An adaptive hyperspectral imager: design, control, processing and applications

Simon Lacroix – LAAS/Robotics
Antoine Monmayrant – LAAS/Photonics
Hervé Carfantan – IRAP/Signal & Image
What is color?

> Color: “The property possessed by an object of producing different sensations on the eye as a result of the way it reflects or emits light”
What is color?

> “The property possessed by an object of producing different sensations on the eye as a result of the way it reflects or emits light”

> Which eye?

Human eye?  Insect eye?  Mantis shrimp eye?
“The property possessed by an object of producing different sensations on the eye as a result of the way it reflects or emits light”

Light: “Electromagnetic radiation within a certain portion of the electromagnetic spectrum”

An energy spectrum:

The human portion
What is color?

> Color: “The property possessed by an object of producing different sensations on the eye as a result of the way it reflects or emits light”

> Light: “Electromagnetic radiation within a certain portion of the electromagnetic spectrum”

> Light through eyes

3 numbers

4 numbers

12 numbers!
Hyperspectral images: “true colors”

- B&W image (aka intensity image): every pixel encodes the integral of energy over a given wavelength interval
- Color image: every pixel encodes the energy captured along three wavelength intervals (“3 image planes”)
- Multi-spectral images: up to a dozen image planes
- Hyperspectral images: hundreds of image planes
Hyperspectral images: “true colors”

- B&W image (aka intensity image): every pixel encodes the integral of energy over a given wavelength interval
- Color image: every pixel encodes the energy captured along three wavelength intervals (“3 image planes”)
- Multi-spectral images: up to a dozen image planes
- Hyperspectral images: hundreds of image planes

➤ Hyperspectral cube”
The reflected spectrum of a surface is characteristic of its physical nature.

Various materials

Various minerals
The reflected spectrum of a surface is characteristic of its physical nature

A wide spectrum of applications

- Astronomy
- Earth observation
- Agriculture
- Gaz detection
- Forensic
- Medicine
- Art paint analysis
- Microscopy
- ...

What for?
The reflected spectrum of a surface is characteristic of its physical nature

A wide spectrum of applications

- Astronomy
- Earth observation
- Agriculture
- Gaz detection
- Forensic
- Medicine
- Art paint analysis
- Microscopy
- ...

What for?
Hyperspectral cameras

> Core component: dispersing element

Grating (diffraction)  Prism (refraction)

> Main difficulty: recovering a 3D data cube with a 2D sensor
Hyperspectral cameras

> Classic technology: imaging a slit through a disperser
Hyperspectral cameras

- Classic technology: imaging a slit through a disperser

- Alternative technologies: snapshot hyperspectral imaging
  - Imaging several orders of diffraction
  - + tomography-like reconstruction
Hyperspectral cameras

> Classic technology: imaging a slit through a disperser

> Alternative technologies: snapshot hyperspectral imaging

- Coded aperture snapshot spectral imaging (CASSI)
- Compressed sensing reconstruction
- Classic technology: imaging a slit through a disperser
- Main issue: sequential acquisition
Hyperspectral cameras

➢ Classic technology: imaging a slit through a disperser
    ➢ Main issue: sequential acquisition

➢ Alternative technologies: snapshot hyperspectral imaging
    ➢ Several issues
        ▪ High CPU load to produce the HS cube
        ▪ Performances fixed by design
        ▪ Tough calibration issues
Hyperspectral cameras

Classic technology: imaging a slit through a disperser
Main issue: sequential acquisition

Alternative technologies: snapshot hyperspectral imaging
Several issues
- High CPU load to produce the HS cube
- Performances fixed by design
- Tough calibration issues

All approaches produce heavy data (~ 1 Gb):
- To acquire
- To process
- To transmit
An adaptive hyperspectral imager

> Principle
A partial masking of the signal defines a spectral filter.
An adaptive hyperspectral imager

> Principle (illustration)

A partial masking of the signal defines a spectral filter
An adaptive hyperspectral imager

