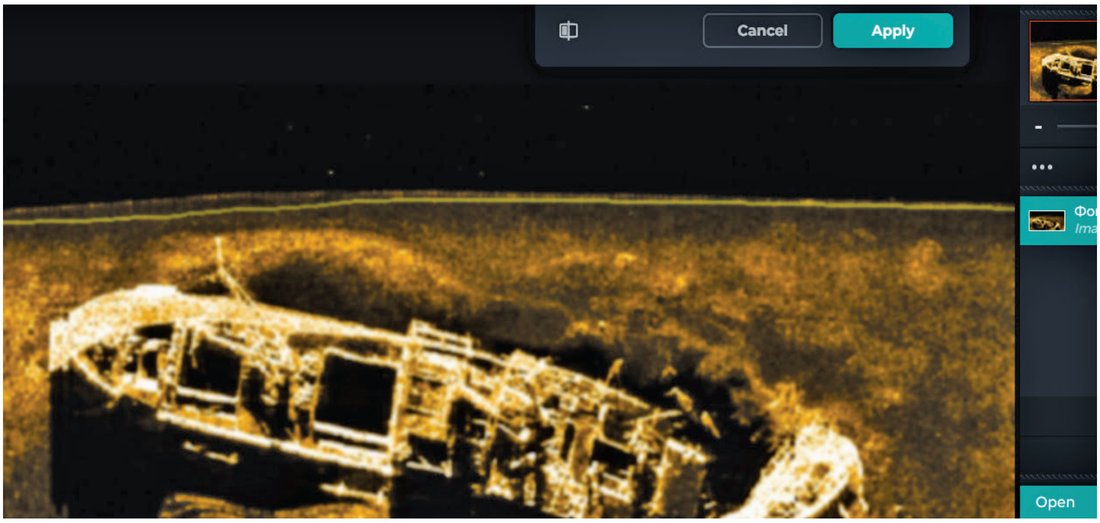

Figure 7. Result of using GB
Source: compiled by the authors based on Side Scan Sonar survey (n.d.), Pixlr Editor (n.d.)

Therefore, GB is particularly effective in cases where the original image has uneven illumination or contains abnormal reflections. In general, this approach is basic for ensuring the accuracy of edge detectors, as it reduces the likelihood of false detections caused by random noise or intensity anomalies. After pre-filtering noise, the main task is to highlight the edges that form the contours of underwater objects. This step aims to identify dramatic changes in pixel intensity corresponding to boundaries between different structures or materials on the sea floor. For this purpose, specialised approaches based on gradient analysis are used, in particular, Canny and Sobel (Table 3).

Table 3. Comparison of Canny and Sobel

Approach	Advantages	Disadvantages
Canny	High accuracy of edge detection	Higher computational complexity compared to Sobel
	Minimisation of false positives by suppressing non-maximal pixels	Sensitivity to parameters (thresholds)
	Ability to highlight even weak edges if they border on strong ones	It is not always optimal for real time due to the long processing time of large images
Sobel	Easy implementation and high speed of operation	Lower edge detection accuracy compared to Canny
	Effective for rough edge detection and initial processing	Vulnerable to noise and requires additional pre-anti-aliasing
	Used for tasks that do not require high-level detail	Poorly distinguishes between weak edges or details in low-contrast images

Source: compiled by the authors

Canny technology ensures high accuracy of edge selection and minimises false positives. The algorithm works sequentially: calculating the intensity gradient, suppressing non-maximal pixels, and processing thresholds that connect weak contours with strong ones. Instead, Sobel is less computationally complex and is used to quickly estimate gradients, although it is less accurate and noise-sensitive. That is, Canny is suiTable for detailed analysis, and Sobel is suiTable for pre-processing or when speed is important. An equally important step is to strengthen the edges, which allows to get clearer borders of objects. This is necessary for further tasks, in particular, classification and detection of underwater structures. The main method of reinforcement is the use of morphological operations, such as dilation and erosion. Dilation increases the thickness of the edges, filling in the gaps between them, which allows increasing their expressiveness. Erosion, on the other hand, reduces the thickness of the edges, eliminating minor or indistinct contours. It is important that these approaches do not change the main contours of objects, but only improve their reflection in the image.

Another way to amplify edges is to use high-pass filters, such as Laplace filters or Gaussian operations. Such filters emit dramatic changes in intensity, strengthening the boundaries between different materials or structures in the image. They make the boundaries of objects clearer and more expressive for further analysis, and the image becomes more informative and allows more accurately determining the location of underwater objects. This stage is crucial for further automated detection and classification, where it is important to have clear and precise contours that correspond to the actual characteristics of underwater objects. The diagram in Figure 8 illustrates the process of edge amplification, from choosing how to amplify edges to filters and getting well-defined edges ready for further analysis.

