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Abstract. Variational methods are widely applied to ill-posed inverse problems for they have the ability to embed prior knowledge about the solution. However, the level of performance of these methods significantly depends on a set of parameters, which can be estimated through computationally expensive and time-consuming methods. In contrast, deep learning offers very generic and efficient architectures, at the expense of explainability, since it is often used as a black-box, without any fine control over its output. Deep unfolding provides a convenient approach to combine variational-based and deep learning approaches. Starting from a variational formulation for image restoration, we develop iRestNet, a neural network architecture obtained by unfolding a proximal interior point algorithm. Hard constraints, encoding desirable properties for the restored image, are incorporated into the network thanks to a logarithmic barrier, while the barrier parameter, the stepsize, and the penalization weight are learned by the network. We derive explicit expressions for the gradient of the proximity operator for various choices of constraints, which allows training iRestNet with gradient descent and backpropagation. In addition, we provide theoretical results regarding the stability of the network for a common inverse problem example. Numerical experiments on image deblurring problems show that the proposed approach compares favorably with both state-of-the-art variational and machine learning methods in terms of image quality.

Keywords: Interior point method, proximal algorithms, deep unfolding, neural network, image restoration, regularization.

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1. Introduction

In this work we focus on inverse problems related to the following model:

$$y = \mathcal{D}(H\overline{x}), \tag{1}$$

where $y \in \mathbb{R}^m$ is the observed data, $\overline{x} \in \mathbb{R}^n$ is the sought signal or image, $H \in \mathbb{R}^{m \times n}$ is the observation operator, which is presumed linear for simplicity, and $\mathcal{D}$ is the noise perturbation operator. The linear operator H is assumed to be known from a physical model or prior identification step [1, 2]. In this context, both variational and deep learning approaches provide efficient methods for delivering an estimate of $\overline{x}$, while offering different benefits and drawbacks, which are discussed hereafter.

In order to find an appropriate solution to an ill-posed inverse problem like (1), variational methods incorporate prior information on the sought variable $\overline{x}$, through constraints or regularization functions, such as the total variation and its various extensions [3] or sparsity-promoting functions [4]. This leads to the following minimization problem:

$$\min_{x \in \mathcal{C}} \; f(Hx, y) + \lambda \mathcal{R}(x) \tag{2}$$

where $f : \mathbb{R}^m \times \mathbb{R}^m \to \mathbb{R}$ is the data-fidelity function, related to the degradation model, $\mathcal{R} : \mathbb{R}^n \to \mathbb{R}$ is the regularization, $\lambda \in]0, +\infty[$ is a regularization parameter and $\mathcal{C}$ is a subset of $\mathbb{R}^n$. Although useful, this approach is sometimes limited by its complexity: solving (2) may require advanced algorithms that may be too slow for real-time applications. In addition, λ is a parameter that needs to be set and $\mathcal{R}$ is usually parametrized by one or several parameters, whose optimal choice may strongly depend on the data at hand. These parameters are often tuned manually or computed using, for instance, cross validation, the discrepancy principle [5], or methods based on Stein unbiased risk estimates (SURE) [6]. However, these methods are often time-consuming and their success is not always guaranteed. Furthermore, despite numerous efforts in designing sophisticated models, solving (2) does not necessarily lead to the best estimate for $\overline{x}$, hence the development of early stopping methods, where the iterative procedure is stopped before convergence [7]. Finding the optimal stopping time depends on the algorithm and requires the use of an oracle such as SURE, which may explain why these techniques are currently restricted to relatively simple cost functions.

Deep Neural Networks (DNNs), and in particular Convolutional Neural Networks (CNNs), provide good performance for various applications related to inverse problems, such as denoising [8], non-blind and blind deblurring [9, 10, 11], super-resolution [12], or CT reconstruction [13]. As detailed in [14], DNNs for inverse problems are very often preceded by a pre-processing step. Indeed, a rough estimation of $\overline{x}$ can be found by using the inverse or pseudoinverse of H. The latter tends, however, to strongly amplify noise. Hence, in this context, DNNs are used as denoisers and artifact-removers. However, since prior knowledge about its output can hardly be incorporated into a DNN, which in most of the cases is viewed as a black-box, the explainability and reliability [15] of such methods could be questioned. Furthermore, the pre-processing step, in itself, can include a penalty, thus amounting to solving a problem of the form (2), where the regularization weight strongly depends on the noise level, *e.g.* [10, 16]. One straightforward way to combine the benefits of both variational-based methods and

DNNs is to unfold an iterative method and untie the parameters of both the model and the algorithm across the layers of the network [17]. Interestingly, the fact that this approach makes use of a limited number of layers can be viewed as an analogue of early stopping methods.

In this paper, we propose a novel neural network architecture called iRestNet, which is obtained by unfolding a proximal interior point algorithm over a finite number of iterations. One key feature of this algorithm is that it produces only feasible iterates thanks to a logarithmic barrier. This barrier enables prior knowledge to be directly incorporated into iRestNet and, as opposed to a projection onto $\mathcal{C}$, it allows differentiation and gradient backpropagation throughout the network. Hence, gradient descent can be used for training. The stepsize, barrier parameter, and regularization weights are untied across the network and learned for each layer, which leads to a better reconstruction than traditional variational methods without any parameter search.

Related works apply deep unfolding to probabilistic models, such as Markov random fields [17], topic models [18], and to different algorithms like primal-dual solvers [19], the proximal gradient method [20, 21] or ISTA [22]. FISTA and ADMM have been unfolded to perform sparse coding [23] and image reconstruction [24], respectively. However, in both cases, all functions and operators are learned, which weakens the link between the resulting network and the original algorithm. Deep unfolding is also used to learn shrinkage functions, which can be viewed as proximity operators of sparsity-promoting functions [25, 26], or to optimize hyperparameters in nonlinear reaction diffusion models [27]. Several recent works consider replacing handcrafted algorithms by learned iterative methods [28, 29]. In these approaches, however, the final goal is to find the minimizer of a given objective function and not to search for the optimal quality solution of an inverse problem, as we propose in this paper. Only a few works so far have considered combining interior point methods (IPMs) with deep learning. Every layer of the network from [30] solves a small quadratic problem using an IPM, while in [31], hard constraints are enforced on weights by using the logarithmic barrier function during training. More recently, an interior point strategy was used to design a recurrent network, whose purpose is to solve a specific convex constrained problem [32]. Our proposed network appears to have more flexibility since the regularization weight can vary among layers and it is trained to solve an inverse problem, not to solve directly a given optimization problem.

To the best of our knowledge, this paper presents the first architecture corresponding to a deep unfolded version of an interior point algorithm with untied stepsize and regularization parameter. As opposed to other unfolding methods like [20, 21], the proximity operator and the regularization term are kept explicit, which establishes a direct relation between the original algorithm and the network. Other contributions of this work include the expression of the required proximity operator, and of its corresponding gradient, for three standard variational formulations, along with numerical experiments demonstrating the benefit of using the proposed approach over other machine learning and variational methods for image deblurring.

This paper is organized as follows: in Section 2, we describe the proximal interior point optimization method which is at the core of our approach, and we provide the proximity operator of the barrier for three useful cases in Section 3. In Section 4, we

present the proposed neural network architecture and its associated backpropagation method. In Section 5, we conduct a stability analysis of the proposed network when the data fidelity term and the regularization function are quadratic. Section 6 is dedicated to numerical experiments and comparison to state-of-the-art methods for image deblurring; finally, some conclusions are drawn in Section 7.

2. Proximal interior point algorithm

2.1. Variational formulation and notation

As detailed in Section 1, the sought image $\overline{x}$ can be classically approximated by the minimizer of a penalized cost function expressed as the sum of a data-fitting term, which measures the fidelity of the solution to the observation model (1), and a regularization term, which is introduced so as to avoid meaningless solutions and improve stability to noise. This leads to problem (2) with $\lambda \in]0, +\infty[$ a regularization parameter. In the remaining of the paper, we will assume that $f(\cdot, y) : \mathbb{R}^m \to \mathbb{R}$ is a twice-differentiable data-fidelity term, and $\mathcal{R} : \mathbb{R}^n \to \mathbb{R}$ is a twice-differentiable regularization function. Note that such assumption is necessary to define the derivative steps involved in the backpropagation procedure for the training of our network. Let $\Gamma_0(\mathbb{R}^n)$ denote the set of functions which take values in $\mathbb{R} \cup \{+\infty\}$ and are proper, convex, lower semicontinuous on $\mathbb{R}^n$. The feasible set $\mathcal{C}$ is defined by p inequality constraints which enforce the fulfillment of some properties that are expected to be satisfied a priori by the image:

$$\mathcal{C} = \{x \in \mathbb{R}^n \mid (\forall i \in \{1, \dots, p\})\ c_i(x) \geq 0\}, \tag{3}$$

where, for every $i \in \{1, \dots, p\}$, $-c_i \in \Gamma_0(\mathbb{R}^n)$. The strict interior of the feasible domain, $\mathrm{int}\mathcal{C}$, is equal to

$$\mathrm{int}\mathcal{C} = \{x \in \mathbb{R}^n \mid (\forall i \in \{1, \dots, p\})\ c_i(x) > 0\}, \tag{4}$$

and it is assumed to be nonempty. Finally, we will assume that either $f(H\cdot, y) + \lambda\mathcal{R}$ is coercive, or $\mathcal{C}$ is bounded. Then the existence of solutions for (2) is guaranteed. It is worthy to emphasize that a large class of penalized formulations encountered in the literature of image restoration fulfills the above requirements, see e.g. [33] and references therein.

Let us introduce additional notations, which will be useful in the rest of the paper. First, for every $g \in \Gamma_0(\mathbb{R}^n)$, $\gamma \in]0, +\infty[$, and $x \in \mathbb{R}^n$, the proximity operator [34] of γg at x is uniquely defined as

$$\mathrm{prox}_{\gamma g}(x) = \underset{u \in \mathbb{R}^n}{\mathrm{argmin}}\ \frac{1}{2}\|x - u\|^2 + \gamma g(u). \tag{5}$$

Finally, for all $(x, y, \lambda) \in \mathbb{R}^n \times \mathbb{R}^m \times]0, +\infty[$, we define

$$h(x, y, \lambda) = f(Hx, y) + \lambda\mathcal{R}(x), \tag{6}$$

and

$$\nabla_1 h(x, y, \lambda) = H^\top \nabla_1 f(Hx, y) + \lambda\nabla\mathcal{R}(x), \tag{7}$$

where $\nabla_1 f$ is the partial gradient of f with respect to its first variable.

2.2. Interior point approaches

In general, problem (2) does not have a closed-form solution on account of the inequality constraints, even for simple regularizations, hence an iterative solver must be used. Several resolution approaches are available, either based on projected gradient strategies [35, 36], ADMM [37], primal-dual schemes [38], or interior point techniques [39]. Standard interior point methods (IPMs) require to invert several $n \times n$ linear systems, which leads to a high computational complexity for large scale problems. Nonetheless, it has recently been shown that combining the interior point framework with a proximal forward–backward strategy [40, 41] leads to very competitive solvers for inverse problems [42, 43].

