INVESTIGATION OF IMPACT OF COLOR SATURATION AND HUE ON NEURAL NETWORK-BASED OBJECT RECOGNITION IN UNDERWATER ENVIRONMENTS

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Abstract. Object detection in underwater environments is often impaired by low visibility and reduced contrast caused by turbidity and light absorption. This study investigates the impact of contrast enhancement techniques – specifically grayscale conversion and the application of Contrast Limited Adaptive Histogram Equalization (CLAHE) – on object recognition accuracy using deep learning models such as YOLOv8. Through the experimental analysis with YOLOv8, we compare the detection performance across RGB, grayscale and CLAHE-enhanced images, in scenario involving submerged automotive tires and nearly transparent objects such as a cellophane bag. The result demonstrates that CLAHE processing significantly improves detection confidence for opaque objects, increasing the average confidence score by 8%. However, it reduces the performance for translucent objects, with detection counts dropping by 44% and confidence scores reduced by 13%. These findings highlight the object-dependent nature of preprocessing methods and suggest that CLAHE is more beneficial in low-contrast scenarios involving opaque objects. This study underlines the importance of tailoring image enhancement strategies depending on object characteristics to optimize neural network-based object recognition in underwater conditions.

Keywords: OpenCV, YOLO, object recognition, object segmentation.

Introduction

Object recognition in underwater environments presents a significant challenge due to light scattering, colour absorption, and turbidity, which result in reduced and degraded image quality. These environmental factors negatively affect the performance of computer vision systems, in particular deep learning-based object detection models such as YOLO and Mask R-CNN, which rely on clear object boundaries and high-contrast features for accurate object detection [1-3]. Underwater images often suffer from non-uniform lighting and colour distortions that make object detection difficult. Traditional approaches based solely on RGB inputs alone are limited in such conditions. As a result, researchers have turned to contrast enhancement techniques such as histogram equalization and its adaptive form – Contrast Limited Adaptive Histogram Equalization (CLAHE). CLAHE enhances local contrast by redistributing pixel intensities in small image tiles and proven effective in underwater image improvement, face recognition, and medical image tasks [4-6; 10]. Despite the benefits of CLAHE, the application of CLAHE in real-time object detection, particularly in underwater scenarios, has not been widely studied. Most prior research has focused on generic object detection in other settings or used CLAHE only for visual enhancement without evaluating its impact on detection confidence [7-9]. Insignificant attention has been given to how object material properties – such as opacity and transparency – interact with the processing techniques.

This study addresses this gap by evaluating the effects of grayscale conversion and CLAHE enhancement on YOLO-based object recognition in underwater conditions. We assess the model performance in detecting both opaque (e.g. submerged tire) and translucent (e.g. cellophane bag) objects by comparing detection counts and confidence scores across RGB, grayscale, and CLAHE enhanced images. By focusing on contrast-based preprocessing and evaluating its effectiveness through object-dependent performance metrics, this study contributes new insights into how enhancement techniques like CLAHE can be optimized for neural network-based detection systems in underwater environments. The findings aim to inform the design of more adaptive computer vision pipelines for tasks such as marine monitoring, pollution detection, and autonomous underwater navigation- where object material properties and environmental conditions vary widely.

Materials and methods

This series of images evaluates the impact of grayscale conversion of set images and the introduction of CLAHE enhancement in local body of water underwater conditions, specific for object detection. Each image includes a region of interest (ROI) that was made using OpenCV for the object and the corresponding background of the image, contrast values are calculated to evaluate object distinguishability. Fig. 1 presents a direct comparison between RGB values and grayscale values of an underwater scene containing fish and a cellophane bag, ROI in this scenario is chosen between a fish and the background. The contrast between the fish and the background is 10.97 in the RGB image, but only 5.04 in the grayscale counterpart. In the grayscale image the difference values are lower between the selection regions in comparison to the RGB image due to the contrast being monochrome and on a single axis. This highlights how the RGB channels contribute to higher perceptual contrast, making objects more distinctive. While grayscale is more efficient for transmitting data and processing, it reduces visual information if left to a monochrome channel, which may impair detection accuracy.