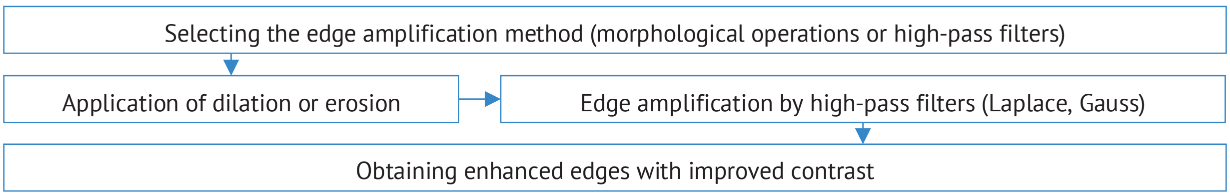

Figure 8. Diagram of the edge reinforcement stage

Source: compiled by the authors

Image pre-processing, highlighting, and edge enhancement are critical to improving the accuracy and clarity of sonar images. They allow significantly reducing the impact of noise, clearly highlighting the contours of underwater objects, and increasing their expressiveness for further analysis (Table 4).

Table 4. Steps for processing the edges of sonar images

Processing stage	Stage goal	Examples
Pre-processing	Reduce the impact of noise and distortion due to various physical and technical factors	Elimination of signal reflections, electronic interference, reduction of high-frequency noise from the image
Edge selection	Identification of sudden changes in pixel intensity for finding object boundaries	Detecting the contours of underwater objects (such as corals or sunken structures) using Canny or Sobel
Edge reinforcement	Improve clear edge expressiveness for further analysis and classification	Application of morphological operations (dilation, erosion), high-pass filters (Laplace, Gauss)

Source: compiled by the authors

That is, pre-processing by noise filtering helps to eliminate interference, edge selection ensures accurate delineation of the contours of underwater objects, and edge amplification by morphological operations and high-pass filters increases their expressiveness for further classification. These steps form a qualitative basis for automated analysis of underwater structures, minimising false detection, and loss of important details.

Analysis of colorimetric methods to improve image interpretation

Colorimetric sonar image processing techniques improve the recognition of underwater structures, which contributes to their more accurate identification. The first stage of improving the following images involves converting images between greyscale and colour spaces depending on the task at hand. This can include either translating the grey image into a colour space to improve visualisation, or decomposing the colour image into separate components for further analysis. During this transformation, pixel values are scaled according to the selected colour palette or individual colour components are extracted, which provides a basis for a deeper interpretation of the object structure. For example, the HSV space (Fig. 9) should be used because of its ability to separate components of brightness, colour tone, and saturation, which facilitates visual interpretation. At this stage, the pixel values in the greyscale are scaled and distributed according to the colour palette, which creates the basis for further analysis.

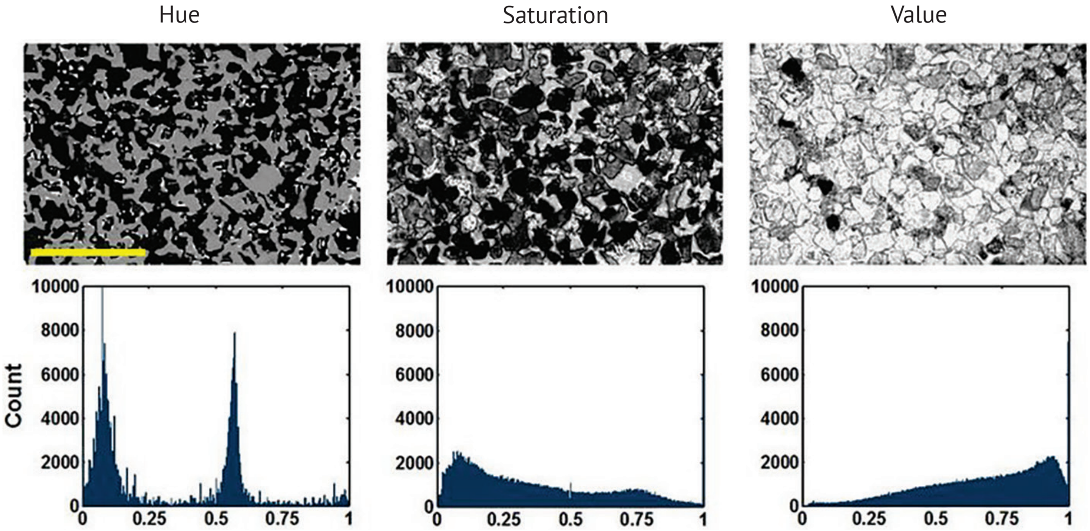

Figure 9. Example of HSV components

Source: compiled by the authors based on R. Richa (2010)

To test the effectiveness of using the HSV colour space, the method of identifying individual components of this space on the sonar image of a sunken ship (Side Scan Sonar survey, n.d.). This image contains a yellow-black palette typical of many sonar systems. The main contours of the vessel are clearly visible, but the contrast of some details is insufficient, which makes it difficult to identify them. The analysis was performed using the GIMP software environment, which allows separating colour channels and evaluating their impact on object visualisation (Fig. 10).

