Underwater Image Restoration Through a Prior Guided Hybrid Sense Approach and Extensive Benchmark Analysis
Summarized on August 3, 2025

1. **Introduction / Abstract**
   Underwater images often suffer from color distortions and blurriness due to how water absorbs and scatters light, especially absorbing red light more than green or blue. This makes underwater photos look bluish or greenish and unclear, which hampers tasks like marine life recognition. The paper proposes a new method called the **Guided Hybrid Sense Underwater Image Restoration (GuidedHybSensUIR)** framework. It combines two types of techniques: convolutional neural networks (**CNNs**, which are good at capturing local image details) and Transformers (a type of model that captures long-range relationships). The method uses a novel **Color Balance Prior** (a guide based on the average color intensity) to help correct color distortions. The authors also created a large benchmark dataset from multiple real underwater image collections and tested 37 existing methods, showing their approach outperforms others overall.

2. **Methodology**
   The researchers designed a U-shaped neural network architecture that processes images at multiple scales:

- The **Detail Restorer** module (using CNNs) focuses on restoring fine, local details at smaller scales.

- The **Feature Contextualizer** module (using Transformers) captures global color relationships at a coarser scale.

- The **Scale Harmonizer** module fuses features from different scales smoothly during decoding.
  The **Color Balance Prior** is computed as the average of the red, green, and blue channels for each pixel, guiding the model to restore balanced colors. This prior is integrated strongly in the Transformer module and weakly in the final decoding step. The model is trained on a combined dataset from four real-world underwater image datasets, ensuring diversity and robustness.

3. **Theory / Mathematics**
   The key theoretical concept is the **Color Balance Prior**, based on the Gray World Assumption, which states that in a normally lit scene, the average intensities of red, green, and blue channels should be equal:

$$a_R \approx a_G \approx a_B$$

   where (a_i) is the average intensity of the (i)-th color channel. Underwater images violate this due to wavelength-dependent light absorption. The prior is defined as:

$$\text{Prior}_i(x, y) = \frac{R(x, y) + G(x, y) + B(x, y)}{3}$$

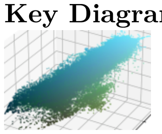
for each pixel ((x,y)), assigning the same average value to all three channels to guide color correction.

The model also uses quaternion convolution (a mathematical operation that treats RGB channels as components of a quaternion) to fuse features from parallel network branches more stably, improving detail restoration. The quaternion convolution is defined as:

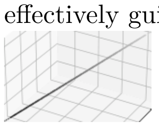
$$Q = R \cdot 1 + A \cdot i + B \cdot j + C \cdot k$$

where (R=0), (C=0), and (A, B) are feature maps from two network blocks, with (1, i, j, k) being quaternion units. This operation captures inter-channel dependencies effectively.

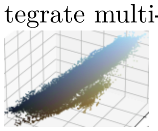
4. **Key Diagrams or Visual Elements**



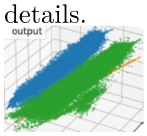
- **Figure 1:** Shows 3D scatter plots of color distributions for an input underwater image, the color balance prior, and the restored output. The prior lies centrally in the restored image's color distribution, indicating it effectively guides color correction.



- **Figure 2:** Illustrates the overall U-shaped GuidedHybSensUIR architecture, highlighting the Detail Restorer modules (CNN-based), the Feature Contextualizer (Transformer-based), and Scale Harmonizers that integrate multi-scale features.



- **Figure 3:** Details the Nonlinear Activation-Free Block (NAFB), a CNN module that selectively enhances or suppresses pixel information to restore details.



- **Figure 5:** Shows the Feature Contextualizer's structure, which includes three types of attention Transformers (Adjust Color Transformer, Keep

Feature Transformer, and Self-Attention Transformer) working in parallel to capture global color and feature relationships.

- **Figure 7:** Depicts the Adjust Color Transformer's attention mechanism, which uses the color balance prior to adjust image features channel-wise.

- **Tables I-III:** Present quantitative comparisons showing the proposed method achieves the best or near-best scores on multiple image quality metrics across several datasets, outperforming 37 other methods.

- **Figures 9-11:** Provide visual comparisons demonstrating superior color correction and detail restoration by the proposed method compared to traditional and deep learning-based approaches.

5. **Conclusion**

   The paper presents a novel underwater image restoration framework that hybridizes CNNs and Transformers to effectively restore both fine details and global color balance. The introduction of a Color Balance Prior guides the model to correct color distortions caused by underwater light absorption. Extensive experiments on a newly compiled benchmark dataset show that this method outperforms 37 state-of-the-art techniques in both quantitative metrics and visual quality. The research advances underwater imaging by providing clearer, more color-accurate images, which is crucial for marine exploration, environmental monitoring, and underwater robotics. The availability of the code and dataset also supports future research and development in this field.