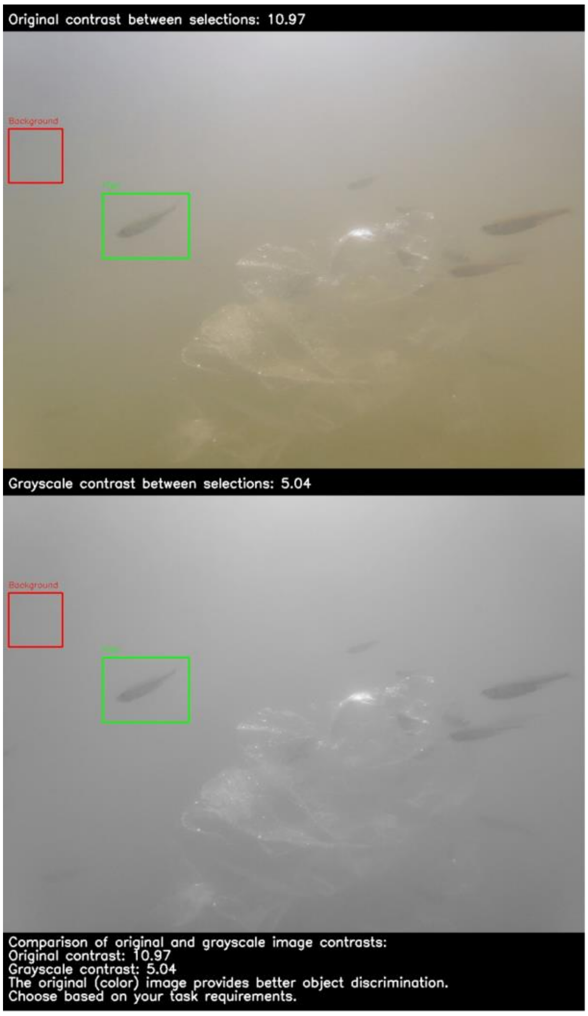

Fig. 1. **RGB and Grayscale contrast difference**

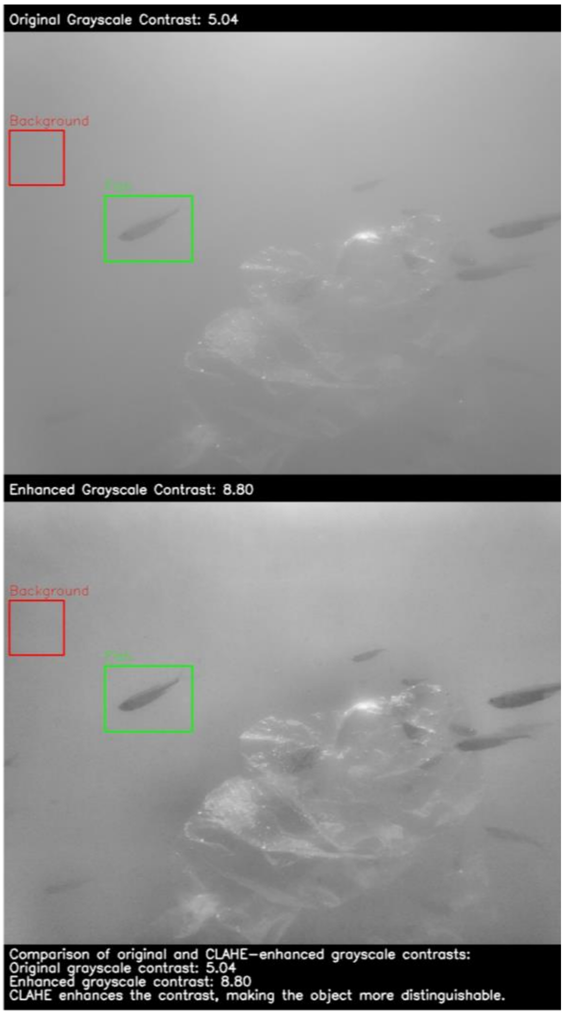

Fig. 2. **Grayscale and CLAHE enhanced**

Fig. 2 builds upon the grayscale Fig. 1 by applying the CLAHE algorithm to enhance the local contrast. The contrast ROI values between the fish and the background increased from 5.04 to 8.80, making the object substantially more distinguishable. This demonstrates that the CLAHE algorithm effectiveness is recovering detail in the low-contrast image, especially under impaired underwater lighting conditions.

These results suggest that CLAHE-enhanced grayscale imagery can serve as a viable compromise between transmission efficiency and visual clarity. By preserving local contrast without the overhead of full-colour data, this method offers practical advantages for real-time object recognition systems in underwater environments. Future work could explore adaptive thresholding techniques in combination with CLAHE to further boost detection accuracy. Additionally, evaluating these methods across varying turbidity levels and object transparencies could provide deeper insights into their robustness in diverse underwater conditions.

