Integrating Content-Aware Loss Functions for Enhanced Model Performance in Spectral Image Reconstruction

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Abstract

This study evaluates the impact of integrating advanced content-aware and multi-scale structure loss functions in image reconstruction models. The original model used a simple composite loss function, while the enhanced model incorporates content-aware spectral and multi-scale structure losses. A comparative analysis of Peak Signal-to-Noise Ratio (PSNR) across training and validation datasets is provided. The results demonstrate that the enhanced loss function achieves faster convergence and higher PSNR within fewer epochs, with each epoch taking the same time as before.

Introduction

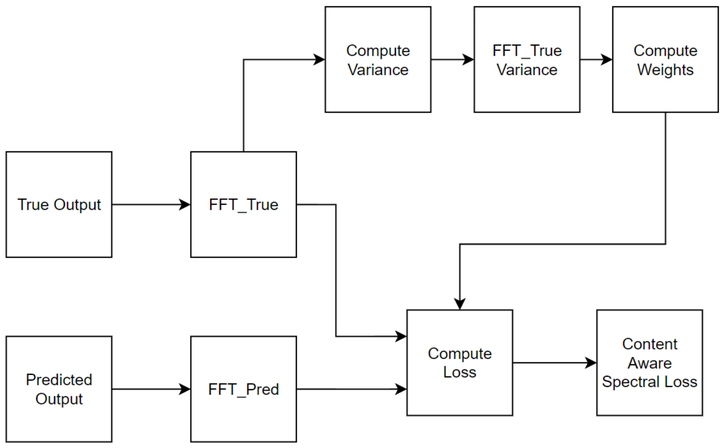
Traditional loss functions such as RMSE (Root Mean Square Error) and spectral losses may fail to preserve complex content details, resulting in suboptimal reconstructions. To address this limitation, two new loss components were introduced: a content-aware spectral loss that adapts to frequency variance and a multi-scale structure loss based on SSIM (Structural Similarity Index Measure).

$$\text{Loss}_{\text{RMSE}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2}$$

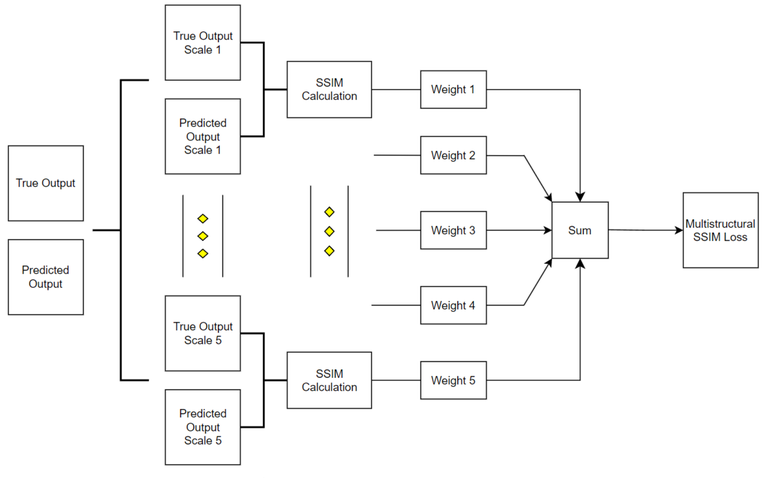
$$\text{Loss}_{\text{Spec}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\nabla y_i - \nabla \hat{y}_i)^2}$$

$$\text{Loss}_{\text{original}} = \text{Loss}_{\text{RMSE}} + \text{Loss}_{\text{Spec}}$$

Methodology



$$\text{Loss}_{\text{Content-Aware Spectral}} = \frac{1}{N}\sum_{i=1}^{N}\frac{\text{Var}(\text{FFT}(y_i))}{\epsilon + \text{Var}(\text{FFT}(y_i))} \cdot (\text{FFT}(y_i) - \text{FFT}(\hat{y}_i))^2$$



$$\text{Loss}_{\text{Multi-Scale Structure}} = \sum_{i=0}^{4}\left(0.5^i\right) \cdot \left(1 - \text{SSIM}\left(y_{\text{down},i}, \hat{y}_{\text{down},i}\right)\right)$$

$$\text{Loss}_{\text{enhanced}} = \frac{\text{Loss}_{\text{Content-Aware Spectral}}}{100} + \text{Loss}_{\text{Multi-Scale Structure}} + \text{Loss}_{\text{RMSE}} + \text{Loss}_{\text{Spec}}$$

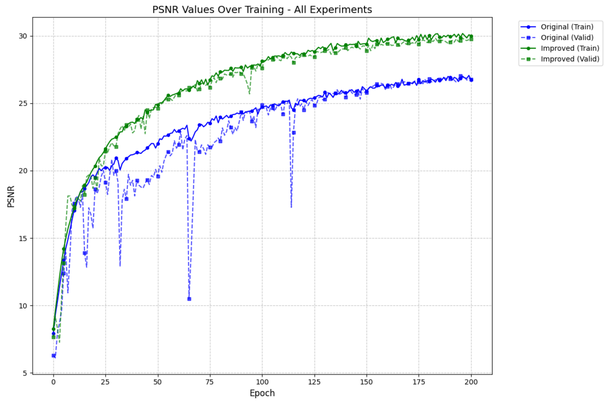
Results

PSNR Comparison

- Original Model: Reached PSNR of 26 after 200 epochs.
- Enhanced Model: Achieved validation PSNR of 30 by epoch 200, marking an 11% improvement over the original.

Convergence Speed

- The enhanced model reached the original model's peak test PSNR of 26 within 100 epochs, demonstrating a 50% reduction in required training time.



Conclusion

Incorporating content-aware and multi-scale structure losses significantly enhances model performance in hyperspectral image reconstruction tasks. The improved loss function achieves higher PSNR in fewer epochs, indicating the efficiency and robustness of these metrics. However, the model's test PSNR suggests a need for further data augmentation or diversity to generalize better on unseen data.