The idea behind IPMs is to replace the initial constrained optimization problem by a sequence of unconstrained subproblems of the form:

$$\min_{x \in \mathbb{R}^n} \; f(Hx, y) + \lambda \mathcal{R}(x) + \mu \mathcal{B}(x) \tag{8}$$

where $\mathcal{B} : \mathbb{R}^n \to \mathbb{R} \cup \{+\infty\}$ is the logarithmic barrier function with unbounded derivative at the boundary of the feasible domain:

$$(\forall x \in \mathbb{R}^n) \quad \mathcal{B}(x) = \begin{cases} -\sum_{i=1}^{p} \ln(c_i(x)) & \text{if } x \in \text{int}\mathcal{C} \\ +\infty & \text{otherwise,} \end{cases} \tag{9}$$

and $\mu \in]0, +\infty[$ is the so–called barrier parameter which vanishes along the minimization process. We assumed that either $f(H\cdot, y) + \lambda\mathcal{R}$ is coercive, or $\mathcal{C}$ is bounded, hence, the set of solutions to (2) is bounded. Since int$\mathcal{C}$ is not empty we can apply [44, Theorem 5(ii)] and the existence of solutions to (8) is guaranteed.

2.3. Proposed iterative schemes

Thanks to the proximity operator, the IPM from [45] does not require any matrix inversion. When the proximity operator is computed in an exact manner, the proposed IPM can be rewritten as Algorithm 1, whose convergence has been proven under some assumptions [45, Theorem 4.1].

Algorithm 1 Exact version of the proximal IPM in [45] applied to problem (2).

Let $x_0 \in \text{int}\mathcal{C}$, $\underline{\gamma} > 0$ and $(\gamma_k)_{k\in\mathbb{N}}$ be a sequence such that $(\forall k \in \mathbb{N})\ \underline{\gamma} \leq \gamma_k$;
for $k = 0, 1, \ldots$ **do**
  $x_{k+1} = \text{prox}_{\gamma_k(h(\cdot,y,\lambda)+\mu_k\mathcal{B})}(x_k)$
end for

Algorithm 1 requires evaluating the proximity operator of the sum of the barrier and the regularized cost function, which can be an issue since, in most of the cases, it does not have a closed-form solution. This is the reason why we propose to modify it by

introducing a forward step, which leads to Algorithm 2.

Algorithm 2 Proposed forward–backward proximal IPM.

Let $x_0 \in \mathrm{int}\mathcal{C}$, $\underline{\gamma} > 0$ and $(\gamma_k)_{k\in\mathbb{N}}$ be a sequence such that $(\forall k \in \mathbb{N})\ \underline{\gamma} \leq \gamma_k$;
for $k = 0, 1, \ldots$ **do**
  $x_{k+1} = \mathrm{prox}_{\gamma_k \mu_k \mathcal{B}}\left(x_k - \gamma_k \nabla_1 h\left(x_k, y, \lambda\right)\right)$
end for

Algorithm 2 only requires computing the proximity operator of the logarithmic barrier. We will provide its expression in Section 3 for three different types of constraints.

2.4. Limitations

In IPMs, the barrier parameter and stepsize sequences, $(\mu_k)_{k\in\mathbb{N}}$ and $(\gamma_k)_{k\in\mathbb{N}}$, are usually set by following some heuristic rules complying with the convergence conditions of the method. These heuristics however do not account for the final goal of the problem, which is to reach an optimal image quality. They can thus lead to a loss in efficiency and versatility of the resulting restoration schemes. Moreover, as already mentioned, an accurate setting of the regularization weights is particularly critical in order to obtain a satisfactory image quality when using such penalized restoration approaches. Existing approaches for selecting λ, which are based on statistical considerations, are usually associated with a substantial increase of the computational cost.

To overcome these limitations, we propose to unfold Algorithm 2 over a given number of iterations and to learn the stepsize, the barrier and the regularization parameters for every iteration in a supervised fashion. Our machine learning method will make use of gradient backpropagation for its training step. The latter requires the derivatives of the proximity operator in Algorithm 2 with respect to its input and to the aforementioned parameters which are to be learned. Therefore, we first conduct an analysis of the proximity operator of the barrier and of its derivatives, for three examples of interest in Section 3.

3. Proximity operator of the barrier

Let $\mathcal{B}$ be defined as in (9) and for all $\mu > 0$, $\gamma > 0$ and $x \in \mathbb{R}^n$, let φ be defined as follows:

$$\varphi(x, \mu, \gamma) = \mathrm{prox}_{\gamma\mu\mathcal{B}}(x). \tag{10}$$

We provide in this section expressions of φ and of its derivatives with respect to its input variable x and the involved barrier and stepsize parameters (μ, γ), for three common types of constraints. The latter will be necessary for training the proposed neural network using a gradient backpropagation scheme.

3.1. Affine constraints

Let us first consider the following half space constraint:

$$\mathcal{C} = \{x \in \mathbb{R}^n \mid a^\top x \leq b\}, \tag{11}$$

with $a \in \mathbb{R}^n \setminus \{0\}$ and $b \in \mathbb{R}$.

Proposition 1 *Let $\gamma > 0$, $\mu > 0$, and $\mathcal{B}$ be the function associated to (11), defined as*

$$(\forall u \in \mathbb{R}^n) \quad \mathcal{B}(u) = \begin{cases} -\ln(b - a^\top u) & \text{if } a^\top u < b, \\ +\infty & \text{otherwise.} \end{cases} \tag{12}$$

Then, for every $x \in \mathbb{R}^n$, the proximity operator of $\gamma\mu\mathcal{B}$ at x is given by

$$\varphi(x, \mu, \gamma) = x + \frac{b - a^\top x - \sqrt{(b - a^\top x)^2 + 4\gamma\mu\|a\|^2}}{2\|a\|^2} a. \tag{13}$$

In addition, the Jacobian matrix of φ with respect to x and the gradients of φ with respect to μ and γ are given by

$$J_\varphi^{(x)}(x, \mu, \gamma) = \mathbb{I}_n - \frac{1}{2\|a\|^2} \left(1 + \frac{a^\top x - b}{\sqrt{(b - a^\top x)^2 + 4\gamma\mu\|a\|^2}} \right) aa^\top, \tag{14}$$

$$\nabla_\varphi^{(\mu)}(x, \mu, \gamma) = \frac{-\gamma}{\sqrt{(b - a^\top x)^2 + 4\gamma\mu\|a\|^2}} a, \tag{15}$$

and

$$\nabla_\varphi^{(\gamma)}(x, \mu, \gamma) = \frac{-\mu}{\sqrt{(b - a^\top x)^2 + 4\gamma\mu\|a\|^2}} a, \tag{16}$$

where $\mathbb{I}_n \in \mathbb{R}^{n \times n}$ denotes the identity matrix.

Proof. The expression for the proximity operator (13) directly follows from [34, Example 24.40], [34, Proposition 24.8 (v)] and [34, Corollary 24.15]. Taking the derivative of (13) with respect to x, μ and γ leads to (14)–(16). □

3.2. Hyperslab constraints

We now consider the following hyperslab set:

$$\mathcal{C} = \{x \in \mathbb{R}^n \mid b_\mathrm{m} \leq a^\top x \leq b_\mathrm{M}\}, \tag{17}$$

where $a \in \mathbb{R}^n \setminus \{0\}$, $b_\mathrm{m} \in \mathbb{R}$ and $b_\mathrm{M} \in \mathbb{R}$ with $b_\mathrm{m} < b_\mathrm{M}$.

Proposition 2 *Let $\gamma > 0$, $\mu > 0$, and $\mathcal{B}$ be the barrier function associated to (17), defined as*

$$(\forall u \in \mathbb{R}^n) \quad \mathcal{B}(u) = \begin{cases} -\ln(b_\mathrm{M} - a^\top u) - \ln(a^\top u - b_\mathrm{m}) & \text{if } b_\mathrm{m} < a^\top u < b_\mathrm{M}, \\ +\infty & \text{otherwise.} \end{cases} \tag{18}$$

Then, for every $x \in \mathbb{R}^n$, the proximity operator of $\gamma\mu\mathcal{B}$ at x is given by

$$\varphi(x, \mu, \gamma) = x + \frac{\kappa(x, \mu, \gamma) - a^\top x}{\|a\|^2} a, \tag{19}$$

where $\kappa(x, \mu, \gamma)$ is the unique solution in $]b_\mathrm{m}, b_\mathrm{M}[$, of the following cubic equation:

$$\begin{aligned} 0 = {} & z^3 - (b_\mathrm{m} + b_\mathrm{M} + a^\top x)z^2 + (b_\mathrm{m} b_\mathrm{M} + a^\top x(b_\mathrm{m} + b_\mathrm{M}) - 2\gamma\mu\|a\|^2)z \\ & - b_\mathrm{m} b_\mathrm{M} a^\top x + \gamma\mu(b_\mathrm{m} + b_\mathrm{M})\|a\|^2. \end{aligned} \tag{20}$$

In addition, the Jacobian matrix of φ with respect to x and the gradients of φ with respect to μ and γ are given by

$$J_{\varphi}^{(x)}(x,\mu,\gamma) = \mathbb{I}_n + \frac{1}{\|a\|^2}\left(\frac{(b_{\mathrm{M}}-\kappa(x,\mu,\gamma))(b_{\mathrm{m}}-\kappa(x,\mu,\gamma))}{\eta(x,\mu,\gamma)} - 1\right) aa^\top, \tag{21}$$

$$\nabla_{\varphi}^{(\mu)}(x,\mu,\gamma) = \frac{-\gamma(b_{\mathrm{m}}+b_{\mathrm{M}}-2\kappa(x,\mu,\gamma))}{\eta(x,\mu,\gamma)}a, \tag{22}$$

and

$$\nabla_{\varphi}^{(\gamma)}(x,\mu,\gamma) = \frac{-\mu(b_{\mathrm{m}}+b_{\mathrm{M}}-2\kappa(x,\mu,\gamma))}{\eta(x,\mu,\gamma)}a, \tag{23}$$

where

$$\begin{aligned}\eta(x,\mu,\gamma) = {} & (b_{\mathrm{M}}-\kappa(x,\mu,\gamma))(b_{\mathrm{m}}-\kappa(x,\mu,\gamma)) \\ & - (b_{\mathrm{m}}+b_{\mathrm{M}}-2\kappa(x,\mu,\gamma))(\kappa(x,\mu,\gamma)-a^\top x) - 2\gamma\mu\|a\|^2.\end{aligned} \tag{24}$$