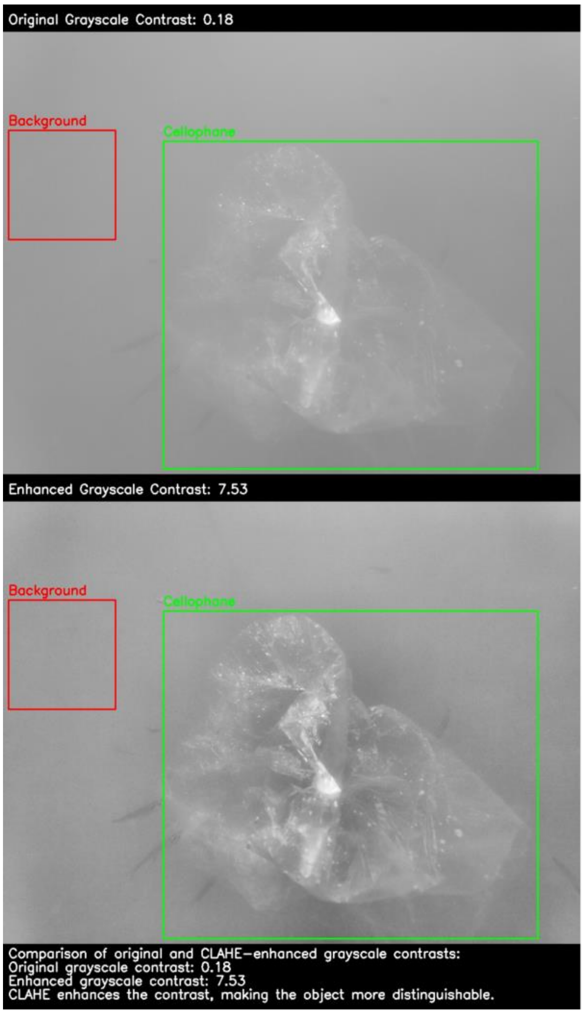

Fig. 3. **CLAHE significant enhancement**

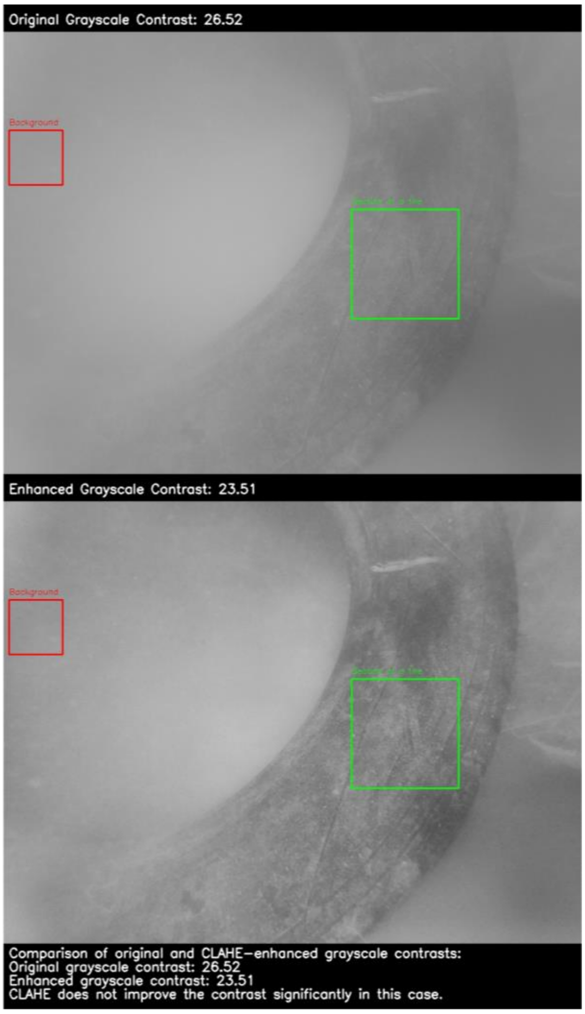

Fig. 4. **Diminishing returns in specific regions**

Fig. 3 explores CLAHE's capabilities in particularly low-contrast scenario, where a semi-transparent plastic object (cellophane) is introduced into the scene, the object is nearly indistinguishable in the original grayscale image. The grayscale image contrast values are 0.18, it is increased to 7.53 after the CLAHE algorithm is applied to enhance the image contrast. This significantly improves the visibility of the cellophane bag, that confirms that CLAHE has a critical advantage in detecting subtle or translucent objects, which may lead to better marine debris detection and other similar applications. Fig. 4 serves as a counterexample, in this scenario the original grayscale image contrast between a submerged automotive tire and its background is already high, posing values at 26.52. The CLAHE algorithm slightly reduces these contrast values to 23.51, suggesting that in high-contrast scenarios such as this, even though the visibility of the object is increased it may result in diminishing returns when applied to object detection. Over-processing in such cases can diminish boundaries by flattening already well-distributed pixel contrasts. Yet, we will see contradicting results further into the study where the same algorithm is applied to YOLO object detection.

