

HIGH DYNAMIC RANGE IMAGING USING DEEP IMAGE PRIORS

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ABSTRACT

Traditionally, dynamic range enhancement for images has involved a combination of contrast improvement (via gamma correction or histogram equalization) and a denoising operation to reduce the effects of photon noise. More recently, modulo-imaging methods have been introduced for high dynamic range photography to significantly expand dynamic range at the sensing stage itself. The transformation function for both of these problems is highly non-linear, and the image reconstruction procedure is typically non-convex and ill-posed. A popular recent approach is to regularize the above inverse problem via a neural network prior (such as a trained autoencoder), but this requires extensive training over a dataset with thousands of paired regular/HDR image data samples.

In this paper, we introduce a new approach for HDR image reconstruction using neural priors that require no training data. Specifically, we employ deep image priors, which have been successfully used for imaging problems such as denoising, super-resolution, inpainting and compressive sensing with promising performance gains over conventional regularization techniques. In this paper, we consider two different approaches to high dynamic range (HDR) imaging – gamma encoding and modulo encoding – and propose a combination of deep image prior and total variation (TV) regularization for reconstructing low-light images. We demonstrate the significant improvement achieved by both of these approaches as compared to traditional dynamic range enhancement techniques.

Index Terms— Deep image prior, untrained neural networks, convolutional networks, low-light enhancement, HDR imaging, inverse imaging, modulo camera.

1. INTRODUCTION

1.1. Motivation

Low-light images, or images captured in poor lighting conditions, are ubiquitous in numerous real-world imaging applications. A combination of limited camera sensor hardware and high photon noise can result in low (effective) dynamic range resolution of the captured images. This motivates the problem of low-light image enhancement via extending (post-acquisition) the dynamic range of the captured images, which can be particularly challenging. Several existing low-light enhancement techniques suffer from over-enhancement and the resulting images appear unnatural. Our goal in this paper is to propose novel data processing techniques that can produce improved high dynamic range (HDR) images from acquired camera sensor data.

Mathematically, low-light image acquisition can be viewed as a non-linear forward problem where each “true pixel value” is distorted by different amounts. When a gamma correction model is

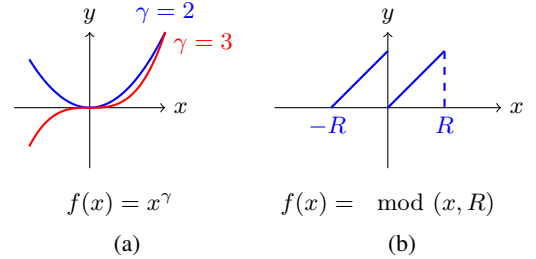


Fig. 1. Transfer functions for (a) gamma encoding with factor $\gamma > 1$ (b) modulo encoding, where x is the true image and y are measurements and R is the the period of modulo function.

assumed, the forward transfer function is indicated in Figure 1(a). Low-light images are also corrupted by (additive) photon sensor noise, so that the effects of this noise are amplified in a non-linear manner when gamma correction is applied.

An alternative technique for extending dynamic range is to devise new transfer functions with favorable properties. In [1] the authors present a Modulo camera setup with a folding architecture based reconstruction approach to achieve ultra high dynamic range imaging by wrapping the illumination data in a periodic manner. Whenever the pixel value of the camera sensor saturates to its maximum capacity during photon collection, the pixel counter is reset to zero and photon collection continues till the next saturation point (Figure 1(b)). Modulo cameras can theoretically achieve unbounded high dynamic range; however the task of inverting modulo imaging measurements is highly ill-posed.

Deep neural network approaches have led to unprecedented success in solving several ill-posed inverse imaging problems. Image denoising [2], super-resolution [3], inpainting, compressed sensing [4] and phase retrieval [5] are among the several imaging applications that have benefited from the usage of deep convolutional networks (CNNs); such CNN models have slowly replaced hand-crafted priors such as sparsity, total variation and block-matching [4, 6, 7, 8].