Proof. Let $x \in \mathbb{R}^n$, $\gamma > 0$, and $\mu > 0$. The expression for the proximity operator (19) follows from [46, Example 4.15] and [34, Corollary 24.15]. Let F be defined as follows:

$$F(x,\mu,\gamma,z) = (b_{\mathrm{M}}-z)(b_{\mathrm{m}}-z)(z-a^\top x) + \gamma\mu(b_{\mathrm{M}}+b_{\mathrm{m}}-2z)\|a\|^2, \tag{25}$$

for $z \in \left]b_{\mathrm{m}}, b_{\mathrm{M}}\right[$. Expanding (25) gives the following:

$$\begin{aligned}F(x,\mu,\gamma,z) = {} & z^3 - (a^\top x + b_{\mathrm{m}} + b_{\mathrm{M}})z^2 + (b_{\mathrm{m}}b_{\mathrm{M}} + a^\top x(b_{\mathrm{m}}+b_{\mathrm{M}}) - 2\gamma\mu\|a\|^2)z \\ & - b_{\mathrm{m}}b_{\mathrm{M}}a^\top x + \gamma\mu(b_{\mathrm{m}}+b_{\mathrm{M}})\|a\|^2.\end{aligned} \tag{26}$$

Hence, by definition of $\kappa(x,\mu,\gamma)$, we have $F(x,\mu,\gamma,\kappa(x,\mu,\gamma)) = 0$. In addition, the derivative of F with respect to its last variable is equal to

$$\nabla F^{(z)}(x,\mu,\gamma,z) = (b_{\mathrm{M}}-z)(b_{\mathrm{m}}-z) - (b_{\mathrm{m}}+b_{\mathrm{M}}-2z)(z-a^\top x) - 2\gamma\mu\|a\|^2. \tag{27}$$

By construction, $(b_{\mathrm{M}}-\kappa(x,\mu,\gamma))(b_{\mathrm{m}}-\kappa(x,\mu,\gamma)) < 0$. Moreover, $-2\gamma\mu\|a\|^2 < 0$ and, since $F(x,\mu,\gamma,\kappa(x,\mu,\gamma)) = 0$, it follows that $(b_{\mathrm{m}}+b_{\mathrm{M}}-2\kappa(x,\mu,\gamma))$ and $\kappa(x,\mu,\gamma)-a^\top x$ share the same sign. Hence,

$$\eta(x,\mu,\gamma) = \nabla F^{(z)}(x,\mu,\gamma,\kappa(x,\mu,\gamma)) \neq 0. \tag{28}$$

From the implicit function theorem [47, Theorem 1B.1], we deduce that the gradient of κ with respect to x and the partial derivatives of κ with respect to μ and γ exist and are equal to

$$\nabla\kappa^{(x)}(x,\mu,\gamma) = \frac{(b_{\mathrm{M}}-\kappa(x,\mu,\gamma))(b_{\mathrm{m}}-\kappa(x,\mu,\gamma))}{\eta(x,\mu,\gamma)}a, \tag{29}$$

$$\nabla\kappa^{(\mu)}(x,\mu,\gamma) = \frac{-\gamma\|a\|^2(b_{\mathrm{m}}+b_{\mathrm{M}}-2\kappa(x,\mu,\gamma))}{\eta(x,\mu,\gamma)}, \tag{30}$$

and

$$\nabla\kappa^{(\gamma)}(x,\mu,\gamma) = \frac{-\mu\|a\|^2(b_{\mathrm{m}}+b_{\mathrm{M}}-2\kappa(x,\mu,\gamma))}{\eta(x,\mu,\gamma)}. \tag{31}$$

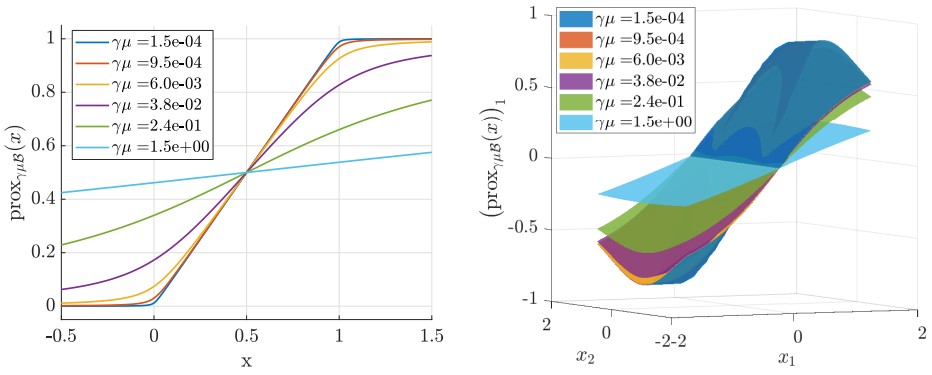

Figure 1. Proximity operator of the logarithmic barrier: $\text{prox}_{\gamma\mu\mathcal{B}}(x)$ for hyperslab constraint as in Section 3.2 with $b_{\text{m}} = 0$ and $b_{\text{M}} = 1$ (*left*), $\big(\text{prox}_{\gamma\mu\mathcal{B}}(x)\big)_1$ for a constraint on the ℓ_2-norm as in Section 3.3 with $\alpha = 0.7$ (*right*).

Differentiating (19) with respect to x, μ and γ and using (29)–(31) yields (21)–(23). □

Note that the three roots of (20) can easily be computed using the Cardano formula. The graph of the resulting proximity operator is plotted on Figure 1 (left) for $n = 1$, $a = 1$, $b_{\text{m}} = 0$, $b_{\text{M}} = 1$, and various values for $\gamma\mu$.

3.3. Bounded ℓ_2-norm

We now consider the case when the feasible set in (2) is an Euclidean ball

$$\mathcal{C} = \{x \in \mathbb{R}^n \mid \|x - c\|^2 \leq \alpha\}, \tag{32}$$

with $\alpha > 0$ and $c \in \mathbb{R}^n$.

Proposition 3 *Let $\gamma > 0$ and let $\mu > 0$. Let $\mathcal{B}$ be the barrier function associated to (32), defined as*

$$(\forall u \in \mathbb{R}^n) \quad \mathcal{B}(u) = \begin{cases} -\ln(\alpha - \|u - c\|^2) & \text{if } \|u - c\|^2 < \alpha, \\ +\infty & \text{otherwise.} \end{cases} \tag{33}$$

Then, for every $x \in \mathbb{R}^n$, the proximity operator of $\gamma\mu\mathcal{B}$ at x is given by

$$\varphi(x, \mu, \gamma) = c + \frac{\alpha - \kappa(x, \mu, \gamma)^2}{\alpha - \kappa(x, \mu, \gamma)^2 + 2\gamma\mu}(x - c), \tag{34}$$

where $\kappa(x, \mu, \gamma)$ is the unique solution in $[0, \sqrt{\alpha}[$ of the cubic equation:

$$0 = z^3 - \|x - c\|z^2 - (\alpha + 2\gamma\mu)z + \alpha\|x - c\|. \tag{35}$$

In addition, the Jacobian matrix of φ with respect to x and the gradients of φ with respect to μ and γ are given by

$$J_{\varphi}^{(x)}(x, \mu, \gamma) = \frac{\alpha - \|\varphi(x, \mu, \gamma) - c\|^2}{\alpha - \|\varphi(x, \mu, \gamma) - c\|^2 + 2\gamma\mu} M(x, \mu, \gamma), \tag{36}$$

$$\nabla_{\varphi}^{(\mu)}(x,\mu,\gamma) = \frac{-2\gamma}{\alpha - \|\varphi(x,\mu,\gamma) - c\|^2 + 2\gamma\mu} M(x,\mu,\gamma)(\varphi(x,\mu,\gamma) - c), \tag{37}$$

and

$$\nabla_{\varphi}^{(\gamma)}(x,\mu,\gamma) = \frac{-2\mu}{\alpha - \|\varphi(x,\mu,\gamma) - c\|^2 + 2\gamma\mu} M(x,\mu,\gamma)(\varphi(x,\mu,\gamma) - c), \tag{38}$$

where

$$M(x,\mu,\gamma) = \mathbb{I}_n - \frac{2(x - \varphi(x,\mu,\gamma))(\varphi(x,\mu,\gamma) - c)^\top}{\alpha - 3\|\varphi(x,\mu,\gamma) - c\|^2 + 2\gamma\mu + 2(\varphi(x,\mu,\gamma) - c)^\top (x - c)}. \tag{39}$$

Proof. Let $x \in \mathbb{R}^n$, $\gamma > 0$, $\mu > 0$. Let us first consider the case when $c = 0$. We denote with φ_0 the following proximity operator:

$$\varphi_0(x,\mu,\gamma) = \operatorname*{argmin}_{u \in \operatorname{int}\mathcal{C}} \frac{1}{2}\|x - u\|^2 - \gamma\mu \ln(\alpha - \|u\|^2). \tag{40}$$

Hence, $\|\varphi_0(x,\mu,\gamma)\|^2 < \alpha$ and $\varphi_0(x,\mu,\gamma)$ is a solution to the following equation:

$$0 = \varphi_0(x,\mu,\gamma) - x + \frac{2\gamma\mu}{\alpha - \|\varphi_0(x,\mu,\gamma)\|^2}\varphi_0(x,\mu,\gamma). \tag{41}$$

Since $\alpha - \|\varphi_0(x,\mu,\gamma)\|^2 + 2\gamma\mu > 0$, (41) becomes

$$\varphi_0(x,\mu,\gamma) = \frac{\alpha - \|\varphi_0(x,\mu,\gamma)\|^2}{\alpha - \|\varphi_0(x,\mu,\gamma)\|^2 + 2\gamma\mu} x. \tag{42}$$

By taking the norm in both sides of (42), we deduce that $\|\varphi_0(x,\mu,\gamma)\| = \kappa(x,\mu,\gamma)$ is a solution to the cubic equation (35). Since the proximity operator at a given x is uniquely defined, there exists only one real solution to (35) which belongs to $[0, \sqrt{\alpha}[$. Plugging the latter into (42) leads to (34). The analysis when $c \neq 0$ is deduced from the case $c = 0$ by using [34, Proposition 24.8 (v)]: the proximity operator of $\gamma\mu\mathcal{B}$ at x is given by

$$\varphi(x,\mu,\gamma) = c + \varphi_0(x - c,\mu,\gamma). \tag{43}$$

Let us study the derivatives of φ_0. For every $v \in \mathbb{R}^n$, let F be defined as

$$F(x,\mu,\gamma,v) = (\alpha - \|v\|^2)(v - x) + 2\gamma\mu v. \tag{44}$$

The Jacobian of F with respect to its last variable is equal to

$$J_F^{(v)}(x,\mu,\gamma,v) = (\alpha - \|v\|^2 + 2\gamma\mu)\mathbb{I}_n + 2(x - v)v^\top. \tag{45}$$

Since $\alpha - \|\varphi_0(x,\mu,\gamma)\|^2 > 0$, according to the Sherman–Morrison Lemma [48], $J_F^{(v)}(x,\mu,\gamma,\varphi_0(x,\mu,\gamma))$ is invertible if and only if

$$\alpha - \|\varphi_0(x,\mu,\gamma)\|^2 + 2\gamma\mu + 2\varphi_0(x,\mu,\gamma)^\top(x - \varphi_0(x,\mu,\gamma)) \neq 0. \tag{46}$$