A. Image Set: Impact of CLAHE on underwater automotive tire detection using YOLO object recognition

This image sequence demonstrates the impact of CLAHE (Contrast Limited Adaptive Histogram Equalization) on the detection of a submerged automotive tire in low-visibility underwater conditions. The object, background environment, and camera perspective remain constant across all three images to ensure a fair comparison of preprocessing effects. The objective is to compare how preprocessing with the CLAHE algorithm applied in both RGB and grayscale images impacts the clarity of features of the object and detection confidence.

Fig. 5. **Original RGB image (no enhancements)**

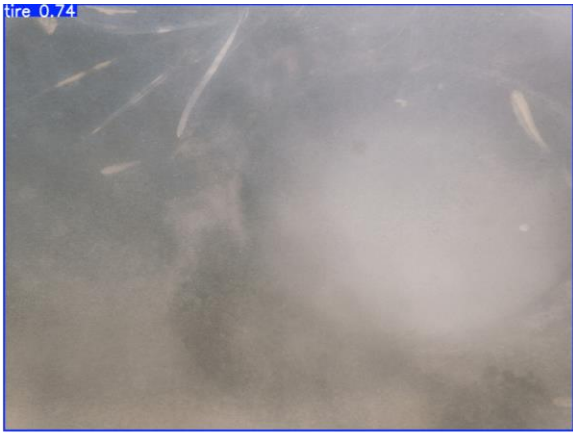

Fig. 6. **RGB image with CLAHE applied**

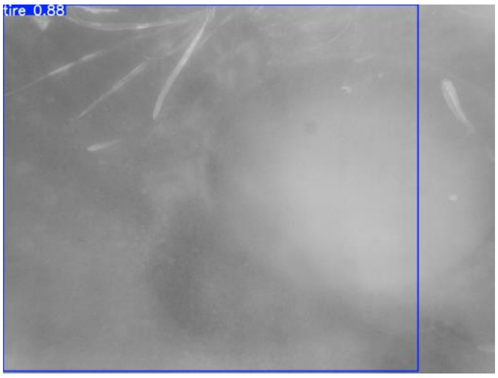

Fig. 7. **Grayscale image with CLAHE applied**

In Fig. 5, the original RGB image shows low contrast due to underwater scattering of sediment and loss of colour fidelity. The automotive tire is barely distinguishable and almost blends into the background. Fig. 6 demonstrates a noticeable improvement in contrast. The CLAHE-enhanced RGB image reveals more detail and texture, improving the visibility of the automotive tire's sidewall, yet returning lower confidence scores due to training on the images without any enhancements. Fig. 7 is converted to a monochrome channel and CLAHE is applied, and shows improvement in contrast and higher confidence scores.

The three detection runs (original, CLAHE RGB, CLAHE grayscale) were compared using YOLOv8 object detection. The outputs of the confidence scores between the original detection run and the CLAHE enhanced were recorded, analysed and summarized.

Summary of the output data for the submerged automotive tire.

- Original Image (RGB, no enhancement):
  - detections: 275
  - average confidence: 0.6578
  - min/max confidence: 0.2522/0.8556
- Grayscale image with CLAHE applied:
  - detections: 244
  - average confidence: 0.7105
  - min/max confidence: 0.2557/0.8789

The CLAHE-enhanced grayscale images led to a higher average confidence score despite producing slightly fewer detections.

B. Image Set: Underwater detection of a cellophane bag with and without CLAHE

This series of images illustrates an underwater object detection scenario involving a nearly transparent object, specifically, a piece of cellophane. Three preprocessing conditions were applied to evaluate the visibility and segmentability of the object under varying image enhancement techniques.

Fig. 8 depicts the original RGB image without any enhancements, serving as the baseline reference. In contrast, Fig. 9 shows the same scene processed as a grayscale image with CLAHE (Contrast Limited Adaptive Histogram Equalization) applied. This enhancement significantly increases local contrast, which aids in revealing subtle contours of the transparent object that are otherwise imperceptible in the original RGB format.