However, the main challenge with these approaches is the requirement of massive amounts of training data. In contrast, recently, there has been a surge of interest in using *untrained* neural networks as image priors for regularizing inverse problems. Seminal works on such *deep image priors* [9, 10, 11] are capable of solving linear inverse imaging problems with no training data whatsoever, while merely imposing an auto-encoder [9] or decoder [10, 11] architecture as structural priors on the image. These approaches have been shown to exhibit superior image reconstruction performance as compared to conventional denoising, super-resolution, or compressive sensing approaches [12, 13, 14, 15].

1.2. Our contributions

In this paper, extending [11], we introduce a new approach that uses untrained deep neural networks as image priors for dynamic

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range enhancement of low-light images. We assume that the image x^* can be (approximately) modeled as a vector belonging to the range spanned by the weights of a deep neural network [9, 10], i.e., $x^* = G(\mathbf{w}; z)$ where \mathbf{w} is a set of the weights of the deep network, z is a fixed latent code, and G captures the overall deep network architecture. We incorporate this prior into natural iterative regularization algorithms: (a) one that simultaneously corrects for brightness (which is modeled as a gamma correction) and denoises a low-light image, and (b) one that reconstructs HDR images from modulo measurements¹. Our experimental results demonstrate significant improvement over conventional regularized inverse-imaging methods with hand-crafted priors, while avoiding the need for any training data whatsoever.

1.3. Prior work

Due to space limitations we only provide a brief overview of prior work. An extensive review of low-light image enhancement schemes can be found in [16].

Low light image enhancement has been extensively studied in the image processing literature. Statistical image reconstruction methods include Histogram Equalization (HE) which involves adjusting the pixel intensities such that the histogram is flat and uniformly spread across all possible values instead of concentrated near low pixel intensities. Further, different regularizations may be imposed on the histogram statistics (for example, contextual and variational contrast enhancement (CVC) [17] and local histogram equalization (HE) [18, 19] which adopt the sliding window strategy to perform HE locally). Another approach is to use an appropriate transformation model such as (adaptive) gamma correction, which can correlate pairs of bright and dark images [20]. Concurrently, retinex theory [21] based approaches assume that the amount of light reaching observers can be decomposed into two parts: illumination and scene reflection [22].

Instead of formulating an appropriate forward model based on the imaging physics, a mapping may also be *learned* by training a neural network over thousands of example images [23]. LL-Net [23] uses an autoencoder based approach which emulates a gamma correction and denoising model trained on pairs of artificially darkened and corrupted images, whereas [24] introduces a new neural network model called Deep-Retinex. EnlightenGAN [25] uses a CycleGAN [26] based approach for image to image translation. The merits of such approaches is that after it is trained, the low-light correction operation is a one-shot procedure. The trained model implicitly learns an appropriate scaling of pixel values, and applies an appropriate regularization based on image database statistics. There are several shortcomings of neural network-based approaches. First, all of these approaches require a large database of paired [24, 23] or unpaired [25] bright and dark images. The requirement to train a huge neural network with thousands of parameters can incur unreasonably high computational costs. Second, this approach allows little control on the *degree* of correction or enhancement for a given image.

The above alleviate the problem of photon saturation, modulo-cameras were introduced in [1]. This computational sensing technique allows for infinite dynamic range [27, 28]. However the inverse mapping is highly ill-posed and requires computational expensive approaches for signal reconstruction based on graph cuts [29, 1] or quadratically constrained quadratic program [30]. [31] uses a sparsity prior to develop an alternating minimization technique

¹For the low-light image enhancement problem, we additionally assume that the image exhibits low total variation (TV).

MoRAM, to solve this problem from compressive Gaussian measurements, while [32] uses an approximate message passing based approach. In [33] authors provide a wavelet based reconstruction approach for inverting modulo signal measurements and also provide theoretical guarantees for the convergence of their algorithm.