Furthermore, it follows from (41) that

$$F(x,\mu,\gamma,\varphi_0(x,\mu,\gamma)) = 0. \tag{47}$$

Applying $\varphi_0(x,\mu,\gamma)^\top$ on (47) leads to $\varphi_0(x,\mu,\gamma)^\top(x-\varphi_0(x,\mu,\gamma)) \geq 0$. In addition, $\alpha - \|\varphi_0(x,\mu,\gamma)\|^2 + 2\gamma\mu > 0$. Hence, $J_F^{(v)}(x,\mu,\gamma,\varphi_0(x,\mu,\gamma))$ is invertible and its inverse is given by the Sherman–Morrison formula:

$$J_F^{(v)}(x,\mu,\gamma,\varphi_0(x,\mu,\gamma))^{-1} = \frac{1}{\alpha - \|\varphi_0(x,\mu,\gamma)\|^2 + 2\gamma\mu} \times \left[\mathbb{I}_n - \frac{2(x-\varphi_0(x,\mu,\gamma))\varphi_0(x,\mu,\gamma)^\top}{\alpha - 3\|\varphi_0(x,\mu,\gamma)\|^2 + 2\gamma\mu + 2\varphi_0(x,\mu,\gamma)^\top x}\right]. \tag{48}$$

From the implicit function theorem [47, Theorem 1B.1] we deduce that the Jacobian of φ_0 with respect to x and the gradients of φ_0 with respect to μ and γ exist and are equal to

$$J_{\varphi_0}^{(x)}(x,\mu,\gamma) = -J_F^{(v)}(x,\mu,\gamma,\varphi_0(x,\mu,\gamma))^{-1} J_F^{(x)}(x,\mu,\gamma,\varphi_0(x,\mu,\gamma)), \tag{49}$$

$$\nabla_{\varphi_0}^{(\mu)}(x,\mu,\gamma) = -J_F^{(v)}(x,\mu,\gamma,\varphi_0(x,\mu,\gamma))^{-1} \nabla_F^{(\mu)}(x,\mu,\gamma,\varphi_0(x,\mu,\gamma)), \tag{50}$$

and

$$\nabla_{\varphi_0}^{(\gamma)}(x,\mu,\gamma) = -J_F^{(v)}(x,\mu,\gamma,\varphi_0(x,\mu,\gamma))^{-1} \nabla_F^{(\gamma)}(x,\mu,\gamma,\varphi_0(x,\mu,\gamma)). \tag{51}$$

When $c \neq 0$, the derivatives of φ are deduced from those of φ_0 using (43):

$$J_{\varphi}^{(x)}(x,\mu,\gamma) = -J_F^{(v)}(x-c,\mu,\gamma,\varphi(x,\mu,\gamma)-c)^{-1} J_F^{(x)}(x-c,\mu,\gamma,\varphi(x,\mu,\gamma)-c), \tag{52}$$

$$\nabla_{\varphi}^{(\mu)}(x,\mu,\gamma) = -J_F^{(v)}(x-c,\mu,\gamma,\varphi(x,\mu,\gamma)-c)^{-1} \nabla_F^{(\mu)}(x-c,\mu,\gamma,\varphi(x,\mu,\gamma)-c), \tag{53}$$

and

$$\nabla_{\varphi}^{(\gamma)}(x,\mu,\gamma) = -J_F^{(v)}(x-c,\mu,\gamma,\varphi(x,\mu,\gamma)-c)^{-1} \nabla_F^{(\gamma)}(x-c,\mu,\gamma,\varphi(x,\mu,\gamma)-c), \tag{54}$$

which lead to (36)-(38). □

Similarly to the previous case, the three solutions to (35) can be obtained by using the Cardano formula. The form of the resulting proximity operator for $n = 2$ is plotted on Figure 1 (right) for $\alpha = 0.7$, $c = 0$, and several values of $\gamma\mu$ and x; for symmetry reasons, only the first component $\left(\text{prox}_{\gamma\mu\mathcal{B}}(x)\right)_1$ is represented.

As shown in this section, the proximity operator of the barrier is easily computatble and differentiable for several classic types of constraints. Next, we detail the proposed approach in Section 4.

4. iRestNet architecture

4.1. Overview

Our proposal is to adopt a supervised learning strategy in order to determine, from a training set of images, an optimal setting for the parameters of Algorithm 2, which should lead to an optimal image restoration quality. To this aim, Algorithm 2 is unfolded over K iterations and the regularization parameter λ is untied accross the

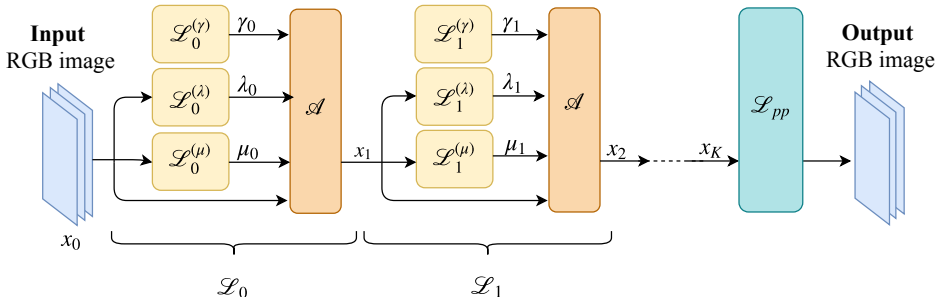

Figure 2. iRestNet global architecture.

network, so as to provide more flexibility to the approach [17]. The update rule at a given iteration $k \in \{0, \ldots, K-1\}$ reads

$$x_{k+1} = \mathcal{A}\left(x_k, \mu_k, \gamma_k, \lambda_k\right) \tag{55}$$

with

$$\mathcal{A}\left(x_k, \mu_k, \gamma_k, \lambda_k\right) = \operatorname{prox}_{\gamma_k \mu_k \mathcal{B}}\left(x_k - \gamma_k \nabla_1 h\left(x_k, y, \lambda_k\right)\right). \tag{56}$$

For every $k \in \{0, \ldots, K-1\}$, we build the k-th *layer* $\mathcal{L}_k$ as the association of three hidden structures, $\mathcal{L}_k^{(\mu)}$, $\mathcal{L}_k^{(\gamma)}$ and $\mathcal{L}_k^{(\lambda)}$, followed by the update $\mathcal{A}$. Structures $\mathcal{L}_k^{(\mu)}$, $\mathcal{L}_k^{(\gamma)}$, and $\mathcal{L}_k^{(\lambda)}$ aim at inferring the barrier parameter μ_k, the stepsize γ_k and the regularization weight λ_k, respectively. Since a finite number K of layers (i.e., updates) is used, the convergence of the resulting scheme is not an issue. Note that we also allow in our framework the use of a post–processing step after going through the K layers, that will be denoted as $\mathcal{L}_{\mathrm{pp}}$. The resulting architecture is depicted in Figure 2.

4.2. Hidden structures

Let us now provide more details about the hidden structures. For every $k \in \{0, \ldots, K-1\}$, the outputs $(\mu_k, \gamma_k, \lambda_k)$ of the structures $\mathcal{L}_k^{(\mu)}$, $\mathcal{L}_k^{(\gamma)}$, and $\mathcal{L}_k^{(\lambda)}$ must be positive. To enforce such constraint, we use the Softplus function [49], defined below, which can be viewed as a smooth approximation of the ReLU activation function:

$$(\forall z \in \mathbb{R}) \quad \operatorname{Softplus}(z) = \ln(1 + \exp(z)). \tag{57}$$

Unlike the ReLU, the gradient of Softplus is never stricly equal to zero, which, given our architecture, helps to propagate the gradient through the network. The stepsize is estimated as follows,

$$\gamma_k = \mathcal{L}_k^{(\gamma)} = \operatorname{Softplus}\left(a_k\right), \tag{58}$$

where a_k is a scalar parameter of the network learned during training. The barrier parameter is obtained using two convolutional and average pooling layers followed by a fully connected layer. The detailed architecture of $\mathcal{L}_k^{(\mu)}$ is depicted in Figure 3.
Traditional methods for estimating the regularization parameter generally depend on the signal-to-noise ratio and on the image statistics [50]. For most applications the noise level is unknown and can be estimated, for instance, by applying a median filter over the wavelet diagonal coefficients of the image [51]. Here, we propose to infer the regularization parameter λ_k from the image statistics only, the noise level being

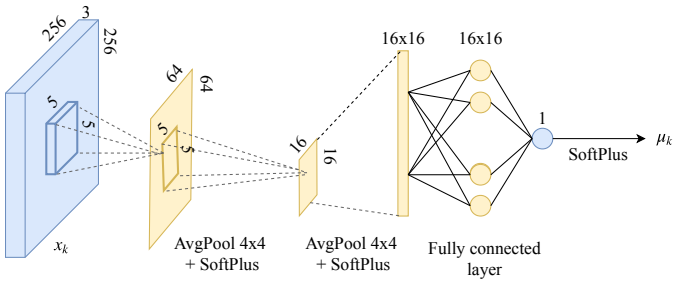

Figure 3. Architecture of $\mathcal{L}_k^{(\mu)}$.

accounted for in an implicit manner, by introducing a multiplicative factor for example. The advantage of this approach is to yield a network which can handle datasets for which the signal-to-noise ratio is unknown and can vary within a reasonable range. The expression of $\mathcal{L}_k^{(\lambda)}$ is then problem–dependent since it is built upon the regularization strategy. A specific example is given in Section 6 for the total variation regularization function.
Regarding the post-processing step $\mathcal{L}_{\text{pp}}$, its detailed architecture also depends on the task to be performed. An example is provided in Section 6 for the case of deblurring: the purpose of $\mathcal{L}_{\text{pp}}$ is then to remove remaining artifacts using convolutional layers, residual learning, batch normalization, and dilation.

4.3. Differential calculus

To train the neural network presented in Figure 2 using gradient descent, one needs to compute the gradient of x_K with respect to the different parameters of the network. The chain rule can be applied since most of the steps in the network correspond to operators having straightforward derivatives. However, particular care should be taken when differentiating $\mathcal{A}$. Since f and $\mathcal{R}$ are assumed to be twice differentiable, the only area of concern is related to $\text{prox}_{\gamma\mu\mathcal{B}}$. If $\text{prox}_{\gamma\mu\mathcal{B}}$ is simple enough, autodifferentiation can be used. Otherwise, as shown in Section 3, for common examples of barrier functions, the differential of this term is well-defined. The corresponding expressions for the derivatives are provided in Propositions 1–3.

