COSI Computational Colour and Spectral Imaging

"Advanced Colour and Spectral Imaging"

Chapter 6: Spectral imaging technologies (acquisition only)

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Spectral imaging technologies

- **Classification based on number and type of spectral bands**
    1. Hyperspectral imaging
    2. Multispectral imaging
- **Classification based on scanning process**
    1. Spatial scan
    2. Spectral scan
    3. Snapshot or single shot
    4. Spatio-spectral scan
- **Classification based on the sensor type**
    1. Linear array sensor
    2. Monochrome matrix sensor
    3. Color matrix sensor
    4. Multispectral matrix sensor
    5. Multiple matrix sensor
    6. Tunable sensitivity matrix sensor
- **Classification based on types of illumination**
    1. Passive illumination
    2. Active illumination

Classification based on number and type of spectral bands

1. **Hyperspectral imaging**
2. **Multispectral imaging**

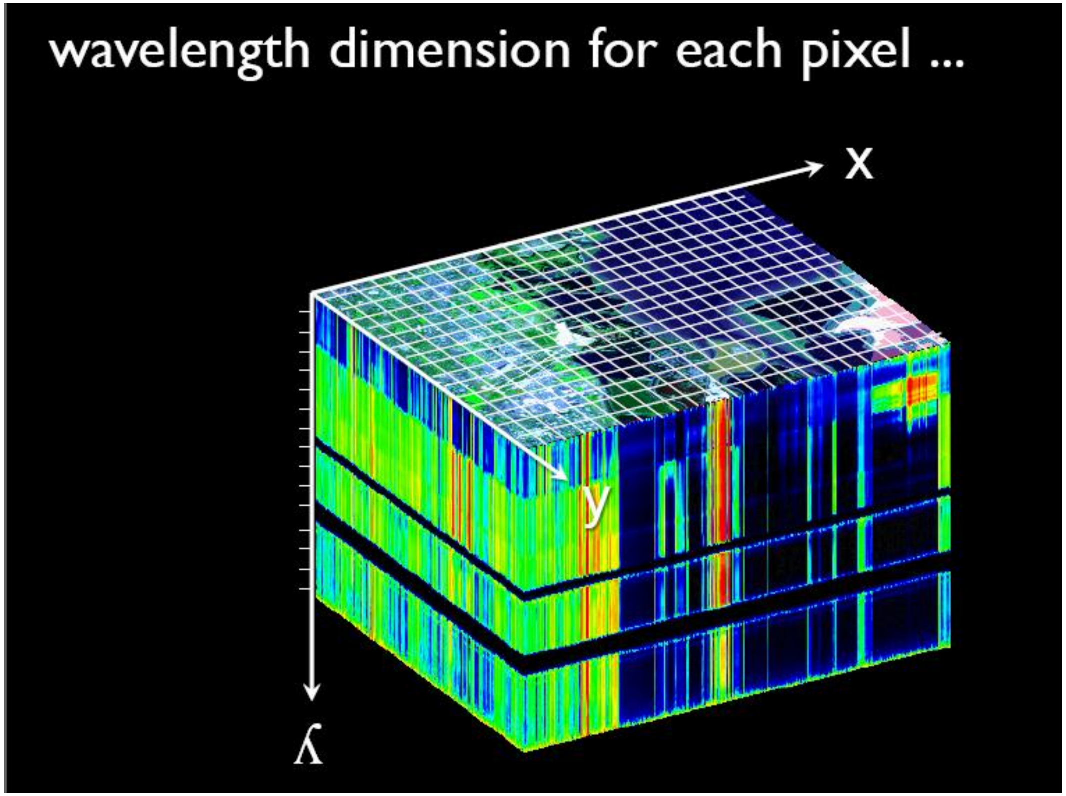
Classification based on number and type of spectral bands

Hyperspectral imaging (HSI)

Narrow spectral bands over a continuous spectral range.
Normally in different spectral regions