1.4. Notation

Throughout the paper, lower case letters denote vectors, such as v and upper case letters for matrices, such as M . The indicator vector is denoted by $\mathbf{1}_{\text{cond}(v)}$ and is a boolean vector the size of v and indicates element-wise satisfaction of a given condition $\text{cond}(\cdot)$. The set of weights of a neural network is represented by $\mathbf{w} = \{W_1, \dots, W_L\}$ where L denotes the number of layers.

2. PROBLEM SETUP

In this section we describe two HDR image formation models and reconstruction techniques that use deep image priors.

2.1. Low-light model

Our first method reconstructs HDR images (assumed an underlying deep image prior) from noisy dark or low-light (LL) images $y \in \mathbb{R}^d$ that are modeled by a gamma correction model that obeys Steven's law corrupted by additive white Gaussian noise ε with variance σ :

$$f(x^*) = y = c \cdot x^{*\gamma} + \varepsilon, \quad (1)$$

where $x^* \in \mathbb{R}^d$ is the true image (whose pixel values lie between 0 and 1), factor $\gamma \in \mathbb{R}^+$ is such that $\gamma > 1$ corresponds to a darkened observed image y and $0 < \gamma < 1$ corresponds to a brightened observed image, and $c \in \mathbb{R}^+$ is a known scaling constant. Since we consider the problem of low-light enhancement, for our problem setting $\gamma > 1$ is known.

2.2. Modulo observation model

Our second method reconstructs HDR images from modulo-valued observations $y \in \mathbb{R}^n$, with periodicity $R \in \mathbb{R}^+$:

$$f(x^*) = y = \text{mod}(Ax^*, R)$$

where $x^* \in \mathbb{R}^d$ is the true image, with pixel values lying between 0 and 1. Here $A \in \mathbb{R}^{n \times d}$ is a linear transformation matrix which models optical acquisition setup. In this paper, we consider a model with two periods, following [31]. Mathematically:

$$f(x) = y = Ax^* + R \cdot \mathbf{1}_{Ax^* < R} \quad (2)$$

where $\mathbf{1}_{Ax^* < R}$ is an element-wise indicator.

2.3. Deep image prior

A deep image prior assumes that the image $x \in \mathbb{R}^{d \times k}$ (k channels each of dimension d) can be represented as the action of a deep generative network $G(\mathbf{w}; z)$ with unknown weights \mathbf{w} on some fixed latent code z , such that $x = G(\mathbf{w}; z)$. The latent code $z := \text{vec}(Z_1)$ with $Z_1 \in \mathbb{R}^{d_1 \times k_1}$ is a low-dimensional parameter with dimension $d_1 k_1 \ll dk$; its elements are generated from an appropriately scaled uniform random distribution and are kept fixed throughout.

The task is to estimate the image

$$\hat{x} = G(\hat{\mathbf{w}}; z) \approx G(\mathbf{w}^*; z) = x^*$$

Algorithm 1 Low-light image enhancement with Deep Image Prior.

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1: Input:  $A, z = \text{vec}(Z_1), \eta, \mathbf{w}^0$ .
2: while termination condition not met do
3:    $\mathbf{w}^{t+1} \leftarrow \mathbf{w}^t - \eta \nabla \mathcal{L}(\mathbf{w}^t)$            {gradient step}
4: end while
5: Output  $\hat{x} \leftarrow G(\mathbf{w}^T; z)$ .

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and corresponding weights $\hat{\mathbf{w}}$, for a fixed seed z , where x^* is assumed to be the true image and the true weights \mathbf{w}^* (possibly non-unique) satisfy

$$\mathbf{w}^* = \min_{\mathbf{w}} \|x^* - G(\mathbf{w}; z)\|_2^2.$$

Substituting the surjective mapping $G : \mathbf{w} \rightarrow x$, and optimizing over \mathbf{w} , we have

$$\min_{\mathbf{w}} \mathcal{L}(\mathbf{w}) := \min_{\mathbf{w}} \|y - f(G(\mathbf{w}; z))\|_2^2 + \lambda \cdot \text{TV}(G(\mathbf{w}; z)), \quad (3)$$