5. Network stability

One critical issue concerning neural networks is to guarantee that their performance remain acceptable when the input is perturbed. For example, the authors of [15] show that the class prediction made by AlexNet can be arbitrarily changed by using small nonrandom perturbations on the test image. For some applications involving high risk and legal responsibility, for instance in medical image processing, the lack of theoretical guarantees is a significant curb on the utilization of deep learning approaches. A recent work [52] provides a theoretical framework which enables to evaluate the robustness of a network. In this section, we will focus on a subclass of problem (2) where both $f(\cdot, y)$ and $\mathcal{R}$ are quadratic functions while $\mathcal{C}$ is defined as in (3). After highlighting the similarities between the proposed architecture and generic feedforward networks in

that case, we will give explicit conditions under which the robustness of the proposed architecture is ensured.

5.1. Relation to generic deep neural networks

Although the proposed architecture may seem specific to Algorithm 2, it is actually very similar to generic feedforward neural networks. Classical feedforward (acyclic) architectures [53] can be expressed as $R_{K-1}\circ(W_{K-1}\cdot+b_{K-1})\circ\cdots\circ R_0\circ(W_0\cdot+b_0)$, where $(R_k)_{0\leq k\leq K-1}$ are nonlinear activation functions, $(W_k)_{0\leq k\leq K-1}$ are weight operators and $(b_k)_{0\leq k\leq K-1}$ are bias parameters. Let us show that iRestNet actually shares a similar structure. For the sake of simplicity, we will consider the variational problem,

$$\underset{x\in\mathcal{C}}{\text{minimize}}\ \frac{1}{2}\|Hx-y\|^2+\frac{\lambda}{2}\|Dx\|^2, \tag{59}$$

where $y\in\mathbb{R}^n$, $H\in\mathbb{R}^{n\times n}$, $D\in\mathbb{R}^{n\times n}$, and $\mathcal{C}$ is defined as in (3). Moreover, we assume that no post–processing layer $\mathcal{L}_{\rm pp}$ is used. Following the notation of Section 4, $(\forall k\in\{0,\ldots,K-1\})$ $(\mu_k,\gamma_k,\lambda_k)$ are given positive real numbers, K being the number of layers of the network. Then, for every $k\in\{0,\ldots,K-1\}$, layer $\mathcal{L}_k$ corresponds to the following update,

$$\begin{aligned} x_{k+1} &= \operatorname{prox}_{\gamma_k\mu_k\mathcal{B}}\left(x_k-\gamma_k\left(H^\top(Hx_k-y)+\lambda_k D^\top Dx_x\right)\right)\\ &= \operatorname{prox}_{\gamma_k\mu_k\mathcal{B}}\left(\left[\mathbb{I}_n-\gamma_k\left(H^\top H+\lambda_k D^\top D\right)\right]x_k+\gamma_k H^\top y\right), \end{aligned} \tag{60}$$

where $\mathcal{B}$ is defined as in (9). For every $k\in\{0,\ldots,K-1\}$, we set

$$W_k=\mathbb{I}_n-\gamma_k\left(H^\top H+\lambda_k D^\top D\right),\quad b_k=\gamma_k H^\top y,\quad\text{and}\quad R_k=\operatorname{prox}_{\gamma_k\mu_k\mathcal{B}}. \tag{61}$$

Then, the K-layer network $\mathcal{L}_{K-1}\circ\cdots\circ\mathcal{L}_0$ is equivalent to $R_{K-1}\circ(W_{K-1}\cdot+b_{K-1})\circ\cdots\circ R_0\circ(W_0\cdot+b_0)$, where $(W_k)_{0\leq k\leq K-1}$ and $(b_k)_{0\leq k\leq K-1}$ are interpreted as weight operators and bias parameters, respectively. It is worth noticing that the operators $(R_k)_{0\leq k\leq K-1}$ defined in (61) can be viewed as specific activation functions since, as shown in [52], every standard activation function can be derived from a proximity operator. In addition, using [34, Proposition 24.8(iii)], for every $k\in\{0,\ldots,K-1\}$, R_k can be re-written as

$$R_k=\operatorname{prox}_{\tilde{\mathcal{B}}_k}+\tilde{b}_k, \tag{62}$$

where $\tilde{b}_k=\operatorname{prox}_{\gamma_k\mu_k\mathcal{B}}(0)$ and $(\forall x\in\mathbb{R}^n)$ $\tilde{\mathcal{B}}_k(x)=\gamma_k\mu_k\mathcal{B}(x+\tilde{b}_k)+x^\top\tilde{b}_k$. The zero vector is therefore a fixed point of $\operatorname{prox}_{\tilde{\mathcal{B}}_k}$ with $\tilde{\mathcal{B}}_k\in\Gamma_0(\mathbb{R}^n)$. Hence, for every $k\in\{0,\ldots,K-1\}$, R_k is the sum of a *stable activation operator* [52, Definition 2.20] $\operatorname{prox}_{\tilde{\mathcal{B}}_k}$ and a bias $\tilde{b}_k$.

5.2. Preliminary results

Before stating our main stability theorem, let us first derive in this subsection some preliminary results, which will appear useful when addressing the robustness of the global network. In the following, $\mathcal{S}_n$ denotes the set of symmetric matrices in $\mathbb{R}^{n\times n}$ and, for every $W\in\mathcal{S}_n$, $\|W\|$ denotes its spectral norm.

Assumption 1 *Assume that $K\geq 1$ is an integer and that, for every $k\in\{0,\ldots,K-1\}$, $W_k\in\mathcal{S}_n$. In addition, there exists a common basis $\mathcal{P}$ such that, for every $k\in\{0,\ldots,K-1\}$, W_k is diagonalizable in $\mathcal{P}$.*

Proposition 4 *Let $K \geq 1$ be an integer and set $\theta_{-1} = 1$. Suppose that Assumption 1 holds. For every $k \in \{0, \dots, K-1\}$, let θ_k be defined by*

$$\begin{aligned}\theta_k =& \|W_k \circ \cdots \circ W_0\| \\ &+ \sum_{\ell=0}^{k-1} \sum_{0 \leq j_0 < \cdots < j_\ell \leq k-1} \|W_k \circ \cdots \circ W_{j_\ell+1}\| \|W_{j_\ell} \circ \cdots \circ W_{j_{\ell-1}+1}\| \cdots \|W_{j_0} \circ \cdots \circ W_0\|.\end{aligned} \tag{63}$$

Then, for every $k \in \{0, \dots, K-1\}$,

$$\begin{aligned}\theta_k =& \max_{1 \leq p \leq n} \left|\beta_k^{(p)} \cdots \beta_0^{(p)}\right| \\ &+ \sum_{\ell=0}^{k-1} \sum_{0 \leq j_0 < \cdots < j_\ell \leq k-1} \max_{1 \leq q_\ell \leq n} \left|\beta_k^{(q_\ell)} \cdots \beta_{j_\ell+1}^{(q_\ell)}\right| \max_{1 \leq q_{\ell-1} \leq n} \left|\beta_{j_\ell}^{(q_{\ell-1})} \cdots \beta_{j_{\ell-1}+1}^{(q_{\ell-1})}\right| \cdots \max_{1 \leq q_0 \leq n} \left|\beta_{j_0}^{(q_0)} \cdots \beta_0^{(q_0)}\right|,\end{aligned} \tag{64}$$

where for every ($k \in \{0, \dots, K-1\}$ and $p \in \{1, \dots, n\}$, $\beta_k^{(p)}$ is the p^{th} eigenvalue of W_k in $\mathcal{P}$. In addition,

$$(\forall k \in \{0, \dots, K-1\}) \quad \theta_k = \sum_{\ell=0}^{k} \theta_{\ell-1} \max_{1 \leq q_\ell \leq n} \left|\beta_k^{(q_\ell)} \cdots \beta_\ell^{(q_\ell)}\right|. \tag{65}$$

Proof. Assumption 1 directly yields (64). Equation (65) follows from [52, Lemma 3.3]. □

Proposition 5 *Let $K \geq 1$ be an integer and let $\alpha \in [1/2, 1]$. Suppose that Assumption 1 holds. Define $W = W_{K-1} \circ \cdots \circ W_0 \in \mathcal{S}_n$. Let β_- and β_+ denote the smallest and largest eigenvalues of W, respectively. Let $(\theta_k)_{0 \leq k \leq K-1}$ be defined as in Proposition 4. The condition*

$$\|W - 2^K(1-\alpha)\mathbb{I}_n\| - \|W\| + 2\theta_{K-1} \leq 2^K \alpha \tag{66}$$

is satisfied if and only if one of the following conditions holds:

(i) $\beta_+ + \beta_- \leq 0$ *and* $\theta_{K-1} \leq 2^{K-1}(2\alpha - 1)$*;*

(ii) $0 \leq \beta_+ + \beta_- \leq 2^{K+1}(1-\alpha)$ *and* $2\theta_{K-1} \leq \beta_+ + \beta_- + 2^K(2\alpha - 1)$*;*

(iii) $2^{K+1}(1-\alpha) \leq \beta_+ + \beta_-$ *and* $\theta_{K-1} \leq 2^{K-1}$.

Proof. Let $\alpha \in [1/2, 1]$. Since $W \in \mathcal{S}_n$, we have,

$$\|W\| = \max\{\beta_+, -\beta_-\}, \tag{67}$$

and

$$\|W - 2^K(1-\alpha)\mathbb{I}_n\| = \max\left\{\beta_+ - 2^K(1-\alpha), -\beta_- + 2^K(1-\alpha)\right\}. \tag{68}$$

Three different cases arise that we review below.

(i) If $\beta_+ + \beta_- \leq 0$ then $\|W\| = -\beta_-$ and

$$\beta_+ - 2^K(1-\alpha) \leq -\beta_- + 2^K(1-\alpha). \tag{69}$$

Hence, $\|W - 2^K(1-\alpha)\mathbb{I}_n\| = -\beta_- + 2^K(1-\alpha)$ and (66) is equivalent to

$$\begin{aligned} & -\beta_- + 2^K(1-\alpha) + \beta_- + 2\theta_{K-1} \leq 2^K\alpha \\ \Leftrightarrow \quad & \theta_{K-1} \leq 2^{K-1}(2\alpha - 1). \end{aligned} \tag{70}$$

(ii) If $0 \leq \beta_+ + \beta_- \leq 2^{K+1}(1-\alpha)$ then $\|W\| = \beta_+$ and (69) is satisfied. Hence, $\|W - 2^K(1-\alpha)\mathbb{I}_n\| = -\beta_- + 2^K(1-\alpha)$ and (66) is equivalent to

$$\begin{aligned} & -\beta_- + 2^K(1-\alpha) - \beta_+ + 2\theta_{K-1} \leq 2^K\alpha \\ \Leftrightarrow \quad & 2\theta_{K-1} \leq \beta_- + \beta_+ + 2^K(2\alpha - 1). \end{aligned} \tag{71}$$

(iii) If $2^{K+1}(1-\alpha) \leq \beta_+ + \beta_-$ then $\|W\| = \beta_+$ and

$$\beta_+ - 2^K(1-\alpha) \geq -\beta_- + 2^K(1-\alpha). \tag{72}$$

Hence, $\|W - 2^K(1-\alpha)\mathbb{I}_n\| = \beta_+ - 2^K(1-\alpha)$ and (66) is satisfied if and only if

$$\begin{aligned} & \beta_+ - 2^K(1-\alpha) - \beta_+ + 2\theta_{K-1} \leq 2^K\alpha \\ \Leftrightarrow \quad & \theta_{K-1} \leq 2^{K-1}, \end{aligned} \tag{73}$$

which completes the proof.