Title	Name	Range	Applications examples
UV	Ultraviolet	200-400 nm	Forensic
VIS	Visible	380-800 nm	Art application
IR	Infrared		
NIR	Near IR	900-1700 nm	Sorting plastic objects
SWIR	Short Wave IR	970-2500 nm	Mineral detection
MWIR	Medium Wave IR	3000-5000 nm	Analyze hot gases
LWIR	Long Wave IR	8000-12000 nm	Mineral detection

Hyperspectral imaging (HSI)



High spectral resolution

- Acquisition time
- Huge data volume
- Complex system
- High cost

Classification based on number and type of spectral bands

Multispectral imaging

- Somewhat narrow (wider than HSI) and discrete spectral bands.
- Does not produce spectral data directly. They rather use **estimation algorithms** to obtain spectral functions from sensor responses.
- Spectral ranges: UV, VIS and IR (with discrete bands)
- Can focus on certain spectral bands which are interesting for a particular application.
- Less accuracy than HSI but good enough in many applications

Faster
Simpler
Smaller data volume
Portable
Cheaper

Less accuracy

Classification based on number and type of spectral bands

1. Hyperspectral imaging
2. Multispectral imaging

Hyperspectral or Multispectral?

>20 bands <20 bands

BUT it depends on the spectral range

20 bands on the range [400-600 nm]?
20 bands on the VIS +IR range?

Classification based on number and type of spectral bands

1. Hyperspectral imaging
2. Multispectral imaging

Table from R. Shrestha 2014

Feature	Hyperspectral	Multispectral
# of bands	>20	<20
Type of bands	Narrow	Wider
Spectral resolution	High	Low
How the spectra is obtained?	Directly measured	Estimated from sensor responses
Measurement accuracy	High	Low
Speed	Low	High
Data size	High	Lower
Complexity	High	Less
Portability	Less	High
Cost	High	Low

Classification based on scanning process

1. **Spatial scan**
2. **Spectral scan**
3. **Snapshot or single shot**
4. **Spatio-spectral scan**

