Compact Single-Shot Hyperspectral Imaging using a Prism

Seung-Hwan Baek† Incheol Kim† Diego Gutierrez* Min H. Kim†

†KAIST * Universidad de Zaragoza, I3A
Spectrum

$L(\lambda)$: Spectrum

Wavelength [nm]

400 500 600 700
RGB Imaging
Hyperspectral Imaging

Hyperspectral camera

Wavelength [nm]
400 500 600 700

Sunlight spectrum
Hyperspectral Imaging

Geology [1]  

Cosmetics [2]  

Biology [3]

[1] NASA  
[3] rshephorse, Flickr  
Previous Systems

Spectral scanning
- [Mansouri et al. 2007], [Gat 2000], [Brusco et al., 2006]

- Static scene only
- Low spectral resolution

Computed Tomography Imaging Spectroscopy (CTIS)
- [Habel et al. 2012], [Johnson et al. 2007], [Okamoto et al. 1993]

- Large system
- Low spatial resolution

Compressible Coded Aperture Spectral Imaging (CASSI)
- [Kim et al. 2012], [Wagadarikar et al. 2008], [Gehm et al., 2007]

- Large system
- Low spatial resolution

Prism-Mask Multispectral Video Imaging System (PMVIS)
- [Cao et al. 2011]

- Low spatial resolution
Compact Hyperspectral Camera

- Compact
- Single-shot
- High spatial/spectral resolution
Input & Output

Input

Output

# of channels: 3

Computational method

# of channels: 23
Challenges

1. How to model the dispersion accurately?
   ➔ Spatially-varying dispersion model

2. How to reconstruct hyperspectral images?
   ➔ Gradient-based reconstruction
DISPERSION MODEL
Without a Prism
With a Prism
With a Prism
With a Prism
With a Prism

$q$

$\lambda = 650\text{nm}$

$\lambda = 550\text{nm}$

$\lambda = 450\text{nm}$
Dispersion Model

\[
\mathbf{p}_\lambda = \Phi_\lambda \left( \mathbf{p}_{\lambda \text{ref}}, z \right)
\]

- \( \mathbf{p}_{\lambda \text{ref}} \): pixel of the reference wavelength \( \lambda_{\text{ref}} \)
- \( z \): scene depth
- \( \mathbf{p}_\lambda \): pixel location of a wavelength \( \lambda \)
Refraction Model

\[ p_d = \Psi_\lambda(p_\lambda, z) \]

- \( p_\lambda \): pixel location of a wavelength \( \lambda \)
- \( z \): scene depth
- \( p_d \): pixel location without the prism
Dispersion Model from Refraction Models

Refraction model

\[ p_d = \Psi_\lambda(p_\lambda, z) \]

Dispersion model

\[ p_\lambda = \Phi_\lambda(p_{\lambda_{ref}}, z) \]
Dispersion Model from Refraction Models

Refraction model

\[ p_d = \Psi_\lambda(p_\lambda, z) \]

Dispersion model

\[ p_\lambda = \Phi_\lambda(p_{\lambda_{ref}}, z) \]
Dispersion Model from Refraction Models

Refraction model: \( p_d = \Psi_\lambda(p_\lambda, z) \)

Dispersion model: \( p_\lambda = \Phi_\lambda(p_{\lambda \text{ref}}, z) \)
Camera geometric and radiometric calibrations are performed first without the prism
Prism Pose Calibration

- Find the pose of the prism which explains the observed dispersion best
- Estimated pose of the prism $\Rightarrow$ refraction model $\Psi$ $\Rightarrow$ dispersion model $\Phi$
Spatial Dependency

- Dispersion direction is nearly invariant to the spatial position
- Dispersion magnitude has large dependency on the spatial position

\[ p_\lambda = \Phi_\lambda (p_{\lambda_{\text{ref}}}, z) \]
Depth Dependency

- For depth over ~700mm, dispersion profile becomes nearly constant.