□

5.3. Averaged operator

The notion of nonexpansiveness, whose definition is recalled below, plays a central role in the analysis of the robustness of nonlinear operators. Indeed, it indicates that a perturbation on the output of a given operator is bounded by the amplitude of the input perturbation.

Definition 1 (Nonexpansiveness) *Let $T : \mathbb{R}^n \to \mathbb{R}^n$. Then, T is nonexpansive if it is Lipschitz continuous with constant* 1*, i.e.,*

$$(\forall x \in \mathbb{R}^n)(\forall y \in \mathbb{R}^n) \quad \|T(x) - T(y)\| \leq \|x - y\|. \tag{74}$$

In the present study we make use of the notion of averaged operator [34], which is stronger than nonexpansiveness.

Definition 2 (α-averaged operator) *Let $T : \mathbb{R}^n \to \mathbb{R}^n$ be nonexpansive, and let $\alpha \in [0, 1]$. Then T is averaged with constant α, or α–averaged, if there exists a nonexpansive operator $R : \mathbb{R}^n \to \mathbb{R}^n$ such that $T = (1-\alpha)I_n + \alpha R$, where I_n denotes the identity operator of $\mathbb{R}^n$.*

The following property provides an upper bound of the effect of an input pertubation, which depends on the constant of a given α–averaged operator.

Proposition 6 *[34, Remark 4.34, Proposition 4.35] Let $T : \mathbb{R}^n \to \mathbb{R}^n$.*

(i) If T is averaged, then it is nonexpansive.

(ii) Let $\alpha \in]0, 1]$. T is α–averaged if and only if for every $x \in \mathbb{R}^n$ and $y \in \mathbb{R}^n$,

$$\|T(x) - T(y)\|^2 \leq \|x - y\|^2 - \frac{1-\alpha}{\alpha}\|(I_n - T)(x) - (I_n - T)(y)\|^2. \tag{75}$$

One can see, in particular, that the smaller the averageness constant α is, the more stable the operator T is.

5.4. Robustness of iRestNet to an input pertubation

Let us consider problem (59), where we assume additionally that $H^\top H$ and $D^\top D$ are diagonalizable in a same basis denoted $\mathcal{P}$. The latter is satisfied for instance if H and D are the results of cyclic convolutive operators. For every $p \in \{1, \ldots, n\}$, let $\beta_H^{(p)}$ and $\beta_D^{(p)}$ denote the p^{th} eigenvalue of $H^\top H$ and $D^\top D$ in $\mathcal{P}$, respectively. Let β_+ and β_- be defined as follows,

$$\beta_+ = \max_{1 \leq p \leq n} \prod_{k=0}^{K-1} \left(1 - \gamma_k \left(\beta_H^{(p)} + \lambda_k \beta_D^{(p)}\right)\right) \tag{76}$$

and

$$\beta_- = \min_{1 \leq p \leq n} \prod_{k=0}^{K-1} \left(1 - \gamma_k \left(\beta_H^{(p)} + \lambda_k \beta_D^{(p)}\right)\right). \tag{77}$$

Theorem 1 below gives sufficient conditions under which the proposed network applied to problem (59) is an averaged operator.

Theorem 1 *Let $\alpha \in [1/2, 1]$, $(W_k, b_k, R_k)_{0 \leq k \leq K-1}$ be defined by (61), and θ_{K-1} be defined as in Proposition 4. Assume that $H^\top H$ and $D^\top D$ are diagonalizable in the same basis. Let β_+ and β_- be defined by (76) and (77), respectively. If one of the following conditions is satisfied*

(i) $\beta_+ + \beta_- \leq 0$ and $\theta_{K-1} \leq 2^{K-1}(2\alpha - 1)$;

(ii) $0 \leq \beta_+ + \beta_- \leq 2^{K+1}(1-\alpha)$ and $2\theta_{K-1} \leq \beta_+ + \beta_- + 2^K(2\alpha - 1)$;

(iii) $2^{K+1}(1-\alpha) \leq \beta_+ + \beta_-$ and $\theta_{K-1} \leq 2^{K-1}$,

then the operator $R_{K-1} \circ (W_{K-1} \cdot + b_{K-1}) \circ \cdots \circ R_0 \circ (W_0 \cdot + b_0)$ is α–averaged.

Proof. Since $H^\top H$ and $D^\top D$ are diagonalizable in the same basis, Assumption 1 holds and the set $\{W_k\}_{0 \leq k \leq K-1}$ satisfies the assumptions of Proposition 5. If one of the conditions (i)–(iii) is satisfied, then we deduce from Proposition 5 that the operator $W = W_{K-1} \circ \cdots \circ W_0$ satisfies [52, Proposition 3.6(iii)]. Therefore, W satisfies [52, Condition 3.1]. In addition, for every $k \in \{0, \ldots, K-1\}$, $R_k(\cdot + b_k)$ is firmly nonexpansive [34, Proposition 12.28]. Finally, [52, Theorem 3.8] completes the proof. □

The conditions provided by Theorem 1 can be easily checked: they only depend on the eigenvalues of $H^\top H$ and $D^\top D$ (i.e. the singular values of H and D), and on the parameters $(\gamma_k)_{0 \leq k \leq K-1}$ and $(\lambda_k)_{0 \leq k \leq K-1}$. Note that θ_{K-1} can be calculated by using Proposition 4. Theorem 1 provides a framework under which iRestNet is

robust to a perturbation of its input: the upper bound of the output perturbation is then controlled and can be derived from Proposition 6. The ability to control the robustness of the network appears as a very desirable property in many application fields, such as medical image processing.

6. Numerical experiments

In this section, we present numerical experiments on a set of problems of image restoration, demonstrating that in many cases the proposed approach yields a better reconstruction quality than standard variational and machine learning methods.

6.1. Problem formulation

We consider the non-blind color image deblurring problem, whose degradation model reads

$$y = H\overline{x} + \omega, \tag{78}$$

where n is the number of pixels, $y = (y^{(j)})_{1\leq j\leq 3} \in \mathbb{R}^{3n}$ is the blurred RGB image, $\overline{x} = (\overline{x}^{(j)})_{1\leq j\leq 3} \in \mathbb{R}^{3n}$ is the ground-truth, $H \in R^{3n\times 3n}$ is a linear operator that models the circular convolution of a known blur kernel with each channel of the color image, and $\omega \in \mathbb{R}^{3n}$ is a realization of an additive white Gaussian noise with standard deviation σ. An estimate of $\overline{x}$ can be derived from the following penalized formulation, which includes a smoothed total variation regularization,

$$\underset{x\in[0,1]^{3n}}{\text{minimize}} \ \frac{1}{2}\|Hx - y\|^2 + \sum_{j=1}^{3} \lambda^{(j)} \sum_{i=1}^{n} \sqrt{\frac{\left(D_v x^{(j)}\right)_i^2 + \left(D_h x^{(j)}\right)_i^2}{\delta^2} + 1}, \tag{79}$$

where $D_v \in \mathbb{R}^{n\times n}$ and $D_h \in \mathbb{R}^{n\times n}$ are the vertical and horizontal gradient operators, respectively, $\delta > 0$ is a smoothing parameter and $(\forall j \in \{1,2,3\})\ \lambda^{(j)} > 0$ is the regularization parameter for the j^{th} channel $x^{(j)}$. For simplicity, we take $\delta = 0.01$ in all experiments; note that the proposed architecture could easily be modified to include the inference of δ. The update $\mathcal{A}$, which is defined in (56), is derived from (79), and is unfolded over K iterations, as it is described in Section 4. The bound constraints in problem (79) fall under the framework studied in Section 3.2, which provides us with the expression for the proximity operator of the barrier and its gradient.

6.2. Network characteristics

The depth of iRestNet is fixed at $K = 50$. Regarding the hidden structures $(\mathcal{L}_k^{(\lambda)})_{0\leq k\leq K-1}$, which are used to predict the regularization parameter, they are chosen with regards to the regularization term in problem (79). For every $j \in \{1,2,3\}$, the penalization weight is taken as a function of the standard deviation of the image vertical and horizontal gradients, $\text{std}(D_v x_k^{(j)})$ and $\text{std}(D_h x_k^{(j)})$, respectively. This leads to the following expression,

$$(\forall k \in \{0,\dots,K-1\})\ \lambda_k^{(j)} = \mathcal{L}_k^{(\lambda)}\left(x_k^{(j)}\right) = \frac{\text{Softplus}\left(b_k\right)\sigma_{\text{app}}(x_k)}{\sqrt{\text{std}\left(D_v x_k^{(j)}\right)^2 + \text{std}\left(D_h x_k^{(j)}\right)^2 + \text{Softplus}\left(c_k\right)}}, \tag{80}$$

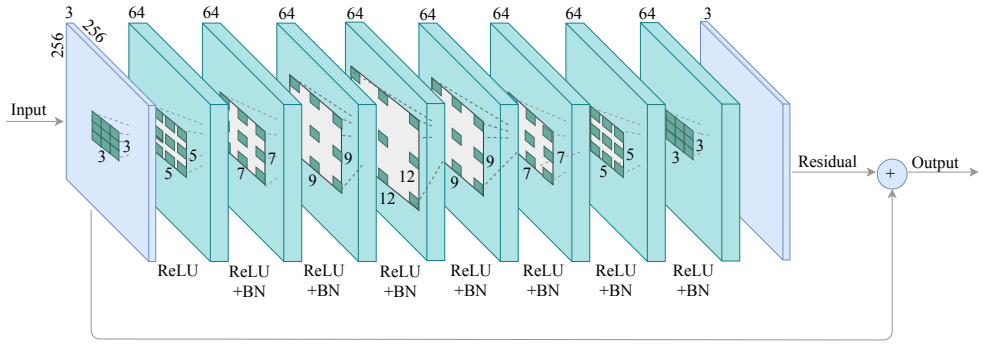

Figure 4. Architecture of $\mathcal{L}_{\text{pp}}$. BN: batch normalization.

where (b_k, c_k) is a pair of scalars learned by the network and $\sigma_{\text{app}}(x_k)$ is an approximation of the noise level in the input image. The noise level is estimated as in [51], where the median is replaced by the average, leading to the following expression for σ_{app},

$$(\forall k \in \{0, \dots, K-1\}) \quad \sigma_{\text{app}}(x_k) = \frac{4}{3n \times 0.6745} \sum_{j=1}^{3} \left\| W_{\text{H}} x_k^{(j)} \right\|_1, \tag{81}$$

where $W_{\text{H}} x_k^{(j)}$ is the vector gathering the diagonal coefficients of the first level Haar wavelet decomposition of $x_k^{(j)}$. It is worth noticing that the proposed architecture does not require any prior knowledge about the noise level, in particular it does not have to be the same for all input images.