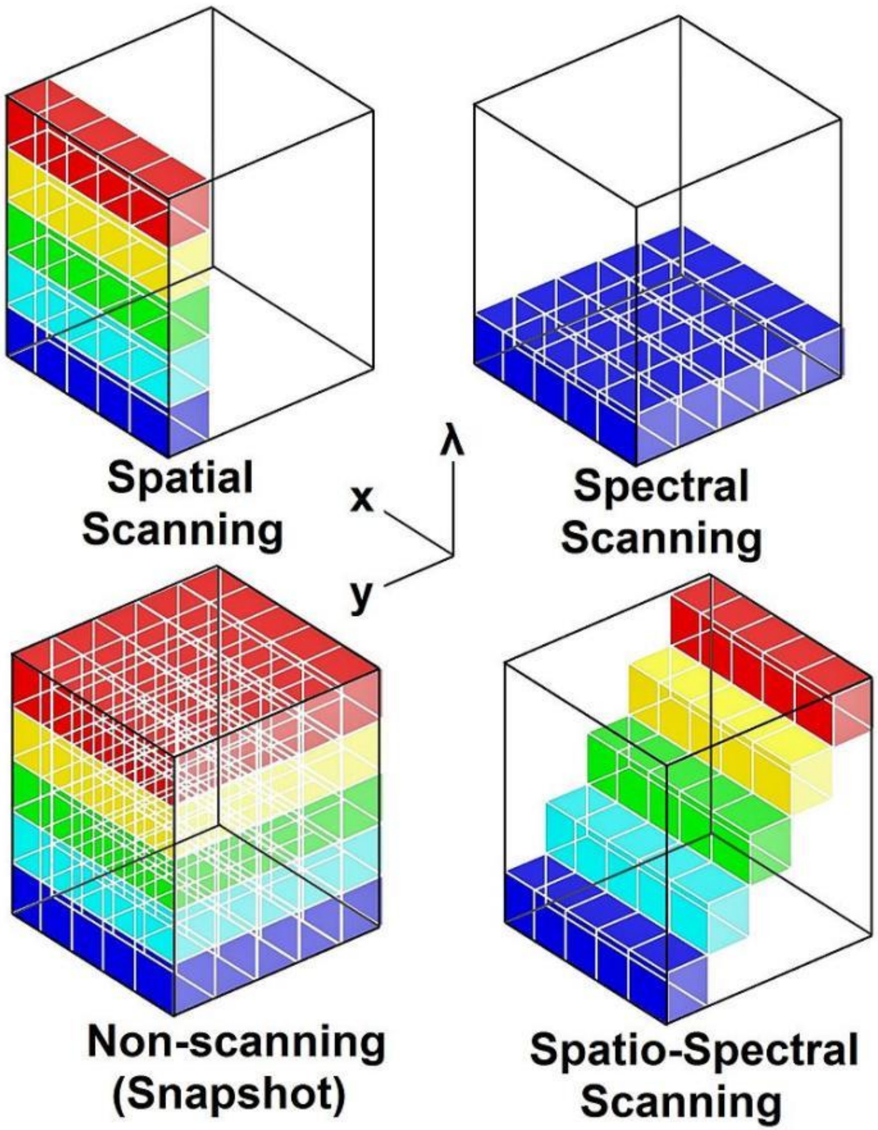
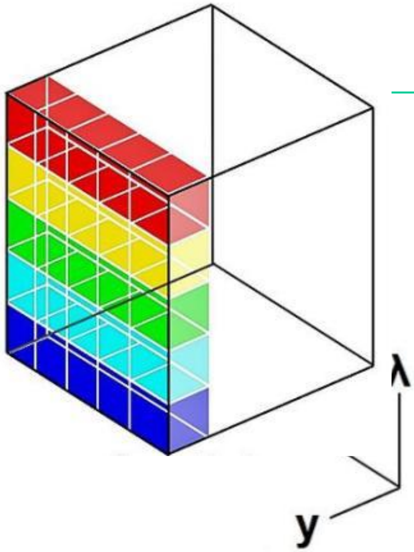


Image from https://en.wikipedia.org/wiki/Hyperspectral_imaging

Classification based on scanning process

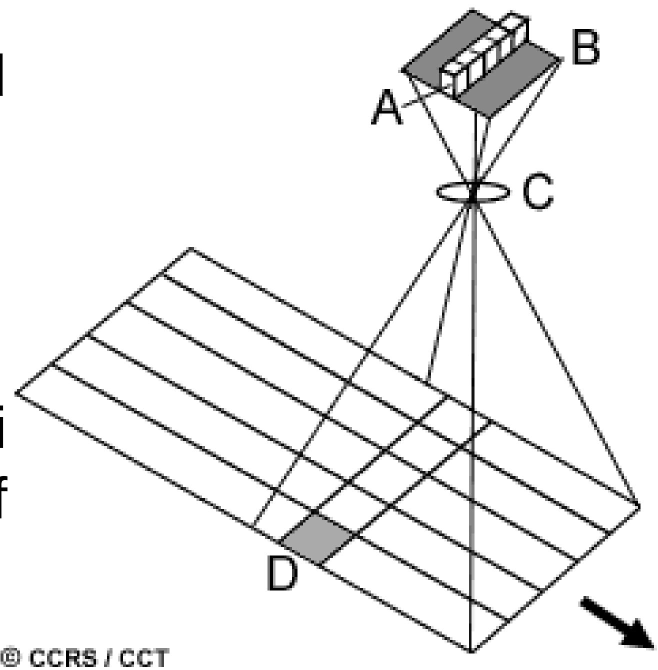
1. Spatial scan



Scans a scene spatially
Capturing full spectral data sequentially.

<u>Line-scan </u>(*pushbroom scan):*
For example: Couce et al. 2006
Projecting a strip of the scene onto a slit and dispersing the slit image with a prism or a grating.

