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High Resolution Spectrally-Programmable Imaging

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Abstract:

Spectrum play a very important role in our understanding of how light interacts with objects, especially when we seek to study the material composition of a scene. Measuring a spectral profile at all spatial points in a scene requires a hyperspectral camera. Despite its wide applicability, measuring a high resolution hyperspectral image is inherently a hard task due to millions of spatial pixels over hundreds of spectral bands, leading to low signal to noise ratio and requirements of complex hardware.

The work in this thesis seeks to simplify the process of capturing spectral information of a scene with design of novel imaging systems. A key observation is that the number of distinct materials in any given scene is very small; which leads to a concise low-dimensional representation of the hyperspectral image. Owing to this low diversity, capturing a small set of spectrally-filtered images of the scene suffices for most sensing and inference tasks.

Central to the contributions of this thesis is an optical system that can provide programmable spectral filtering. The first contribution of this thesis shows that capturing sharp images with arbitrarily high resolution spectral filtering is not possible. This fundamental limit is provided in the form of the space-spectrum uncertainty principle, which sets a lower bound on product of spectral and spatial spreads. We then show that the resolutions can be enhanced computationally, if the pupil function is carefully engineered to introduce invertible spatial and spectral blurs.

We show that such programmable cameras can be used to optically sense a low rank approximation of hyperspectral images using an adaptive sensing strategy. We note that the dominant spatial and spectral singular vectors can be sensed by building two optical operators, namely a spatially-coded spectrometer, and a spectrally-programmable camera. By alternating between the two operators and using output of one operator as input to the second, we can directly measure a low-rank approximation. Finally, we show that spectral programmability can be used to enable per-pixel material classification. This is achieved by capturing images of the scene with learned, discriminative spectral filters and then using the images to classify materials. At its culmination, this thesis lays groundwork for making hyperspectral cameras more practical by introducing computing into the sensing pipeline and moving most of computational burden into the optical domain.