> Principle (illustration)

A partial masking of the signal defines a spectral filter
An adaptive hyperspectral imager

> Principle (illustration)

A partial masking of the signal defines a spectral filter.
An adaptive hyperspectral imager

> Principle (illustration)

A partial masking of the signal defines a spectral filter
An adaptive hyperspectral imager

> Principle (illustration)

A partial masking of the signal defines a spectral filter
An adaptive hyperspectral imager

> Principle (illustration)

A partial masking of the signal defines a spectral filter
An adaptive hyperspectral imager

> Principle (illustration)

A partial masking of the signal defines a spectral filter
An adaptive hyperspectral imager

> Principle (illustration)

For the same mask, different spatial rays are differently spectrally filtered
An adaptive hyperspectral imager

> Principle (illustration)

For the same mask, different spatial rays are differently spectrally filtered
An adaptive hyperspectral imager

> Design: dual 4f-line

An adaptive hyperspectral imager

> Design: dual 4f-line

Digital Micro-mirror Device
An adaptive hyperspectral imager

> Design: dual 4f-line
Properties

- Possibility to acquire an intensity image
Properties

- Possibility to acquire an intensity image

- “Colocation”
An adaptive hyperspectral imager

Properties

- Possibility to acquire an intensity image
- “Colocation”
- Independence of lines
An adaptive hyperspectral imager

> Properties

- Possibility to acquire an intensity image
- “Colocation”
- Independence of lines
- Simplicity of the model

\[
\lambda(x_f, x_m) = \lambda_c + x_f / (\beta \alpha) - x_m / \alpha
\]
An adaptive hyperspectral imager

Properties
- Possibility to acquire an intensity image
- “Colocation”
- Independence of lines
- Simplicity of the model
- Programmable acquisition

Various acquisition schemes
First proof of concept

Design implementation

- DMD
- F2
- G
- Beam Splitter
- CMOS camera
- Optical Coupler
- Mask
- Fiber Light Source
First proof of concept
First proof of concept

> Scanning a slit on the DMD

Imaged object: known light source through a mask

“bi-λ” illumination
Overview of the system possibilities

The control of the DMD allows to:

- *Configure* the system for a given purpose / characteristic
- *Control* the system to optimize its output (*active perception* paradigm)

Taxonomy of acquisition schemes, along 2 “dimensions”

1. Type of recovered information (defined by operational goals)
   - Full HS cube
   - Specific information (*e.g.* a set of given spectra)
2. Way to control the system
   - Pre-configured DMD patterns
   - *On-line* controlled / adapted patterns

Criteria to consider for application contexts:

- Number of acquisitions
- Computational load to recover the information
- Quantity/quality of recovered information
Example 1: scanning slit

- Fills the whole cube
Overview of the system possibilities

Example 2: monochromatic imager
- Random access to any spectral plane in one acquisition
Example 3: spectrum response image

- Exhibits the presence of a given spectrum in one acquisition

Monochromatic image

Spectrum correlation
> Example 4: generalized bayer mosaics
  - Numerous possible patterns
Example 5: near-snapshot partitioning

- 2 acquisitions: 1 panchro, 1 controlled
Example 6: quadratic regularization

- Recovering the full cube from a small set of random DMD acquisitions (PhD of Ibrahim Ardi, IRAP/LAAS)

Reconstruction of a 31 wavelengths cube from 5 images
> Really engineered
> Images the visible 500-700 nm
> Integrated acquisition & DMD control
Earth observation applications?

- Configurability yields a series of trade-offs in terms of:
  - Number of acquisitions
  - Computational load to recover the information
  - Quantity/quality of recovered information
Earth observation applications?

- Configurability yields a series of trade-offs in terms of:
  - Number of acquisitions
  - Computational load to recover the information
  - Quantity/quality of recovered information

- Matrix sensor in a push-broom configuration:
  - Time delayed integration
  - Real-time adaptive control of the acquisitions
Co-design: interdisciplinary cross fertilization