For further analysis, three key components of HSV were identified: Hue, Saturation, and Value (Brightness) (Fig. 11). The Hue component shows a low contrast between the object and the environment. This is because the hue of the colour in the original image is fairly uniform. In this case, the Hue component does not contain enough information for high-quality detail recognition, since hue changes are not the main factor in distinguishing structures in the sonar image. For its part, the Value component shows a significant increase in contrast. The main outlines of the ship have become more expressive, which helps to better identify its shape and structure. This component turned out to be one of the most informative, since it is directly related to the level of reflected sonar signal. Objects with high brightness are more reflective, which allows highlighting important features. Moreover, the result of the Saturation component is characterised by even higher contrast, but it has certain disadvantages. Some fine details are lost, and the overall texture of the image becomes more simplified. This can be useful in cases where it is necessary to clearly highlight the main outline of an object, but to preserve finer details, it is advisable to combine this component with brightness.

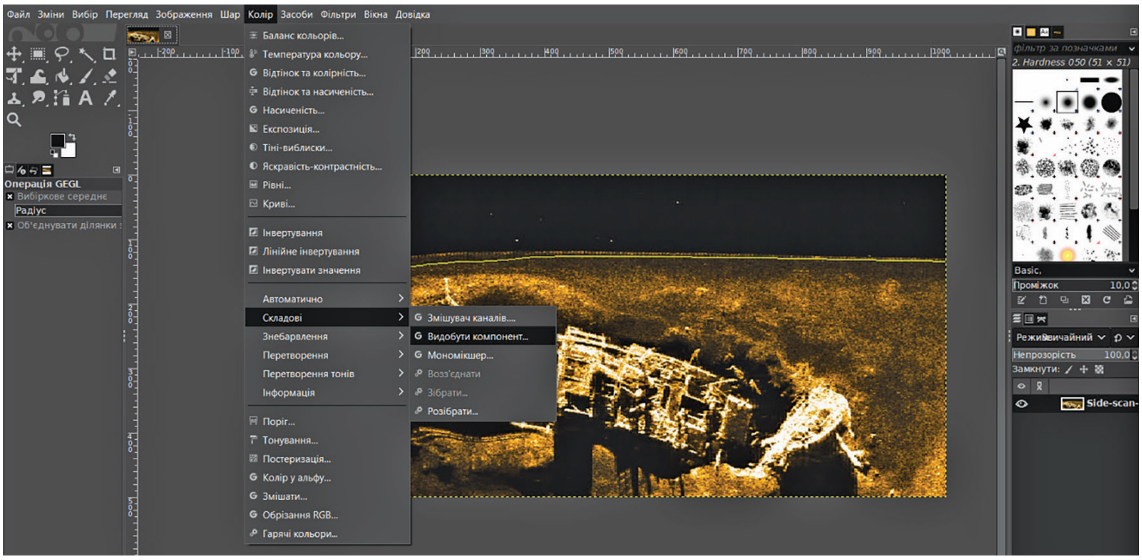

Figure 10. Configuring settings in GIMP
Source: compiled by the authors based on Side Scan Sonar survey (n.d), GIMP (n.d.)

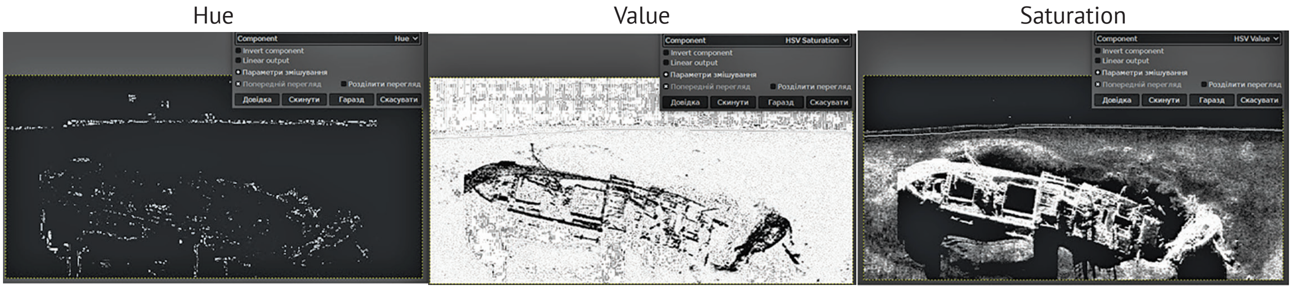

Figure 11. Application of HSV components
Source: compiled by the authors based on Side Scan Sonar survey (n.d.), GIMP (n.d.)

The HSV Value component was most useful for analysing the structure of a sunken ship, since it provides a clear distinction between the object and the background. The combination of HSV Value and HSV Saturation can give an even better result, highlighting contours and improving detail. The second stage involves applying colorimetric models to analyse structures and details (Fig. 12). At this stage, the resulting image space is processed to highlight its key features. Mathematical methods are used to analyse colour variations and determine the contours of objects, textures, and small details. The colour distribution in space is analysed to recognise important features, such as areas with increased brightness or heterogeneous texture, which may be evidence of underwater structures or artefacts.