to obtain $\hat{\mathbf{w}} = \arg \min_{\mathbf{w}} \mathcal{L}(\mathbf{w})$ and corresponding image \hat{x} . Here, we have imposed a Mean-Squared Error (MSE) loss, and an additional Total Variation (TV) regularization to smoothen out the effective image $\hat{x} = G(\hat{\mathbf{w}}; z)$ with Lagrangian multiplier λ , which is chosen appropriately. Alternatively, one can use a variable splitting approach of the form,

$$\begin{aligned} \min_{x, \mathbf{w}} \mathcal{L}(x, \mathbf{w}) &:= \min_{x, \mathbf{w}} \|y - f(x)\|_2^2 + \lambda \cdot \text{TV}(x), \\ \text{s.t. } x &= G(\mathbf{w}; z) \end{aligned} \quad (4)$$

Specifically, the untrained network $G(\mathbf{w}; z)$ takes the form of an expansive neural network; a decoder architecture similar to the one in [10], or that of the generator of a DCGAN [34, 35]. Fixing this architectural framework, we define the deep network prior as follows:

Definition 1. A given image $x \in \mathbb{R}^{d \times k}$ is said to obey an untrained neural network prior if it belongs to a set \mathcal{S} defined as: $\mathcal{S} := \{x | x = G(\mathbf{w}; z)\}$, where z is a (randomly chosen, fixed) latent code vector and $G(\mathbf{w}; z)$ has the form of a generator [34] or decoder [10].

3. RECONSTRUCTION ALGORITHMS

3.1. Low-light model

A combination of the forward model described above coupled with deep image prior leads to a natural recovery algorithm. The loss function in Eq. 3 with f assuming the form in Eq. 1 can be (heuristically) minimized using gradient descent by optimizing over the weights \mathbf{w} of the deep image prior; the procedure is described in Algorithm 1. The gradients $\nabla \mathcal{L}(\mathbf{w})$ in Step 3 of Algorithm 1 are computed using back-propagation using standard software frameworks for deep learning such as TensorFlow and PyTorch, with learning rate η . The weights \mathbf{w}^0 are initialized according to He’s initialization [36]. Each iteration t yields a new image estimate $x^t = G(\mathbf{w}^t; z)$ which belongs to the range of the deep image prior, \mathcal{S} .

3.2. Modulo observation model

The forward model in Eq. 2 is both non-differentiable and non-bijective, so we require additional algorithmic adjustments. In Algorithm 2, we propose a two-stage reconstruction approach.

The basic idea is to first estimate the “bin” into which the modulo observations are folded; if we can do this well, then it essentially

Algorithm 2 Modulo sensing with Deep Image Prior.

INITIALIZATION STAGE

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1: Input:  $A, z = \text{vec}(Z_1), \eta, \mathbf{w}^0$ .
2:  $y_{init} = y - R \cdot p_{init}$ 
3:  $x^0 = \arg \min_{x \in \mathcal{S}} \|y_{init} - Ax\|_2^2$  {Net-GD for CS}

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DESCENT STAGE

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4: Input:  $A, z, x^0, \eta, \mathbf{w}^0$ 
5: while termination condition not met do
6:    $p^t = \mathbf{1}_{Ax^t < 0}$ 
7:    $y_c = y - R \cdot p^t$ 
8:    $v^t \leftarrow x^t - \eta \nabla_x \|y_c - Ax\|_2^2$            {gradient step}
9:    $x^{t+1} \leftarrow \arg \min_{x \in \mathcal{S}} \|v^t - x\|_2^2$  {project to  $\mathcal{S}$ }
10: end while
11: Output  $\hat{x} \leftarrow G(\mathbf{w}^T; z)$ .