Fig. 8. **Original RGM image (no enhancements)**

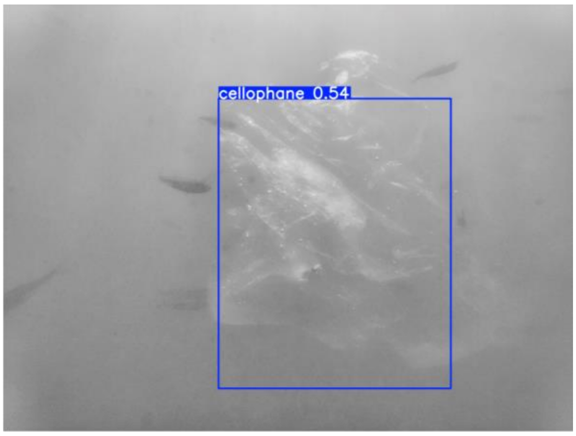

Fig. 9. **Grayscale image with CLAHE applied**

Due to low opacity and reflective properties of the plastic material, visibility of the object is limited. The test was designed to evaluate if the CLAHE algorithm would enhance the detection of the transparent marine debris when colour and contrast of the object are limited. In Fig. 8 the cellophane bag is partially distinguishable due to faint colour variations and ambient reflections. The confidence score is moderately high in this instance, textural cues and colour gradients likely assist the model in identifying the object boundary. In Fig. 9, while the contrast is locally improved, converting the image to a monochromatic channel removes subtle information that was critical for detection, resulting in the image lacking spectral depth needed to differentiate the cellophane from the toned background, resulting in a lower confidence score.

Summary of the output data for the submerged cellophane bag:

- Original Image (RGB, no enhancement):
  - detections: 187
  - average confidence: 0.5666
  - min/max confidence: 0.2535/0.8050
- Grayscale image with CLAHE applied:
  - detections: 105
  - average confidence: 0.4592
  - min/max confidence: 0.2512/0.7134

This is a 13% drop in average confidence scores and a 44% reduction in total detections, this indicates that a clear decline is present in the model's performance using the CLAHE algorithm for detecting transparent objects. The grayscale enhancement was helpful earlier in detecting opaque objects, while underperforming in scenarios where fine colour cues and translucency defines the object boundaries.

Results and discussion

The results of this study reveal that CLAHE preprocessing significantly enhances object recognition performance in underwater environments, particularly for opaque objects under low-visibility conditions. In the case of the submerged automotive tire contrast values increased and object features became more distinguishable, leading to a higher average confidence score in YOLO-based detection. When comparing RGB, grayscale, and CLAHE-enhanced images, grayscale images with CLAHE showed the most substantial improvement in contrast and detection accuracy, highlighting the value of local contrast amplification.

However, this enhancement does not universally apply across all object types. Transparent or semi-transparent objects, such as a cellophane bag, demonstrated a clear decrease in detection performance when processed with CLAHE in grayscale mode. The removal of spectral colour information, which is crucial for identifying subtle boundaries in translucent materials, resulted in a 44% reduction in detection count and a 13% drop in average confidence.

These findings suggest that while CLAHE is a powerful tool for enhancing visibility and aiding detection, especially when bandwidth or hardware limitations call for grayscale preprocessing, its effectiveness is strongly object dependent. Opaque objects benefit from enhanced contrast, whereas transparent ones require preservation of full RGB information to maintain detection reliability. Therefore, the choice of preprocessing techniques should be aligned with the specific characteristics of the target object and the underwater environment.

Conclusions

1. The application of the CLAHE algorithm significantly improved object visibility in underwater images, particularly under low-contrast conditions, as demonstrated in the detection of a submerged automotive tire.
2. When comparing RGB and grayscale images, CLAHE processing increased contrast values and raised the average YOLO detection confidence by 8%, indicating the algorithm's effectiveness.
3. In contrast, the detection of transparent objects such as a cellophane bag showed a decline in performance with CLAHE, with a 44% reduction in detection count and a 13% drop in average confidence.
4. These results suggest that the effectiveness of CLAHE is highly dependent on the optical properties of the object – opaque objects benefit from contrast enhancement, while transparent ones lose critical spectral information.
5. Therefore, CLAHE preprocessing should be applied selectively, considering the object type and environmental conditions, to optimize the performance of deep learning-based detection models in underwater environments.

Author contributions

Conceptualization, U.Ž.; methodology, U.Ž. and A.Š.; software, A.Š.; validation, A.Š.; formal analysis, A.Š.; investigation, U.Ž. and A.Š.; data curation, A.Š.; writing – original draft preparation, A.Š.; writing – review and editing, U.Ž. and A.Š..; visualization, A.Š.; project administration, U.Ž.; funding acquisition, U.Ž. All authors have read and agreed to the published version of the manuscript.

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