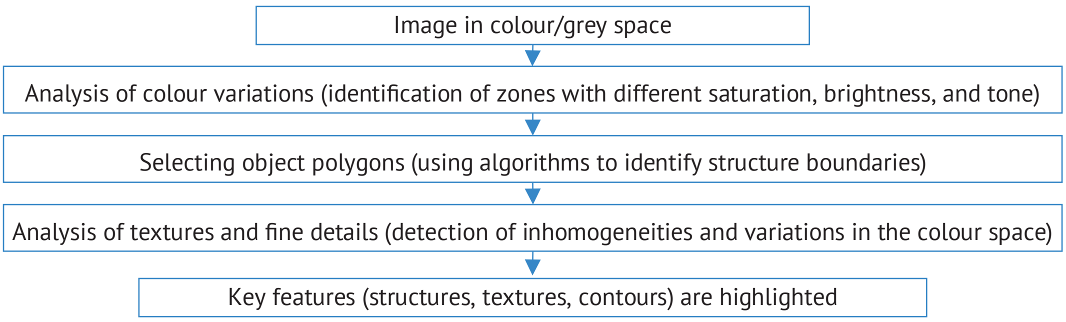

Figure 12. Scheme of using colorimetric models for analysing structures and parts
Source: compiled by the authors

In turn, the third stage involves optimising the pseudo-colour gamut to simplify data interpretation. After the initial transformation and accentuation of structures, the colour palette is adjusted to adapt the image to specific tasks. This may include changing colour saturation to improve contrast, or correcting colour tones to more accurately identify underwater structures or materials. Optimisation is carried out considering the features of the image, such as noise levels or lighting features, and is aimed at maximising the information content of the visualisation. For a more detailed analysis, you should compare the proposed step with other steps in image processing using colorimetric methods (Table 5).

Table 5. Steps to improve images using colorimetric methods

Processing stage	Stage goal	Examples
Convert images between greyscale and colour spaces	Improve visualisation or highlight key components for analysis	Using HSV space to separate brightness, tone, and saturation
Application of colorimetric models for structure analysis	Identify and enhance key image features by analysing colour characteristics	Using mathematical methods to determine contours, textures, and details
Pseudo-colour gamut optimisation	Adjusting the colour palette to improve contrast and information content	Saturation and tone correction for more accurate identification of underwater structures

Source: compiled by the authors

That is, image conversion between greyscale and colour spaces provides more efficient visualisation and selection of individual components, and colour model analysis allows highlighting key structures and details that are difficult to distinguish in the greyscale. In addition, pseudo-colour gamut optimisation simplifies data interpretation, making images more informative and suiTable for further analysis. Thus, as part of the study, an algorithm for improving the quality of sonar images was proposed, which includes the use of contrast enhancement methods, edge processing, and colorimetric methods. This approach significantly improves the accuracy and efficiency of sonar image analysis, providing a comprehensive improvement in image quality and simplifying their further processing and interpretation.

DISCUSSION

The research was aimed at improving the quality of sonar images by improving contrast, processing edges for detail, and applying colorimetric techniques. On the other hand, X. Cui *et al.* (2025) considered a method for decomposing images into basic and detailed layers, adaptive gamma correction, and a hybrid filter to reduce noise and improve contrast. Both approaches have been shown to be effective in reducing noise and improving image quality, but the study shows an advantage due to the use of adaptive approaches that allow for better detail and accuracy in interpreting underwater objects. The results obtained confirm the effectiveness of the SSS image processing methods used, in particular, CLAHE, GB filters, and HSV component analysis. The quality assessment showed an improvement in contrast and detail, which is consistent with the results of the study by P. Zhou *et al.* (2024), where the use of multi-layer fusion based on non-subsampled shearlet transform (NSST), modified multi-scale Retinex (MMSR) and sparse dictionary learning (SDL) helped to increase contrast and reduce noise. This confirms the feasibility of using contrast enhancement and pre-processing techniques to improve the visualisation of sonar images.

Unlike the paper by C. Lei *et al.* (2024), where the Sonar Image Graph Attention Network (SI-GAT) model is used to classify sonar images, the current study focuses on improving image contrast and detail using the HSV model and image processing methods. Despite the difference in approaches, improving image quality can have a positive impact on further processing steps, including classification. In addition, the use of ML methods, in particular, graph neural networks, may be a promising area for further research, for example, in signal intensity correction tasks that consider factors such as distance, beam pattern, depth, sonar type, and calibration. The findings of this paper are consistent with the study by X. Yuan *et al.* (2024), where the model You Only Look Once v9-side scan network (YOLOv9) is proposed for detecting underwater objects. In this paper, the model uses DL methods, in particular, the strategy of refining negative samples, mixing attention, and spatial channel reconstruction of convolutional layers. As for the current study, it focuses on image pre-processing, including contrast enhancement, filtering, and edge processing. This improved input quality can help to improve accuracy for further analysis, including underwater object detection and classification tasks, including using models such as YOLOv9.