⇒ Depth-invariant dispersion

\[ p_\lambda = \Phi_\lambda (p_{\lambda \, \text{ref}}), \text{ for } z > 700\text{mm} \]
HYPERSPECTRAL IMAGE RECONSTRUCTION
Image Formation

\[ j = \Omega \Phi i \]

**Dispersed RGB image**  \=  **Camera response function**  \( \times \)  **Dispersion matrix**  \( \times \)  **Hyperspectral image**

**Known**  \=  **Known**  \( \times \)  **Known**  \( \times \)  **Unknown**
Sparse Spectral Cues

- Spectral cues only exist around edges
- Direct reconstruction is severely ill-posed
Spectral Cues around the Edge Region

\[ I(\lambda_i) \]

Without dispersion

\[ \sum I(\lambda_i) \approx \]

Position

Intensity

\[ \lambda_1 \lambda_2 \lambda_3 \]

Red

[400 500 600 700 [nm]]
Spectral Cues on the Edge Region

\[ I(\lambda) \approx \sum I(\lambda_i) \]

With dispersion

Position

Intensity

Red

[400, 500, 600, 700] [nm]
Spectral Cues on the Edge Region

With dispersion

\[ I(\lambda) < I(\lambda) \approx \sum I(\lambda_i) \]

• For edge regions, there could be many solutions which give the same observation
For edge regions, we can mitigate ill-posedness in the gradient domain.
Edges and Gradient Domain

1. Reduce the region of interests on the pixels around edges
2. Solve the problem in the gradient domain
**Workflow**

1. **Input**
2. **Edge restoration**
3. **Spectrum in the gradient domain**
4. **Spectrum estimation in the intensity domain**

- Input image of a swan.
- Edge restoration of the swan.
- Spectrum of the swan in the gradient domain.
- Spectrum estimation of the swan in the intensity domain.
Edge Restoration for Detecting Region of Interests

\[ i_{\text{aligned}} = \arg \min_i \| \Omega \Phi i - j \|_2^2 \]

- Remove dispersion around edges
- Cross-channel prior \(\rightarrow\) image without dispersion
Gradient Reconstruction

\[ \hat{g}_{xy} = \arg \min_{g_{xy}} \left\| \Omega \Phi g_{xy} - \nabla_{xy} j \right\|_2^2 \]

- Estimate spatial gradient which explains the dispersion best
- Restrict reconstruction on the edge pixels only

Data term in the gradient domain
Spectral sparsity of the spatial gradient
Smoothness of the spatial gradient

Spatial gradient with dispersion
Detected edge position
Estimated spatial gradient

Input
Output
Reconstructing the Spectral Images

\[ i_{\text{opt}} = \arg \min_i \| \Omega \Phi i - j \|_2^2 \]

- Intensity data term
- Gradient data term
- Smoothness of the spectral curvature

• Gradient-aided hyperspectral reconstruction
Reconstruction Summary

Edge Restoration

Spectral Gradient Reconstruction

Spectral Image Reconstruction
RESULTS
Real Scene with a ColorChecker

- Ground-truth spectrum is measured for each color patch using a spectro-radiometer
Results on Various Scenes

Input

Each spectral channel

Reconstructed sRGB

Spectral power distribution

Radiance

Wavelength [nm]

Ours

GT

0.0

0.2

0.4

0.6

0.8

430

480

530

580

630

1

2

1

2

1

2

1

2
Comparison with Other Hyperspectral Imaging Systems

CASSI

CTIS

PMVIS

Ours
Comparison with Other Hyperspectral Imaging Systems

<table>
<thead>
<tr>
<th>System</th>
<th>PSNR</th>
<th>SSIM</th>
</tr>
</thead>
<tbody>
<tr>
<td>CASSI</td>
<td>22.99dB</td>
<td>0.82</td>
</tr>
<tr>
<td>CTIS</td>
<td>24.41dB</td>
<td>0.70</td>
</tr>
<tr>
<td>PMVIS</td>
<td>19.98dB</td>
<td>0.73</td>
</tr>
<tr>
<td>Ours</td>
<td>27.63dB</td>
<td>0.88</td>
</tr>
</tbody>
</table>
Limitations: High-frequency Spatial Structures

- Reconstruction accuracy degrades severely when the dispersion profiles of neighboring edges become overlapped.
Limitations: High-frequency Spectral Information

- Our method cannot capture the high-frequency spectral details
Future Work

• Reconstruction algorithm for various edge structures
  • Deep priors for hyperspectral images

• Depth from dispersion
  • Estimate depth from dispersion

• Integration with CTIS
  • Better reconstruction algorithm for CTIS
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Acknowledgements

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Simple camera setup + Dispersion modeling + Reconstruction algorithm → Hyperspectral image