Super-resolution vascular ultrasound through deep unfolded convolutional ISTA

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Background, Motivation and Objective

Ultrasound localization microscopy (ULM) enables super-resolved vascular imaging by pinpointing microbubbles (MBs) that are well-isolated in diffraction-limited ultrasound scans. This separability condition dictates the use of relatively low MB concentrations, and hence long acquisition times (minutes) are required to achieve sufficient vascular coverage. To relax these constraints, sparse-coding methods that exploit the sparsity of the underlying distribution can be used. Unfortunately, the corresponding proximal gradient schemes require numerous iterations to converge, making it impractical for real-time imaging.

In pursuit of a method for fast sparse signal recovery, we recently proposed to employ deep neural networks that are trained with simulations of the forward problem (deep-ULM). In this work, we expand upon this by explicitly embedding a strong signal prior in the network architecture, yielding an improved and more efficient deep learning solution for ULM.

Statement of Contribution/Methods

Inspired by the ISTA (Iterative Shrinkage-Thresholding Algorithm) proximal gradient method for sparse coding, we design a deep network architecture that explicitly leverages knowledge of the underlying signal structure (i.e. MB sparsity). To do so, we unfold the recurrent ISTA iterations as a deep feedforward neural network, with each layer comprising independent trainable convolutions and shrinkage parameters. The network naturally inherits a per-layer nonlinear activation directly from the proximal operator of the sparsity promoting ℓ_1 norm in ISTA (soft-thresholding). The resulting method, which we term *deep unfolded ULM*, is fast, robust, compact (only ~500 parameters, vs ~700.000 in deep-ULM) and interpretable. We assess its performance on ultrafast (400 Hz) contrast-enhanced ultrasound acquisitions of rat spinal cords after injury.

Results/Discussion

Figure 1 shows *deep unfolded ULM* on a high-concentration short ~5-second scan of an injured rat spinal cord, achieving a 5-fold resolution gain (full-width-half-maxima of 20 µm vs 101µm) with respect to the mean-intensity images. Compared to a general convolutional network, the proposed method exhibits improved fidelity, clearly visualizing the tortuous and irregular vascular architecture.

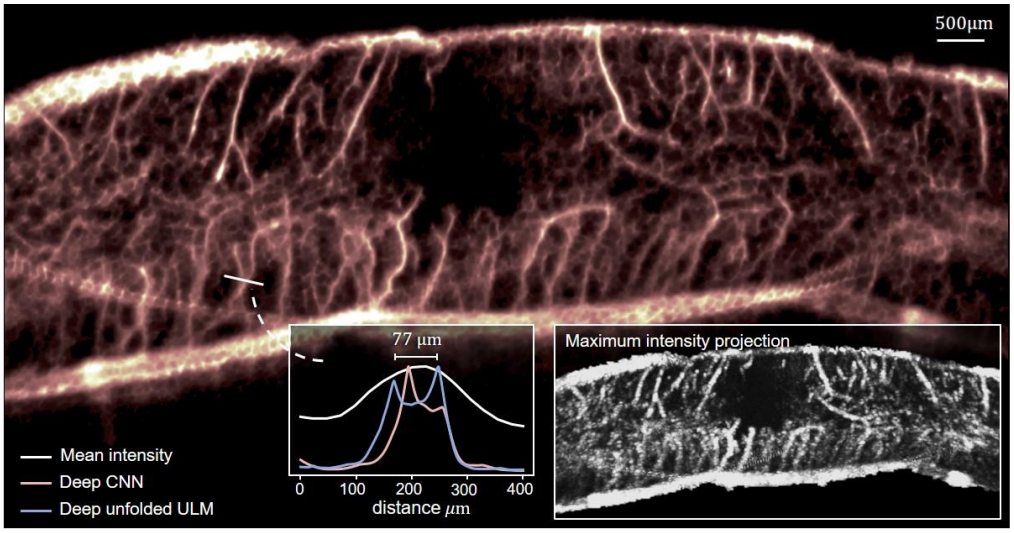

Figure 1. *In-vivo* deep unfolded ULM of an injured rat spinal cord, revealing the tortuosity and irregular architecture of the vascular network that is not appreciable in the diffraction-limited maximum and mean intensity projection images. Deep unfolded ULM significantly outperforms regular convolutional neural network (CNN) designs that do not explicitly leverage signal structure (i.e. sparsity) as a prior, exhibiting improved robustness when applied *in-vivo*.