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becomes a linear inverse problem. Let p denote the bin-index of vector Ax which is ‘1’ if $Ax < 0$ and ‘0’ if $Ax > 0$. Then, a crude estimate of $p = p_{init}$ can be obtained as follows, as per [31]:

$$p_{init} = \begin{cases} 0, & y < \frac{R}{2} \\ 1, & y > \frac{R}{2} \end{cases}. \quad (5)$$

With p_{init} , one can first solve a linear recovery problem from imperfect measurements $y_{init} = y - R \cdot p_{init}$, (Steps 2 and 3 of Algorithm 2), subject to the constraint that the reconstructed signal x^0 lies in the range of a deep image prior. This can be implemented using the Net-GD algorithm from [11]. In our experiments, we observed that this procedure yields a good enough initialization for the problem of signal reconstruction from modulo measurements.

Given a good initialization, one can apply an alternating minimization type scheme as described in Steps 6-9 of Algorithm 2; these alternately refine the estimates of the image as well as the bin-indices, mirroring the approach of [37, 38]. We formulate the ‘corrected’ linear measurements $y_c = y - R \cdot p^t$ and use these to solve a linear recovery problem with a single step of projected gradient descent in Steps 8 and 9. This is similar to solving the setting in Eq. 4, but with a warm start (and with $\lambda = 0$). For both stages of Algorithm 2, we initialize the weights \mathbf{w}^0 as per He initialization [36]. The gradients $\nabla_x \|y_c - Ax\|_2^2$ in Step 8 of Algorithm 2 can be computed using back-propagation with learning rate η . The projection in Step 9 of Algorithm 2 can be solved as $\min_{\mathbf{w}} \|v^t - G(\mathbf{w}; z)\|_2^2$ via the Adam optimizer.

4. EXPERIMENTAL RESULTS

Performance metrics: We compare reconstruction quality using two metrics: (i) normalized Mean-Squared Error (nMSE), which is calculated as $\|\hat{x} - x^*\|^2 / \|x^*\|^2$, and (ii) Structural Similarity Index (SSIM) [39]. We tabulate their variation against different modeling parameters such as noise level σ , γ (for low-light image enhancement) and different compression rates $f = n/d$ (for modulo signal recovery), averaged over all trials.

4.1. Low-light model

Forward model: We select $\gamma = 3, 4$ and noise variance $\sigma = 0.01, 0.03$. For sake of simplicity we fix scaling constant $c = 1$.



Fig. 2. (LL) (a) Original image, (b) image darkened with factor γ , followed by addition of noise with variance σ , (c) gamma corrected image (d) gamma correction followed by TV denoising (e) Algorithm 1 using Deep Image Prior.

Dataset: We have used two test images: San Francisco (rows 1 and 2 of Figure 2) and Red Rock (rows 3 and 4 of Figure 2). Both have been reshaped to $128 \times 128 \times 3$ (i.e., input dimension $d = 49152$). The pixel values of all images are scaled to lie between 0 and 1.

Deep network architecture: We use a 4-layer DCGAN architecture consisting of transposed convolutions, ReLU operations, and batch normalizations. The final layer has a sigmoid activation to restrict the dynamic range of the output image. The widths of each layer vary between $k = 40$ to $k = 100$ and the performance corresponding to the best setting is reported in Figure 2.

Algorithms and baselines: We implement 3 schemes for the low-light image enhancement: (i) gamma correction (ii) gamma correction followed by Total Variation (TV) denoising and (iii) deep image prior based denoising (Algorithm 1).

Implementation details: Algorithm 1 was implemented using the PyTorch framework with Python 3 (with GPU support) using Adam optimizer. For implementing TV denoising, we use the scikit-learn image library. The Lagrangian parameter λ is tuned for each image appropriately to get best performance.

Running time: We report the average running times for different algorithms across different γ and σ values for our example images is 35.43s (Algorithm 1), and 0.16s (TV).

From our results in Figure 2, we note that DIP coupled with TV regularization can perform comparable or better image enhancement from darkened and corrupted images in all cases.

4.2. Modulo observation model

Dataset: We use 3 test images from the MNIST database each of size 28×28 pixels. The pixel values of all images are scaled to lie between 0 and 1.