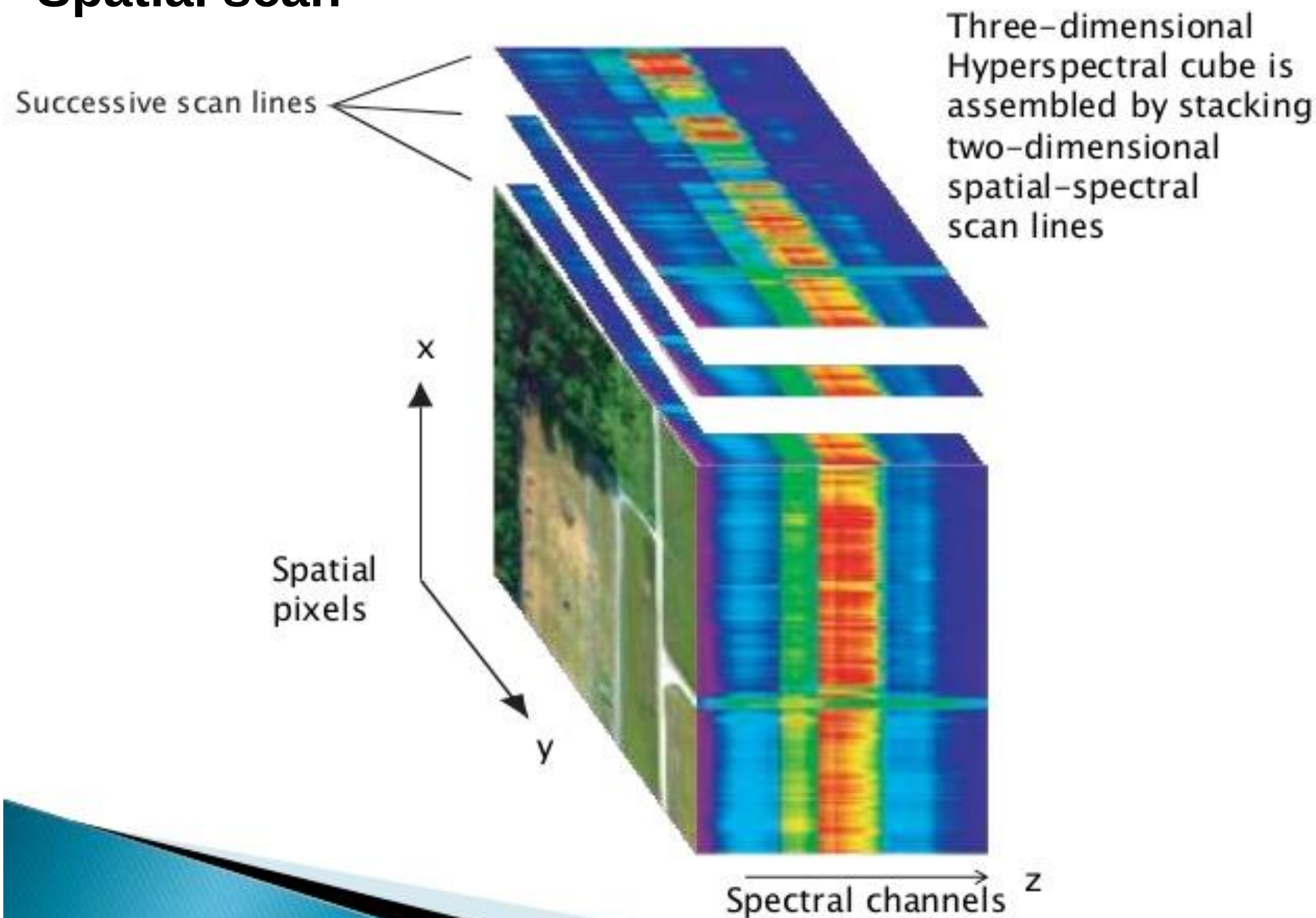
<u>Point-scan</u> (*whiskbroom*): too slow for many applications. For example Manabe&Inokuchi 1996. A point-like aperture is used instead of a slit, and the sensor is essentially one-dimensional instead of 2-D



http://www.nrcan.gc.ca/earth-sciences/geomatics/satellite-imagery-air-photos/satellite-imagery-products/educational-resources/9337

