

Performance Analysis for Projection-Correction Methods in Motion Deblurring Problems

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- The project analyzes the performance of two **Projection-Correction** algorithms for reconstructing medical images affected by **motion blur**.
- The studied algorithms are:
 - **Diffusion Posterior Sampling (DPS)**
 - **Regularization by Denoising with Diffusion (RED-Diff)**
- Both methods are based on **pre-trained diffusion models**.
- Objective: evaluate the effectiveness of these methods in recovering degraded images.

- **Objective:** Analyze the performance of *Projection-Correction* methods **DPS** and **RED-Diff** for motion blur removal on medical images
- **Phase 1:** Dataset preprocessing (128x128)
- **Phase 2:** Data augmentation to increase dataset diversity
- **Phase 3:** Training a DDIM diffusion model on medical data
- **Phase 4:** Simulation of motion blur and its removal
- **Phase 5:** Implementation and comparison of *Projection-Correction* methods: **DPS** and **RED-Diff**
- **Phase 6:** Quantitative evaluation of performance using metrics such as **PSNR** and **SSIM**

- We use the "Mayo Clinic CT Dataset" of low-dose CT scans.

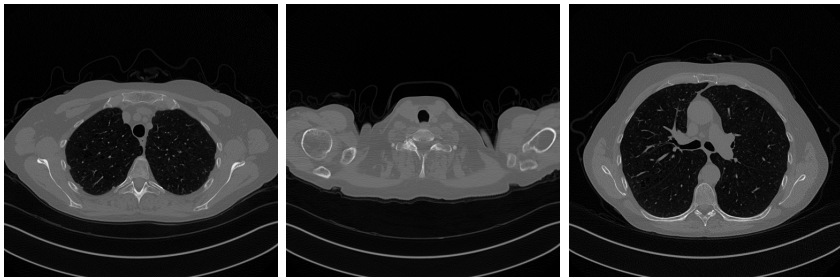


Figure: Examples of CT slices from the Mayo Clinic dataset

Before applying augmentations, each image is converted using:

- ❶ **Grayscale:** single channel via `transforms.Grayscale(num_output_channels=1)`
- ❷ **Resize:** to 128×128 pixels using bicubic interpolation
- ❸ **Normalization:** values scaled to $[-1, 1]$ using mean 0.5 and std 0.5

```
base_transform = transforms.Compose([
    transforms.Grayscale(1),
    transforms.Resize((128,128), interpolation=Image.BICUBIC),
    transforms.ToTensor(),
    transforms.Normalize([0.5], [0.5]),
])
```

For each clean image, we apply the following transformations:

- **Fixed rotations:** $\pm 5^\circ$ via `rotate_fixed()`
- **Horizontal flip:** `horizontal_flip()`
- **Gaussian noise:** mean 0, std 10 via `add_gaussian_noise()`
- **Salt-and-pepper noise:** probability 2% via `add_salt_pepper()`
- **Brightness adjustment:** factor 1.2 via `change_brightness()`
- **Contrast adjustment:** factor 1.3 via `change_contrast()`

- `raw_data/`: directory containing CT slice images (`train/`, `test/`)
- `checkpoints/`: saved model weights (`*.pth`)
- `scripts/`: main scripts for training and evaluation
- `utils.py`: module with utility functions (dataset, model, checkpoint I/O)
- `notebooks/`: exploratory and prototyping notebooks
- `result/`: output images, plots, and metrics
- `report/`: report materials (`media/`, `capitoli/`)

- **Model Type:** UNet2DModel from HuggingFace Diffusers library
- **Task:** Denoising diffusion probabilistic model for grayscale image generation
- **Input/Output:**
 - Input channels: 1
 - Output channels: 1
 - Sample size: 128×128 pixels

- **Block Configuration:**

- Layers per block: 2
- Block output channels: (64, 128, 256)
- Dropout rate: 0.1

- **Downsampling Path:**

- DownBlock2D \rightarrow DownBlock2D \rightarrow AttnDownBlock2D
- Progressive feature extraction with attention in the deepest layer