Like the previous study, J. Zhu *et al.* (2024) considered neural networks, namely, the convolutional channel-Wasserstein generative adversarial network (CC-WGAN), to generate new sonar images to expand limited data sets. Instead, the current research aims directly to improve the quality of existing images by improving contrast, detail, and processing using approaches such as CLAHE, Canny, and Sobel. Although these studies are different, they have a common goal – to improve the quality of sonar images. However, if the current paper created new images to expand the data sets, then the study focused on improving existing sonar images. Sonar images are similar to traditional images and can be treated as such, although their creation is based on other physical principles. This paper discussed the application of an image quality improvement algorithm, including contrast, edge processing, and colorimetric methods. In turn, Q. Ma *et al.* (2025) showed the slid adaptive horizontal inference (SAHI) algorithm to improve the accuracy of small object detection in sonar images. Both approaches are aimed at improving the accuracy of detection in limited cases, but in the current study, more attention is paid to improving the quality of images at previous stages of processing, which contributes to more accurate analysis and classification of underwater objects.

In addition, the GB filter was applied in this study to reduce noise in sonar images, which helped to improve the clarity and detail of the contours of underwater objects. Similarly, the study by M. Gao *et al.* (2024) used a generative adversarial network to improve underwater images, where a synthetic dataset was created to train the model, considering various factors of image degradation. However, unlike this approach, the study focused on reducing noise and improving contrast to facilitate detection of underwater objects, rather than super-resolution. Therefore, when combined with image-based approaches, the current method can complement existing methods, improving the accuracy of underwater object detection. While the current study focused on improving the quality of sonar images by applying methods of improving contrast, edge processing and colorimetric methods, L. Kai (2020) focused on processing and correcting sonar images suffering from artefacts and distortions caused by difficult water conditions and the movement of an autonomous underwater vehicle. This paper uses image analysis methods and the scale-invariant feature transform (SIFT) algorithm to detect and compensate for distortions that occur during shooting. Using this approach can significantly improve the quality and information content of sonar images, which is crucial for the accuracy of underwater object analysis. The methods proposed in this paper can contribute to more efficient feature detection, which can potentially improve the use of algorithms such as SIFT in underwater navigation and structure analysis tasks. While the present study included an overview of morphological operations such as dilation and erosion, Z. Zhang *et al.* (2024) proposed an algorithm that combines filtering, intensity correction, and morphological operations to detail images. The current results were mainly aimed at processing edges and highlighting contours, while adaptive contrast improvement and normalisation of signal intensity helped to effectively cope with uneven lighting and improve contrast. Therefore, the current approach is multi-faceted and covers not only detail, but also improving the overall image quality. Moreover, the semantic segmentation model in the study by D. Yang *et al.* (2022), based on CNN, differs in that it focuses on automating image analysis. Although no neural networks were used in the current study, the focus was on manual methods and pre-processing steps that provided high detail for further analysis. Thus, the current results can complement the mentioned approach, providing an improvement in the initial data for training models.

On the other hand, X. Wen *et al.* (2024) proposed an improved YOLOv7 model using a Swin-Transformer and a Convolutional Block Attention Module (CBAM) to improve the accuracy of object detection in sonar images. This approach focuses directly on detection, while current research focuses on image pre-processing, in particular, on improving contrast and highlighting edges. Since the quality of input images affects the accuracy of detection models, the proposed methods can serve as a preparatory stage for more efficient object recognition, in particular, for models like YOLOv7. Therefore, the results of the current study complement the approach of this paper, improving the overall image quality and, accordingly, the accuracy of subsequent analysis stages. In the current study, uneven lighting correction was used to control noise, while H. Xia *et al.* (2024) considered Criminisi method for reducing striped noise, which demonstrates high efficiency in preserving textures. This method consists of using dynamic weights, the Sobel operator to determine edges, and an optimised block search process. In the current study, Sobel was also considered for detecting edges and strengthening the contours of underwater structures. That is, the current results are consistent with the approach of other study, although they include a simpler and faster way to detect edges, which allows achieving the desired image efficiency for specific applications. Additionally, H. Liu *et al.* (2025) proposed a method for combining Forward Looking Sonar (FLS) and SSS data to create a complete map of the sea floor. The current approach did not focus on combining images from different sonars, but the use of equalisation and intensity normalisation can be adapted to pre-process the data before combining them.