The architecture of the post-processing layer $\mathcal{L}_{\text{pp}}$ is inspired from [54]: it is made of 9 convolutional layers with filters of size 3×3. The dilation factor changes from one layer to another, so as to widen the window without creating memory issues. The artifacts that remain in the image after going through the 50 blocks of iRestNet map a small space, which is well captured by residual learning. Hence, we add a skip connection between the input of $\mathcal{L}_{\text{pp}}$ and its output. Finally, a ReLU activation function is used after each convolution, and residual learning is combined with batch normalization, a technique which is widely used in deep learning to fasten and stabilize the training process [54]. The final architecture of $\mathcal{L}_{\text{pp}}$ can be found in Figure 4.

6.3. Dataset and experimental settings

The training set is made of 1200 RGB images: 200 images stem from the Berkeley segmentation (BSD500) training set, while the remaining 1000 images are taken from the COCO training set. We use the BSD500 validation set, which is made of 100 images, to monitor the training and check if there is overfitting. The performance of the proposed method is evaluated on two different test sets: the BSD500 test set, which is made of 200 RGB images, and the Flickr30 test set used in [9], which is made of 30 RGB images. The test images have been center-cropped using a window of size 256×256. Blurry images are produced using the following 25×25 blur kernels and noise levels:

- A Gaussian kernel, which models atmospheric turbulence, with a standard

deviation of 1.6, and a Gaussian noise standard deviation of $\sigma = 0.008$. This configuration is denoted as GaussianA. To evaluate the robustness of the proposed method with respect to the noise level, the same kernel is used with a Gaussian noise whose standard deviation is uniformly distributed between 0.01 and 0.05. The latter is denoted as GaussianB.

- The Gaussian kernel with a standard deviation of 3, and a Gaussian noise standard deviation of $\sigma = 0.04$, denoted as GaussianC.
- The eighth and third motion test kernels from [55], which are a real-world camera shake kernels, with a Gaussian noise standard deviation of $\sigma = 0.01$. These settings are denoted as MotionA and MotionB, respectively.
- The square uniform kernel of size 7×7, with a Gaussian noise standard deviation of $\sigma = 0.01$. This configuration is referred to as Square.

6.4. Training

For each degradation model, one iRestNet network is trained. We use a greedy approach for training the first 40 layers. For $\mathcal{L}_0$, a minibatch of 10 images is selected at every iteration, randomly cropped using a window of size 256×256, blurred with the given kernel, and degraded with Gaussian noise; the training of $\mathcal{L}_0$ stops after a fixed number of epochs: 50 for Square and 40 for the other configurations. Then, for each image of the training set, a random crop of size 256×256 is selected, blurred, corrupted with noise and passed through $\mathcal{L}_0$, the output is saved and used as an input to train $\mathcal{L}_1$. When the training of $\mathcal{L}_1$ is complete, its output is used to train the next layer, etc... For every block, the learning rate is initially set at 10^{-2}, and multiplied by 0.9 every 10 epochs. The rest of the network, $\mathcal{L}_{\text{pp}} \circ \mathcal{L}_{49} \cdots \circ \mathcal{L}_{40}$, is trained as one block during 300-1200 epochs, depending on the blur kernel and noise level. The validation set is used to monitor this last step of the training. In particular, the parameter configuration that gives the best performance on the validation set during the training is the one saved and used for the tests.
To accelerate the training, for every $k \in \{1, \ldots, K-1\}$, the weights of $\mathcal{L}_k$ are initialized with those of $\mathcal{L}_{k-1}$. This training strategy is chosen with regards to its low memory requirement: the number of layers is not limited by the hardware. Note that for the first 40 layers, after each layer the quality of the restored training images should improve. This property comes from the training strategy, it is not encoded in the network: if memory was not an issue, then iRestNet could be trained in an end-to-end fashion.
We use the ADAM optimizer to minimize the training loss, which is taken as the opposite of the structural similarity measure (SSIM) [56] defined below

$$\text{SSIM}(x, \overline{x}) = \frac{(2\mu_x\mu_{\overline{x}} + c_1)(2\sigma_x\sigma_{\overline{x}} + c_2)(2\text{cov}_{x\overline{x}} + c_3)}{(\mu_x^2 + \mu_{\overline{x}}^2 + c_1)(\sigma_x^2 + \sigma_{\overline{x}}^2 + c_2)(\sigma_x\sigma_{\overline{x}} + c_3)}, \tag{82}$$

where $\overline{x}$ is the ground truth, x is the restored image, (μ_x, σ_x) and $(\mu_{\overline{x}}, \sigma_{\overline{x}})$ are mean and standard deviation of x and $\overline{x}$, respectively, $\text{cov}_{x\overline{x}}$ is the cross–covariance of x and $\overline{x}$, and c_1, c_2 and c_3 are constants. As the SSIM captures features that are related to the human eye perception, it is more discriminative with regards to artifacts than the mean square error for instance. The gradient of the SSIM loss with respect to the trainable parameters of the network is computed using the code provided by the authors of [56], the chainrule, autodifferentiation, and the expression given in

Section 3.2 for the derivatives of the barrier proximity operator.
Codes are implemented in Pytorch. Some hidden layers make use of functions that are not differentiable everywhere, like ReLU or the absolute value for instance. Since this nondifferentiability happens only at specific points for which the left and right derivatives are well–defined, Pytorch can handle it as explained in [57]. All trainings are conducted using a GeForce GTX 1080 or 1070 GPU, or a Tesla V100 GPU. The training takes approximately 3 to 4 days for each kernel.

6.5. Evaluation metrics and competitors

The restoration is evaluated in terms of the SSIM metric. The reconstruction given by the proposed approach is compared with a solution to problem (79) obtained using the projected gradient algorithm [35]. For every blurred image, the same regularization parameter is taken for all channels, $\lambda^{(1)} = \lambda^{(2)} = \lambda^{(3)} = \lambda$, and the pair (λ, δ) which leads to the best SSIM is selected using the simplex method. The solution given by this variational approach is referred to as VAR. The latter is an unrealistic scenario since it assumes that there is a perfect estimator of the error, but it gives an upperbound on the image quality that one can expect by solving (79). We also use the following deep learning image restoration methods for comparison: EPLL [58], MLP [10], and IRCNN [54]. In order to provide a fair comparison, these methods are tested under the same conditions as they were trained for, and, when the setting is not relevant, no score is provided. Since MLP, EPLL and IRCNN require the knowledge of the noise level, for the GaussianB degradation model, we make use of the estimation of the noise standard deviation given by the method in [51]. In addition, since some comparison methods, like EPLL for instance, do not estimate well the borders of the images, the SSIM index is computed excluding a 6-pixel-wide frame for all images and all tested methods.

6.6. Results and discussion

The average SSIM obtained with the different methods for the various blur kernels and noise levels on the BSD500 test set can be found in Table 1. The mean SSIM achieved with iRestNet on this test set is greater than those obtained with the other methods for all degradation models except MotionA. For this kernel, the average SSIM achieved with iRestNet is higher than the results of VAR, EPLL and MLP, and it is close to, but lower than the one obtained with IRCNN, which appears as the most competitive method. IRCNN involves two steps: first, a Wiener filter is applied to the blurred image, then, a neural network is used to predict the residual and denoise the image. These two steps are repeated 30 times, for 30 different manually tuned regularization parameters. In contrast, iRestNet does not require any tuning from the user regarding the regularization parameters during training.
For completeness, the SSIM of all images of the BSD500 test set are plotted in Figure 5 for the 6 different degradation models. As one can see, iRestNet performs well in terms of SSIM on almost all images: except for MotionA, the percentage of images on which the proposed approach achieves a better SSIM than the comparison methods lies between 76% (Square) and 96% (GaussianA).
An example of the visual results obtained with the different methods can be found on Figure 6 for one image from the BSD500 test set, on which GaussianC has been applied. One can see from inspecting Figure 6 that the contrast and the details are

	GaussianA	GaussianB	GaussianC	MotionA	MotionB	Square
Blurred	0.678	0.523	0.327	0.385	0.552	0.547
VAR	0.805	0.726	0.589	0.819	0.830	0.758
EPLL	0.786	0.701	0.564	0.803	0.822	0.744
MLP	0.822	0.735	0.611	0.855	-	-
IRCNN	0.842	0.770	0.622	**0.902**	0.908	0.834
iRestNet	**0.853**	**0.788**	**0.635**	0.900	**0.912**	**0.839**

Table 1. SSIM results on the BSD500 test set.

	GaussianA	GaussianB	GaussianC	MotionA	MotionB	Square
Blurred	0.725	0.547	0.356	0.377	0.593	0.581
VAR	0.860	0.778	0.641	0.856	0.869	0.819
EPLL	0.846	0.760	0.613	0.843	0.870	0.815
MLP	0.874	0.798	0.669	0.891	-	-
IRCNN	0.886	0.819	0.678	**0.927**	0.930	**0.887**
iRestNet	**0.893**	**0.833**	**0.687**	0.922	**0.933**	0.883

Table 2. SSIM results on the Flickr30 test set.

better retrieved with iRestNet than with the competitors on this image. Figures 7 and 8 show, respectively, the barrier parameter, and the stepsize and regularization parameters, obtained by passing the image from Figure 6 through the 50 layers of iRestNet. As one can expect, the barrier parameter decreases and rapidly reaches a small value, while the stepsize and regularization parameters seem to behave in opposite ways. There is almost no blue in the image, which could explain why the regularization parameter for the blue channel is higher than for the red and green ones.

Since no image was taken from Flickr for training iRestNet, the results on the Flickr30 test set show how well the performance of the trained networks are transferable on test sets with statistics that are different from those of the training set. Table 2 contains the average SSIM obtained with the different methods on the Flickr30 test set. Similarly to the BSD500 test set, iRestNet compares favorably with the other approaches on the Flickr30 test set. This is confirmed by the inspection of Figure 9, which shows the visual results for one image from Flickr30 and GaussianA settings.