- **Upsampling Path:**

- AttnUpBlock2D \rightarrow UpBlock2D \rightarrow UpBlock2D
- Symmetric architecture with attention mechanism

- **Training Scheduler:** DDPM Scheduler
 - Number of timesteps: 1000
 - Used for forward diffusion process during training
 - Adds noise progressively over 1000 steps
- **Inference Scheduler:** DDIM Scheduler
 - Number of timesteps: 1000
 - Deterministic sampling process
 - Used for image generation and inverse problems
 - Shares beta schedule with DDPM scheduler

- **Optimizer:** Adam
 - Learning rate: 1×10^{-4}
 - Weight decay: 1×10^{-5}
- **Loss Function:** Mean Squared Error *MSE*
 - Compares predicted noise with actual noise
 - Standard objective for diffusion models
- **Performance Optimizations:**
 - Model compilation with `torch.compile`
 - Mixed precision training with GradScaler
 - Cosine annealing learning rate scheduler

- **Total Parameters:** 15.722.625
- **Key Features:**
 - Attention mechanisms in deepest layers for better feature learning
 - Symmetric U-Net design for optimal information flow
 - Dropout regularization to prevent overfitting
 - Grayscale-optimized with single channel processing

- **Objective:** Train a denoising diffusion model (DDIM U-Net) on grayscale images
- **Main Components:**
 - 1 Data Augmentation
 - 2 DataLoader
 - 3 Model Compilation
 - 4 Training loop with mixed-precision

- **Base Dataset:** Dataset Mayo
 - Grayscale \rightarrow 1 channel
 - Resize images to 128×128
- **Augmentations** (8 types):
 - *None*: no transformation
 - Rotation $\pm 5^\circ$ (rotation + centering)
 - Flip horizontal
 - Gaussian noise (mean=0, std=10)
 - Salt and pepper noise (prob=2%)
 - Brightness (factor=1.2)
 - Contrast (factor=1.3)

- **DDPMScheduler** for training diffusion process
 - Timesteps 1000
- **DDIMScheduler** for sampling
 - Timesteps 1000

- **Why:** optimize the model for better performance
- **Usage:**

```
model = torch.compile(model)
```
- **Benefits:** improved batch throughput

- **GradScaler and autocast:**
 - GradScaler for scaling gradients
 - autocast for automatic mixed precision
- Reduce memory usage and speed up training

- ❶ Loss function: MSE
- ❷ Start the training `model.train()`
- ❸ For each epoch:
 - Move images to GPU (if available)
 - Generate noise and timesteps
 - Compute noise prediction on the input data
 - Prediction + MSE loss
 - Optimization + `scheduler.step()`
- ❹ Save validation samples to visualize the model performance during training
- ❺ Compute and log average losses
- ❻ Save model weights each epoch

- **Validation:**

- `model.eval()` to set the model to evaluation mode
- MSE loss on validation set

- **Checkpoint:**

- Save the model weights to a `.pth` file
- Update loss, PSNR and SSIM history in `history.txt`
- Monitor train vs validation loss over epochs aswell as PSNR and SSIM between the generated and original images
 - For each epoch sample 10 images from the validation set and compute the metrics

- **Metrics:**

- PSNR: Peak Signal-to-Noise Ratio
- SSIM: Structural Similarity Index

- **Sample Generation:**

- Pure noise sampling using DDIM scheduler
- Validation reconstruction:
 - Add noise to clean validation images
 - Model predicts and removes the noise

- **Quality Assessment:**

- PSNR range: 20-40 dB (higher = better reconstruction)
- SSIM range: 0-1 (closer to 1 = better similarity)
- Average metrics computed over 5-10 validation samples

- **Pure Noise Sampling:**

- Tests model's ability to generate realistic images
- Uses DDIM scheduler for iterative denoising
- Saves generated images as `generated_epoch_{epoch}.png`

- **Validation Reconstruction:**

- Adds noise to clean validation images
- Model predicts and removes the noise
- Direct assessment of denoising performance

