Coded-Exposure Deblurring with Physics-Aware Priors

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Motivation

Motion blur is a common problem in photography and computational imaging, particularly when capturing dynamic scenes under low light or long exposure conditions. Traditional single-image deblurring techniques are often unstable because the blur operator removes certain spatial frequencies completely, making the inverse problem ill-conditioned.

Coded exposure, also known as a flutter shutter, improves this condition by modulating the shutter/sensor integration during exposure in a binary pattern that redistributes frequency energy and reduces deep spectral nulls in the motion transfer function (MTF). Although this approach improves theoretical invertibility, practical reconstructions still suffer from amplified noise and fixed regularization that fails to adapt to scene content or blur characteristics. Recent progress in image restoration has shown that deep priors such as plug-and-play optimization and diffusion-based score priors can recover fine details in degraded images. However, these priors are usually applied with fixed or monotonic denoising schedules that do not consider the physical properties of the imaging system.

This project introduces a *physics-aware* prior schedule that adapts the denoising strength based on the measured or simulated blur MTF. The denoiser is made stronger where the MTF magnitude is low and weaker where the data is reliable, which stabilizes the inversion process without retraining. The approach remains compatible with existing plug-and-play (PnP/HQS/ADMM) and diffusion pipelines while improving robustness under realistic Poisson–Gaussian noise and fixed photon budgets. The expected outcome is sharper, more stable reconstructions and a clear demonstration of how integrating physical models with learned priors can enhance modern computational imaging.

Related Work

Early optics-driven deblurring modifies image capture to make inversion better conditioned. *Coded exposure* (flutter shutter) transforms the standard box filter into a broadband binary sequence that avoids deep spectral zeros, enabling stable deconvolution and preserving higher spatial frequencies (Raskar, Agrawal, & Tumblin, 2006). Building on this idea, Jeon *et al.* propose *Modified Legendre Sequences* (MLS) that generate fluttering patterns with low autocorrelation and more uniform spectral energy, yielding a more balanced frequency response and improved deblurring conditioning versus pseudo-random or m-sequence codes (Jeon, Lee, Han, Kim, & Kweon, 2013).

While capture-time codes improve physical conditioning, recent algorithmic advances aim to complement them via learned priors. Modern plug-and-play (PnP) priors replace handcrafted regularizers with learned denoisers.

DPIR formalizes PnP with a deep denoiser inside half-quadratic splitting, yielding strong generalpurpose restoration but with fixed noise schedules that ignore imaging physics (Zhang, Li, Zuo, & Zhang, 2020). Diffusion-based PnP extends this by integrating a diffusion prior with per-iteration data consistency, yet denoising strength is typically monotonic and independent of the system MTF (Zhu *et al.*, 2023).

Our contribution complements these efforts by introducing a physics-aware prior schedule that adapts denoising strength using the measured or simulated MTF—stronger where the MTF is weak and lighter where data fidelity is reliable—bridging capture-time physical modeling (as in MLS-based coded exposure) with inference-time adaptive prior control while remaining compatible with PnP and diffusion pipelines.

Project Overview and Final Goals

Objective. Demonstrate that an *MTF-aware denoising schedule* inside a PnP/HQS deblurring loop improves stability and perceptual quality for *coded-exposure* (vs. box) motion blur under equal photon budgets and Poisson–Gaussian noise.

Approach.

- **Data.** Synthetic generation of blurred measurements by integrating a binary flutter code over the exposure for 1D constant-velocity motion; add Poisson–Gaussian noise using calibrated parameters. Small real demo (optional): capture a planar target undergoing controlled motion and estimate PSFs/MTFs.
- **Methods.** Forward model $y = k * x + n$ with k from the exposure code. Deblur using PnP/HQS with a deep denoiser prior (e.g., DPIR/FFDNet) and *physics-aware* denoising schedule $\sigma(f)$ that depends on $|\mathrm{OTF}(k)|$ (global or band-wise). Baselines: (i) box vs. coded exposure; (ii) fixed vs. monotone vs. MTF-aware schedules; (iii) RL/Wiener classical baselines.
- **Evaluation.** PSNR/SSIM/LPIPS; spectral SNR analyses; edge/text crop comparisons; robustness to code patterns (random, m-sequence/Legendre); fairness via equal photon budgets and matched iteration counts.
- **Ethics.** No human/identifying data; synthetic or benign lab captures. Code and parameter files released for reproducibility.
- **Deliverables.** (1) Reproducible code repo with configs and ablations; (2) short report with figures (spectral SNR plots, qualitative crops); (3) optional short video/appendix for a tiny real demo.

Final Goals (end-of-project).

- Clear, ablated evidence that *MTF-aware* PnP scheduling reduces noise amplification/ringing in weak-frequency bands vs. fixed/monotone schedules at equal photon budgets.
- A compact guideline for designing shutter codes and scheduler mappings $\sigma(\cdot)$ (and, time permitting, a learned controller that predicts σ from code+noise).
- A polished write-up suitable for a course report or workshop submission, plus a public repo enabling replication.

Milestones and Timeline

Week	Milestone	Intermediate Goal(s)
By Oct 24	Finalize scope; stand up simulator	Box vs. coded exposure forward model; Poisson–Gaussian noise injection; initial PSF/OTF/MTF sanity plots
By Oct 31	Baselines running	Implement Wiener and RL; PnP/HQS loop with a standard denoiser (DPIR/FFDNet) and fixed σ
By Nov 7	Physics-aware schedule v1	Compute MTF-informed σ (global/band-wise); integrate into PnP; first qualitative results
By Nov 14	Ablations & metrics	Compare fixed/monotone/MTF-aware; random vs. Legendre/ m-sequence codes; spectral-SNR and LPIPS
By Nov 21	Stress tests	Robustness to photon budget, motion magnitude, and noise params; prepare figures
By Nov 28	(Optional) tiny real demo	Capture simple target; estimate PSF/MTF; process single coded image (or short burst)
By Dec 5	Report & repo polish	Final plots/tables; write-up; reproducibility checklist; slide-ready summary

References

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[3] Zhang, K., Li, Y., Zuo, W., & Zhang, L. (2020). *Plug-and-Play Image Restoration with Deep Denoiser Prior*. arXiv:2008.13751.

[4] Zhu, X., Zhang, J., Liang, Z., Cao, R., Wen, B., Timofte, R., & Van Gool, L. (2023). *Denoising Diffusion Models for Plug-and-Play Image Restoration*. arXiv:2305.08995.