Forward model: We use a Gaussian measurement matrix of size $n \times d$ with n varied such that $n/d = 0.25, 0.5, 0.75, 1, 2$. The elements of A are picked such that $A_{i,j} \sim \mathcal{N}(0, 1/n)$ and we report averaged reconstruction error values over 10 different instantiations

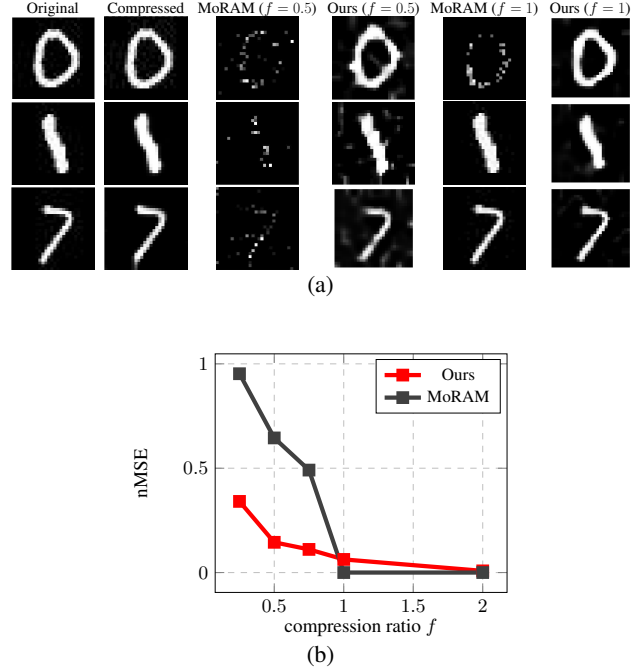


Fig. 3. (Modulo) Reconstructed images from modulo measurements (a) at compression rates of $f = n/d = 0.5, 1$ for MNIST images, (b) nMSE at different compression rates $f = n/d$ for MNIST digit '1' averaged over 10 trials.

of A for a fixed image (image of digit '1' from MNIST), network configuration and compression ratio n/d in Figure 3 (b). The period R is picked as $R = (1.8) \cdot \max_i a_i^\top x^*$, where $i = \{1, \dots, n\}$.

Deep network architecture: We use the deep decoder architecture [10] with a 3 layer configuration with channel sizes $k_1 = 25, k_2 = 15, k_3 = 10$ and consisting of ReLU, upsampling and 1×1 convolutions $W_1 \in \mathbb{R}^{k_1 \times k_2}, W_2 \in \mathbb{R}^{k_2 \times k_3}$ and $W_3 \in \mathbb{R}^{k_3 \times 1}$. We further use batch normalization on all layers and a sigmoid operation on the final layer. For further details refer to the setup in [11].

Algorithms and baselines: We implement 2 schemes for signal reconstruction from modulo measurements, (i) Algorithm 2 and (ii) Modulo recovery using Alternating Minimization (MoRAM) [31] for all images.

Implementation details: Algorithm 2 was implemented using PyTorch framework with Python 3 with GPU support. The Adam optimizer was used for solving Steps 3 and 9 of Algorithm 2 whereas SGD optimizer was used to compute a single update in Step 8. MoRAM [31] was implemented using MATLAB code that uses a combination of CoSaMP [40] and Justice Pursuit [41] interchangeably for the sparse signal estimation stage, depending on which approach yielded better performance for the images chosen. Since the images chosen from MNIST are sparse to begin with, we did not use any sparsifying transform on the images.

Running time: We report the average running times for different algorithms across different measurement levels for examples from MNIST is 25.59s (Algorithm 2) and 9.1s (MoRAM).

From our results in Figure 3, we can see that DIP can reconstruct higher quality images from modulo observations at much lower compression rates. At high compression rates, sparsity priors are more beneficial; this is plausibly due to the fact that we have chosen an under-parameterized network for our prior which can induce small representational error.

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