Ultimately, K.S. Basha & A. Nambiar (2024) proposed a new "S3Simulator" dataset created using advanced simulation technologies to reproduce underwater conditions and synthesise various sonar images. The Segment Anything Model (SAM) was used to segment images of objects, such as ships and planes. However, in the current study, images were transformed using HSV conversion to improve contrast and detail, which aims to improve image quality for further detection of underwater objects. Although the approaches are implemented differently, they have complementary results that can lead to improved accuracy of underwater image analysis, including both sonar and optical images. Thus, the study confirmed the effectiveness of the applied algorithm for improving the quality of sonar images, in particular, in the context of improving contrast, detail through edge processing and the use of colorimetric methods. The results are consistent with other studies aimed at reducing noise, improving contrast, and detailing images for more accurate interpretation of underwater objects. Comparison with other approaches shows that the processing methods used in this study provide a high level of image quality in the early stages of processing, which contributes to effective subsequent analysis and classification.

CONCLUSIONS

The results of the study included sequencing an algorithm to improve the quality of sonar images, in particular, to improve contrast and facilitate the interpretation of sonograms. It was found that the use of intensity normalisation, adaptive contrast enhancement using CLAHE, and uneven lighting correction facilitates image perception. Analysis of image quality metrics showed that using CLAHE compared to HE provides higher PSNR values (particularly for Image 1 – 16.345 vs. 12.943 for HE), SSIM (e.g., 0.779 vs. 0.698 for Image 1), and significantly lower MSE values (e.g., 1,508.438 vs. 3,301.756 for Image 1), indicating better preservation of image detail and structure while reducing noise. In addition, the use of colour models such as HSV provides a clearer picture of underwater structures, making them easier to identify and analyse. For its part, edge processing has shown high efficiency in pre-processing, edge selection, and amplification (Canny, Sobel), including the use of filtering to reduce noise. In particular, the GB filter demonstrated efficiency in reducing high-frequency noise and smoothing textures, which positively affected the quality of input data for further analysis. Edge amplification using morphological operations and high-pass filters helped to obtain more detailed images from underwater objects, which had a positive effect on the accuracy of their classification. In turn, colorimetric methods have significantly facilitated the interpretation of sonars, improved data visualisation, and provided the ability to adapt them to specific tasks. Analysis of the ship image when applying HSV showed that the Value component is the most informative, since it provides a clear distinction between the object and the background, while Saturation increases contrast, but can simplify the texture. The described steps enabled more efficient work with various types of images, which can be useful in the further development of underwater image processing systems.

One of the main limitations of sonogram processing is the lack of additional information, such as navigation data, ship movements, or calibration, especially for older recordings on analogue media. Most methods do not use any data other than that contained in the sonogram itself, which limits their ability to make accurate corrections. In addition, due to the large amount of data, it is necessary to ensure high computational efficiency for processing sonograms, which puts additional restrictions on the choice of methods. Moreover, the variety of underwater acoustic conditions and factors affecting sonar signal reflection makes it impossible to apply universal solutions, limiting the feasibility of using the same type of approaches. For effective sonogram processing, it is recommended to use methods that consider specific conditions that affect the acoustic environment, such as the unevenness of the sea floor and various factors that vary depending on the study site. Developing algorithms to correct intensity and improve contrast should consider these conditions and maintain a trade-off between computational efficiency and accuracy. Consideration of the specific characteristics of each study, including depth variability and sediment types, will provide more accurate results. Since most older sonograms do not contain accompanying data, it is necessary to develop methods that work without additional information, with the maximum use of the data available in the images themselves.

ACKNOWLEDGEMENTS

None.

FUNDING

None.

CONFLICT OF INTEREST

None.

REFERENCES

[1] Al-Rawi, M., Galdran, A., Isasi, A., Elmgren, F., Carbonara, G., Falotico, E., Real-Arce, D.A., Rodriguez, J., Bastos, J., & Pinto, M. (2017). Cubic spline regression based enhancement of side-scan sonar imagery. In *OCEANS 2017 – Aberdeen* (pp. 1-7). Aberdeen: IEEE. doi: 10.1109/OCEANSE.2017.8084567.

[2] Basha, K.S., & Nambiar, A. (2024). S3Simulator: A benchmarking side scan sonar simulator dataset for underwater image analysis. In A. Antonacopoulos, S. Chaudhuri, R. Chellappa, C.-L. Liu, S. Bhattacharya & U. Pal (Eds.), *Pattern recognition: 27th international conference* (pp. 219-235). Heidelberg: Springer-Verlag. doi: 10.1007/978-3-031-78444-6_15.

[3] Blondel, P. (2009). *The handbook of sidescan sonar.* Heidelberg: Springer Berlin. doi: 10.1007/978-3-540-49886-5.

[4] Bogomolov, N.F., Shlykov, V.V., & Vovianko, S.I. (2021). Computer processing of speckle interferograms for optical diagnostics of biological microobjects. *Biomedical Engineering and Technology*, 6. doi: 10.20535/2617-8974.2021.6.244563.

[5] Cui, X., Li, M., Li, J., Jiang, B., Li, L., & Li, S. (2025). Side-scan sonar submarine pipeline image enhancement incorporating gamma correction and blurring algorithms. *IEEJ Transactions on Electronics Information and Systems*, 145(1), 83-92. doi: 10.1541/ieejeiss.145.83.