7. Conclusion

From a variational formulation of an inverse problem, we have derived in this paper a novel neural network architecture by unfolding a proximal interior point algorithm. It can be noted that the proposed approach can be extended to a set of regularization functions, or to penalizations which are parametrized by several variables. Useful constraints on the sought solution can be enforced thanks to a logarithmic barrier, so providing more control over the output of the network. We have shown for three standard types of constraints that the involved proximity operator can easily be computed, and that its derivatives are well-defined and computable. In the case of a quadratic case cost function, the theoretical result of Section 5 regarding

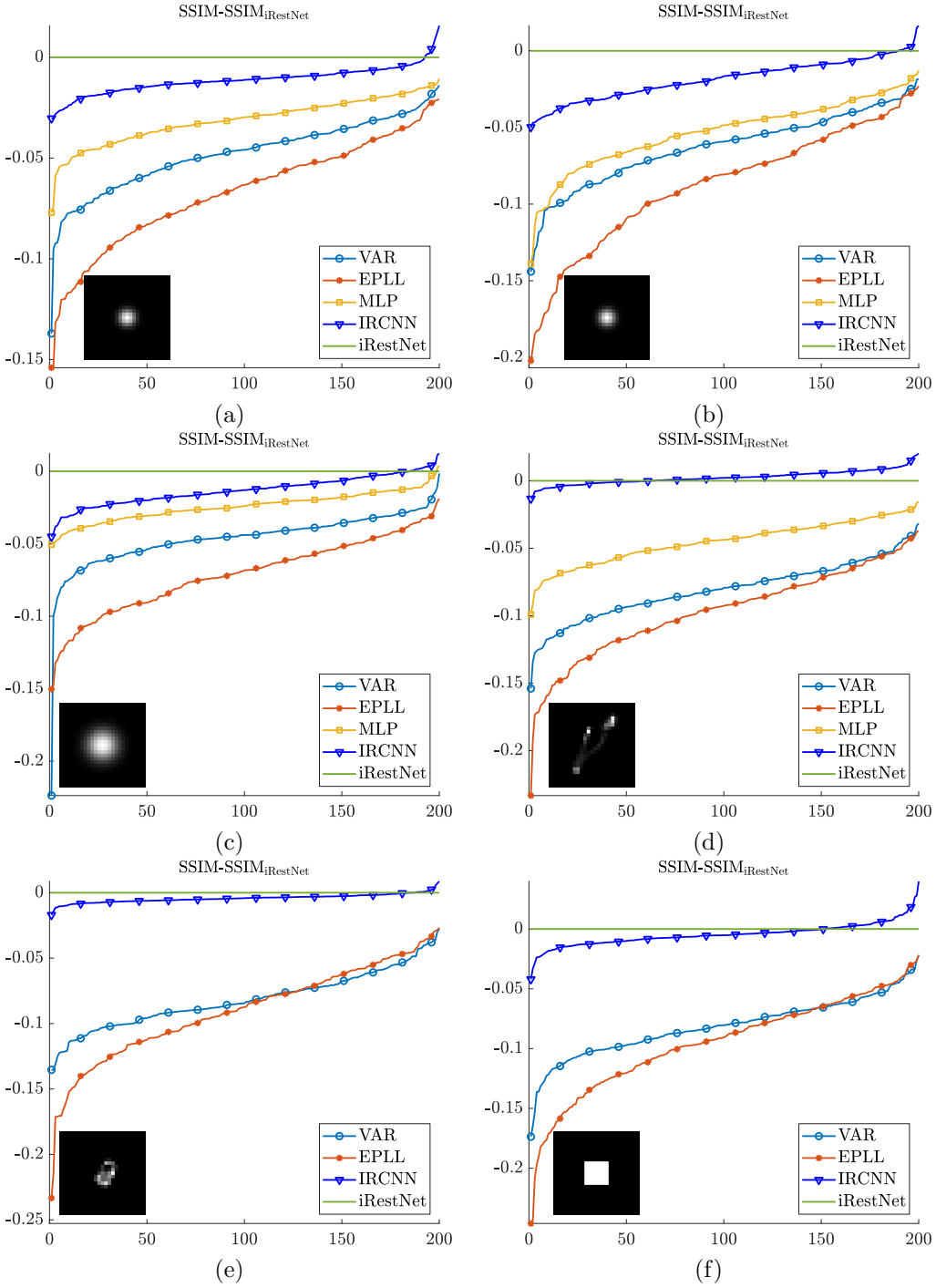

Figure 5. Sorted improvement of iRestNet with regards to other methods on the BSD500 test set using the SSIM metric: a negative value indicates a better performance of iRestNet. (a): GaussianA, (b): GaussianB, (c): GaussianC, (d): MotionA, (e): MotionB, (f): Square.

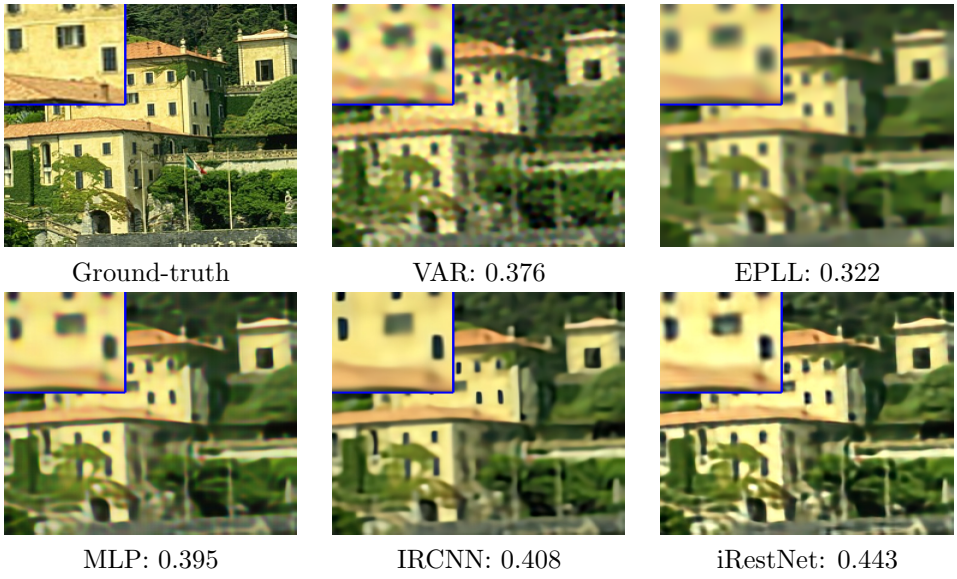

Figure 6. Visual results and SSIM obtained with the different methods on one image from the BSD500 test set degraded with GaussianC.

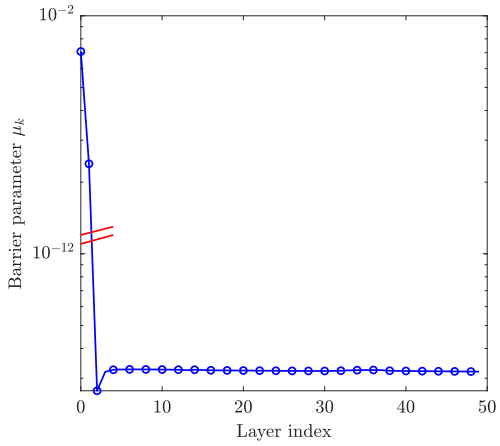

Figure 7. Image from Figure 6 with GaussianC: barrier parameter $(\mu_k)_{0\leq k\leq K-1}$. For clarity, there is a break on the y-axis from 10^{-3} to 10^{-12}, which is indicated by two red lines.

the robustness of the network with respect to an input perturbation, ensures the reliability of the proposed method, which is crucial for many applications. It would be interesting to extend the scope of this study to a wider class of problems, and to illustrate this stability result by numerical experiments on different applications like classification. As demonstrated by our experiments in image restoration, iRestNet performs favorably compared to state-of-the-art variational and machine learning methods. An advantage of the proposed approach is that, in contrast with its evaluated competitors, it does not require any knowledge about the noise level and it does

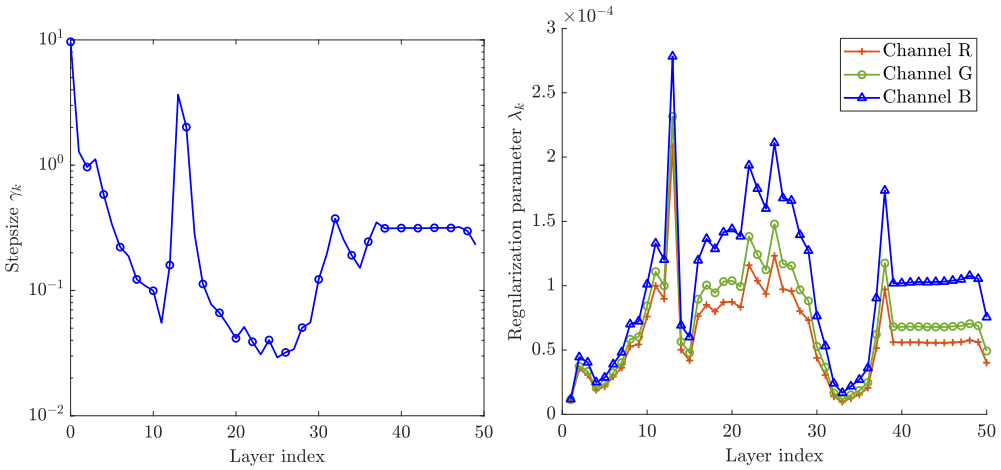

Figure 8. Image from Figure 6 with GaussianC: stepsize $(\gamma_k)_{0\leq k\leq K-1}$ (left) and regularization parameter for all 3 channels for every layer $(\mathcal{L}_k)_{0\leq k\leq K-1}$ (right).

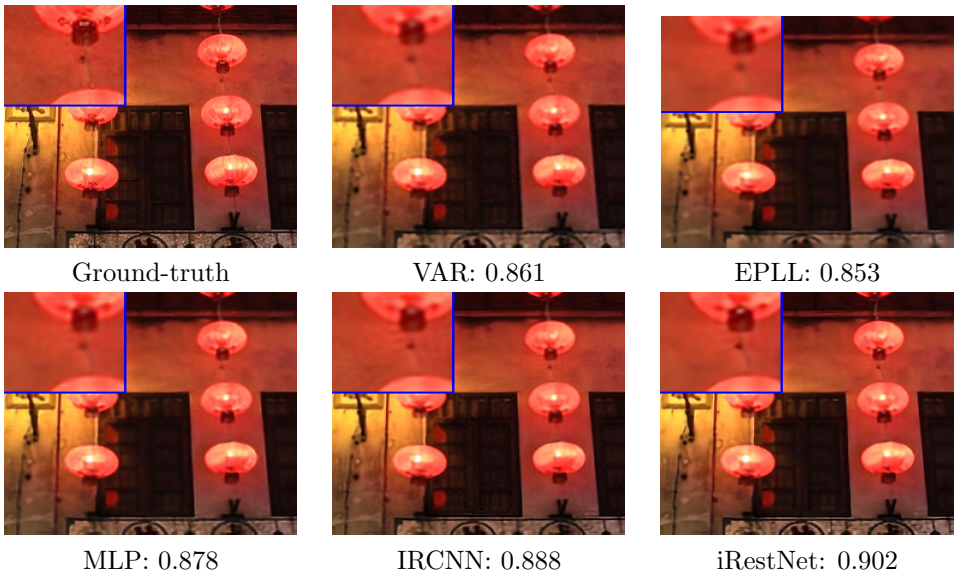

Figure 9. Visual results and SSIM obtained with the different methods on one image from the Flickr30 test set degraded with GaussianA.

not involve any hand-selection of the regularization parameters. One limitation of iRestNet is that the network needs to be trained for a given blur kernel. A direction for future works is to extend the method to situations in which the observation model is not fully known, so as to address blind or semi-blind deconvolution problems.

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