- **History Tracking:**

- All metrics saved to `history.txt`
- Enables trend analysis and model comparison

- **Loss Monitoring:**

- Training vs Validation Loss curves over epochs
- MSE loss

- **Quality Metrics Visualization:**

- PSNR trends with average values
- SSIM trends with average values
- Both metrics computed on validation reconstructions
- Useful to track model performance

- **Comprehensive Monitoring:**

- Three-panel subplot: Loss, PSNR, SSIM (as shown in the Figure 2)
- Data read from `history.txt` file
- Enables performance trend analysis

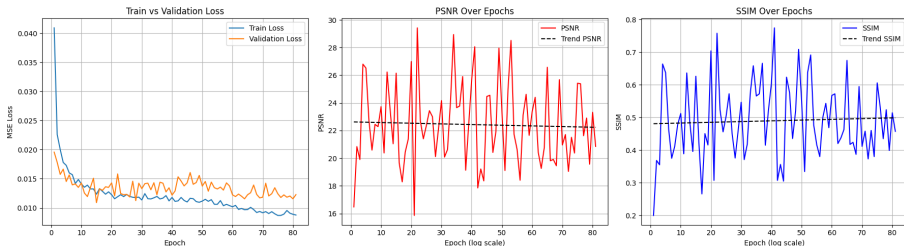


Figure: Training Loss, PSNR, and SSIM trends over epochs

- **Checkpoint Structure:**

- Model state dictionary
- Optimizer state dictionary
- Current epoch number for resuming training
- Naming: `ddim_unet_epoch81.pth`
- `load_checkpoint()` utility function

- **DPS** is a method for solving inverse problems using pre-trained diffusion models
- Key idea: combine data fidelity with diffusion model prior during reverse sampling
- Modifies the standard DDIM reverse process to incorporate measurement consistency

Algorithm Overview:

- 1 Start with noisy initialization $x_T \sim \mathcal{N}(0, I)$
- 2 For each timestep t : predict x_0 using UNet
- 3 Apply posterior correction: $x_0^{post} = x_0^{pred} + \gamma_t \cdot K^T(y - Kx_0^{pred})$
- 4 Continue DDIM step with corrected x_0^{post}

Posterior Correction Weight:

$$\gamma_t = \frac{\sigma_{prior}^2}{\sigma_y^2 + \sigma_{prior}^2}$$

where $\sigma_{prior}^2 = 1 - \alpha_t$ and σ_y is measurement noise

Algorithm Steps:

- 1 Initialize x_t with random noise
- 2 Predict noise $\epsilon_\theta(x_t, t)$ using UNet
- 3 Compute $x_0^{pred} = \frac{x_t - \sqrt{1 - \alpha_t} \epsilon_\theta}{\sqrt{\alpha_t}}$
- 4 Apply DPS correction with gradient step
- 5 Update to next timestep using DDIM

- **RED-Diff** is an optimization-based method for solving inverse problems using diffusion models
- Key idea: combine data fidelity loss with regularization from denoising diffusion priors
- Uses gradient-based optimization to reconstruct images by minimizing combined objective

Algorithm Overview:

- 1 Initialize reconstruction μ from adjoint operation: $\mu = K^T(y)$
- 2 For each timestep t : sample noise and create noisy version x_t
- 3 Compute data fidelity loss: $\mathcal{L}_{obs} = \frac{1}{2\sigma_y^2} \|K(\mu) - y\|^2$
- 4 Compute regularization loss using diffusion model guidance
- 5 Update μ using gradient descent on combined loss

Combined Objective:

$$\mathcal{L} = \mathcal{L}_{obs} + \lambda \cdot w_t \cdot \mathcal{L}_{reg}$$

where w_t is a time-dependent weighting strategy

Algorithm Steps:

- 1 Initialize $\mu \leftarrow K^T(y)$ with gradient enabled
- 2 Sample noise $\epsilon \sim \mathcal{N}(0, I)$ and create $x_t = \sqrt{\alpha_t}\mu + \sqrt{1 - \alpha_t}\epsilon$
- 3 Predict noise $\epsilon_\theta(x_t, t)$ using UNet
- 4 Compute regularization loss: $\mathcal{L}_{reg} = w_t \cdot \|\epsilon_\theta - \epsilon\|^2$
- 5 Update μ using Adam optimizer on total loss
- 6 Repeat for all timesteps in reverse order

Weighting Strategies: linear, sqrt, square, log, clip, const

- **Library:** IPPy
- **Degradation Type:** Motion Blur
- **Implementation:** Linear operator approach
- **Purpose:** Create realistic inverse problems for model evaluation

- **Operator:** `operators.Blurring`
- **Parameters:**
 - Image shape: (128×128) pixels
 - Kernel type: "motion"
 - Motion angle: 45°
 - Kernel sizes tested: $[5, 7, 9, 11, 13, 15]$ pixels
- **Mathematical Model:**

$$y = K(x) + n \quad (1)$$

where K is the blur operator, x is the clean image, and n is noise

- **Dataset:** Validation set from the before-mentioned dataset
- **Degradation:** Motion blur with varying kernel sizes
- **Methods Compared:**
 - DPS (Diffusion Posterior Sampling)
 - RED-Diff (Regularization by Denoising)
- **Evaluation Metrics:**
 - PSNR (Peak Signal-to-Noise Ratio) in dB
 - SSIM (Structural Similarity Index)

- **Motion Blur Configuration:**

- Kernel sizes tested: [5, 7, 9, 11, 13, 15] pixels
- Motion angle: 45°
- Kernel type: Linear motion blur

- **Evaluation Protocol:**

- 5 images per kernel size for statistical reliability
- Batch size: 1 (individual image processing)

- **For each test image:**

- 1 Load ground truth image x_{gt}
- 2 Apply motion blur: $y = K(x_{gt})$
- 3 Reconstruct using DPS: $x_{dps} = \text{DPS}(y, K)$
- 4 Reconstruct using RED-Diff: $x_{red} = \text{RED-Diff}(y, K)$
- 5 Compute metrics: $\text{PSNR}(x_{gt}, x_{rec})$, and $\text{SSIM}(x_{gt}, x_{rec})$

Figure 3 shows the PSNR values for both methods across different kernel sizes.

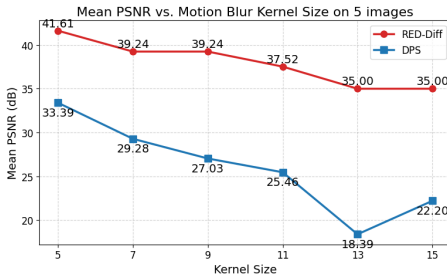


Figure: PSNR values for DPS and RED-Diff across different kernel sizes.

Figure 4 illustrates the SSIM values for both methods across different kernel sizes.

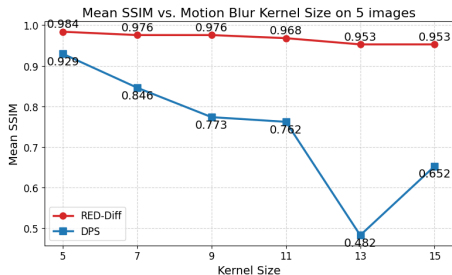


Figure: SSIM values for DPS and RED-Diff across different kernel sizes.

- **Trend Analysis:**

- Both methods show performance degradation with larger kernels, even though the RED-Diff method generally outperforms DPS.
- PSNR and SSIM correlate with blur severity

- **Qualitative Assessment:**

- Side-by-side comparisons: Original → Blurred → Reconstructed
- Visual quality correlation with quantitative metrics
- Edge preservation and artifact analysis

- **Key Findings:**

- RED-Diff better preserves fine details
- RED-Diff shows less artifacts compared to DPS
- RED-Diff keeps consistent performances across different kernel sizes
- DPS is more sensitive to kernel size variations, as shown in the PSNR and SSIM results

Thank you for your attention