[6] Fletcher, T., Booth, M.T., & Pritt, J.J. (2024). A comparison of recreational and survey-grade side-scan sonar systems in mapping reservoir fish habitat. *North American Journal of Fisheries Management*, 44(6), 1422-1438. doi: 10.1002/nafm.11060.
[7] Gao, M., Li, Z., Wang, Q., & Fan, W. (2024). DAE-GAN: Underwater image super-resolution based on symmetric degradation attention enhanced generative adversarial network. *Symmetry*, 16(5), article number 588. doi: 10.3390/sym16050588.
[8] GIMP – GNU Image Manipulation Program. (n.d.). Retrieved from https://www.gimp.org/.
[9] Ivaniuk, V.I., Potapova, K.R., Nalyvaichuk, M.V., Hurinenko, S.O., & Vovk, L.B. (2023). Computer vision system of autonomous unmanned underwater vehicles based on modified sea-thru method and YOLO neural network. *Taurida Scientific Herald. Series: Technical Sciences*, Technical Sciences, 5, 40-54. doi: 10.32782/tnv-tech.2023.5.5.
[10] Kai, L. (2020). Side scan sonar image geocoding based on carrier velocity coarseness correction. *Journal of Physics Conference Series*, 1576, article number 012012. doi: 10.1088/1742-6596/1576/1/012012.
[11] Katrusha, O. (2024). Correction of roll-caused stripe noise in side scan sonar images. *Information Technologies and Computer Engineering*, 21(3), 77-85. doi: 10.63341/vitce/3.2024.77.
[12] Klein, O., Melnyk, V., Zhukovskyi, P., & Vizhevskyi, V. (2023). Modeling, architecture and cyber physical systems for computer vision. *Measuring and Computing Devices in Technological Processes*, 3, 50-56. doi: 10.31891/2219-9365-2023-75-5.
[13] Lei, C., Wang, H., & Lei, J. (2024). SI-GAT: Enhancing side-scan sonar image classification based on graph structure. *IEEE Sensors Journal*, 24(15), 24388-24404. doi: 10.1109/JSEN.2024.3416193.
[14] Li, S., Zhao, J., Yu, Y., Wu, Y., Bian, S., & Zhai, G. (2022). Anisotropic total variation regularized low-rank approximation for SSS images radiometric distortion correction. *IEEE Transactions on Geoscience and Remote Sensing*, 60, article number 5925412. doi: 10.1109/TGRS.2022.3229301.
[15] Liu, H., Ye, X., Zhou, H., & Huang, H. (2025). A mapping method fusing forward-looking sonar and side-scan sonar. *Journal of Marine Science and Engineering*, 13(1), article number 166. doi: 10.3390/jmse13010166.
[16] Liu, Y., & Ye, X. (2023). A gray scale correction method for side-scan sonar images considering rugged seafloor. *IEEE Transactions on Geoscience and Remote Sensing*, 61, article number 4209810. doi: 10.1109/TGRS.2023.3334492.
[17] Lu, Z., Zhu, T., Zhou, H., Zhang, L., & Jia, C. (2023). An image enhancement method for side-scan sonar images based on multi-stage repairing image fusion. *Electronics*, 12(17), article number 3553. doi: 10.3390/electronics12173553.
[18] Ma, Q., Jin, S., Bian, G., Cui, Y., & Liu, G. (2025). DBnet: A lightweight dual-backbone target detection model based on side-scan sonar images. *Journal of Marine Science and Engineering*, 13(1), article number 155. doi: 10.3390/jmse13010155.
[19] Nguyen, V.D., Luu, N.M., Nguyen, Q.K., & Nguyen, T.-D. (2023). Estimation of the acoustic transducer beam aperture by using the geometric backscattering model for side-scan sonar systems. *Sensors*, 23(4), article number 2190. doi: 10.3390/s23042190.
[20] Pixlr Editor. (n.d.). Retrieved from https://pixlr.com/editor/.
[21] Richa, R. (2010). *Preservation of transport properties trends: Computational rock physics approach*. Stanford: Stanford University.
[22] Side scan sonar survey. (n.d.). Retrieved from https://www.oceandiscovery.org/en/side-scan-sonar-undersokningar/.
[23] Sivachandra, K., & Kumudham, R. (2024). A review: Object detection and classification using side scan sonar images via deep learning techniques. In V.K. Gunjan, J.M. Zurada & N. Singh (Eds.), *Modern approaches in machine learning and cognitive science: A walkthrough* (pp. 229-249). Cham: Springer. doi: 10.1007/978-3-031-43009-1_20.
[24] Steiniger, Y., Kraus, D., & Meisen, T. (2022). Survey on Deep learning based computer vision for sonar imagery. *Engineering Applications of Artificial Intelligence*, 114, article number 105157. doi: 10.1016/j.engappai.2022.105157.
[25] Wen, X., Wang, J., Cheng, C., Zhang, F., & Pan, G. (2024). Underwater side-scan sonar target detection: YOLOv7 model combined with attention mechanism and scaling factor. *Remote Sensing*, 16(13), article number 2492. doi: 10.3390/rs16132492.
[26] Xia, H., Cui, Y., Jin, S., Bian, G., Liu, G., Zhang, W., & Peng, C. (2024). Improvement of criminisi's stripe noise suppression method for side-scan sonar images. *Applied Sciences*, 14(20), article number 9574. doi: 10.3390/app14209574.
[27] Yang, D., Wang, C., Cheng, C., Pan, G., & Zhang, F. (2022). Semantic segmentation of side-scan sonar images with few samples. *Electronics*, 11(19), article number 3002. doi: 10.3390/electronics11193002.
[28] Yuan, X., Li, J., Wang, W., Zhou, X., Li, N., & Yu, C. (2024). Improved YOLOv9 for underwater side scan sonar target detection. *Computer Journal*, article number bxae134. doi: 10.1093/comjnl/bxae134.

[29] Zhang, Y., Li, H., Zhu, J., Zhou, L., & Chen, B. (2021). Contrast study of side scan sonar image enhancement methods. In *2021 OES China ocean acoustics* (pp. 995-999). Harbin: Institute of Electrical and Electronics Engineers. doi: 10.1109/COA50123.2021.9520059.
[30] Zhang, Z., Wu, R., Li, D., Lin, M., Xiao, S., & Lin, R. (2024). Image stitching and target perception for autonomous underwater vehicle-collected side-scan sonar images. *Frontiers in Marine Science*, 11, article number 1418113. doi: 10.3389/fmars.2024.1418113.
[31] Zhou, P., Chen, J., Tang, P., Gan, J., & Zhang, H. (2024). A multi-scale fusion strategy for side scan sonar image correction to improve low contrast and noise interference. *Remote Sensing*, 16(10), article number 1752. doi: 10.3390/rs16101752.
[32] Zhu, J., Li, H., Qing, P., Hou, J., & Peng, Y. (2024). Side-scan sonar image augmentation method based on CC-WGAN. *Applied Sciences*, 14(17), article number 8031. doi: 10.3390/app14178031.

Обробка сонарних зображень для покращеного моделювання підводного середовища

Олександр Катруша

Магістр
Національний технічний університет України
«Київський політехнічний інститут ім. Ігоря Сікорського»
03056, просп. Берестейський, 37, м. Київ, Україна
https://orcid.org/0009-0008-7097-4843

Артем Бурдейний

Магістр
Національний технічний університет України
«Київський політехнічний інститут ім. Ігоря Сікорського»
03056, просп. Берестейський, 37, м. Київ, Україна
https://orcid.org/0009-0009-3113-2149

Анотація. Метою дослідження було представити послідовність розробки алгоритму підвищення якості зображень, отриманих за допомогою сонара бокового огляду. Для досягнення цієї мети використовувалися методи математичної обробки зображень, такі як посилення контрасту, обробка країв і колориметричні методи. Кроки для покращення контрастності зображення включали нормалізацію інтенсивності сигналу, адаптивне посилення контрастності за допомогою обмеженого контрастного вирівнювання гістограм і корекцію нерівномірного освітлення. Продемонстровано діаграму спрямованості гідролокатора та схему нормалізації інтенсивності зображення. Фільтр адаптивного вирівнювання гістограми з обмеженим контрастом показав вищі значення пікового відношення сигнал/шум та індексу структурної подібності порівняно зі звичайним вирівнюванням гістограми, що вказує на краще збереження деталей, структури зображення та зменшення шуму. Аналіз обробки країв, зокрема Canny і Sobel, показав їх потенційну ефективність у покращенні деталей підводних структур. Крім того, використання гаусового згладжування дозволило знизити рівень високочастотного шуму і зробити текстури більш гладкими. В результаті відбулося зменшення зернистості, м'якість контурів об'єктів і загальне згладжування сцени. Крім того, кубічна сплайн-регресія показала нормалізовані дані зображення. У свою чергу колориметричний аналіз зосереджувався на перетворенні зображень між градаціями сірого та кольоровими просторами, що полегшувало ідентифікацію підводних об'єктів і структур. Було наведено приклад компонентів Hue-Saturation-Value, які продемонстрували різний вплив на якість візуалізації зображення сонара. Компонент Value забезпечив найбільш виразне розрізнення між об'єктом і фоном, тоді як компонент Hue був неефективним для аналізу структури. Поєднання значень і насиченості дозволило покращити деталізацію контуру. Оптимізація псевдоколірної гами дозволила адаптувати зображення під різні завдання, сприяючи більш точному розпізнаванню об'єктів. Отримані результати підтверджують доцільність використання представлених методів у широкому спектрі прикладних задач, пов'язаних з візуалізацією та аналізом підводного середовища

Ключові слова: зміна контрастності; виділення країв; колориметричний аналіз; усунення спотворень; адаптивне згладжування