Classification based on scanning process

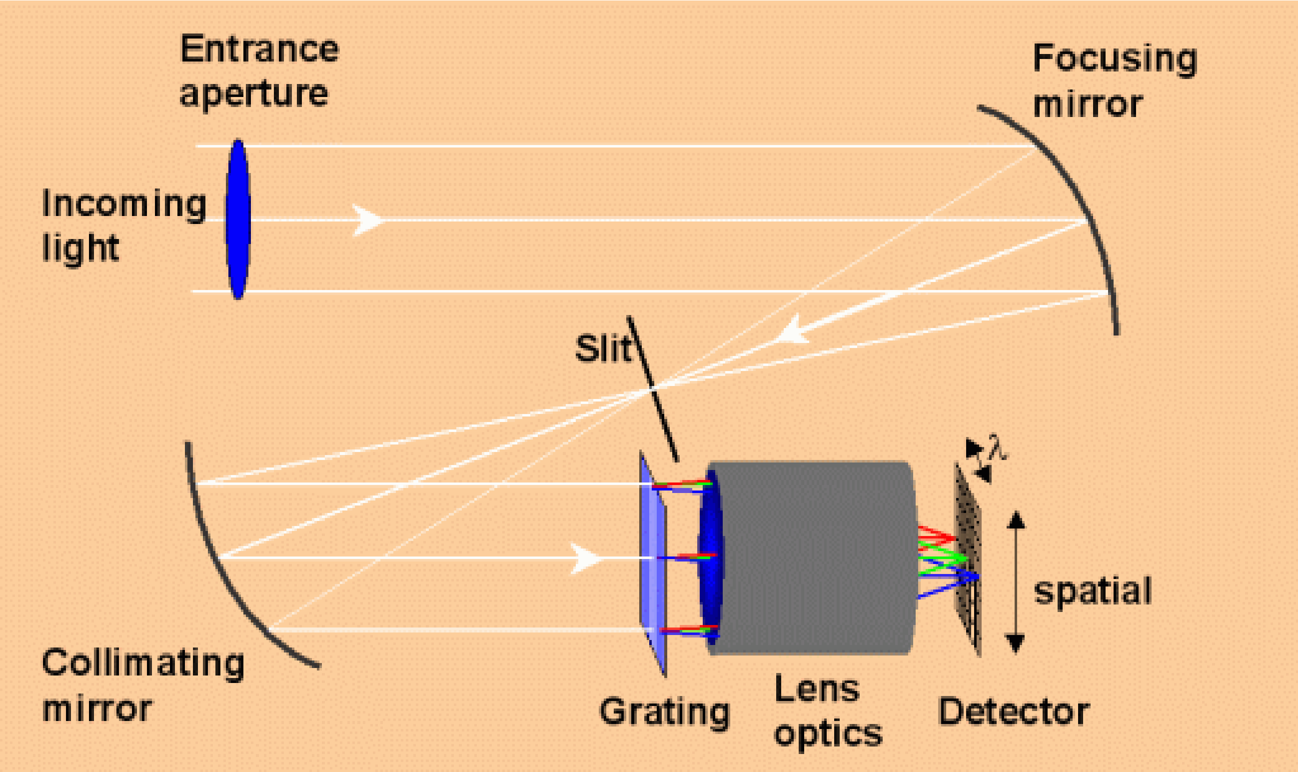
1. Spatial scan



Classification based on scanning process

1. Spatial scan

The light passed out from the slit is collimated and different wavelengths are separated using a dispersive element and then the light is focused onto the sensor array.



The optics thus projects a spectrum of light from each pixel interval along the line defined by the slit on a column of sensors of array.

http://www.neo.no/hyspex/

Classification based on scanning process

1. Spatial scan

http://www.middletonspectral.com/

pushbroom scan with moving sample

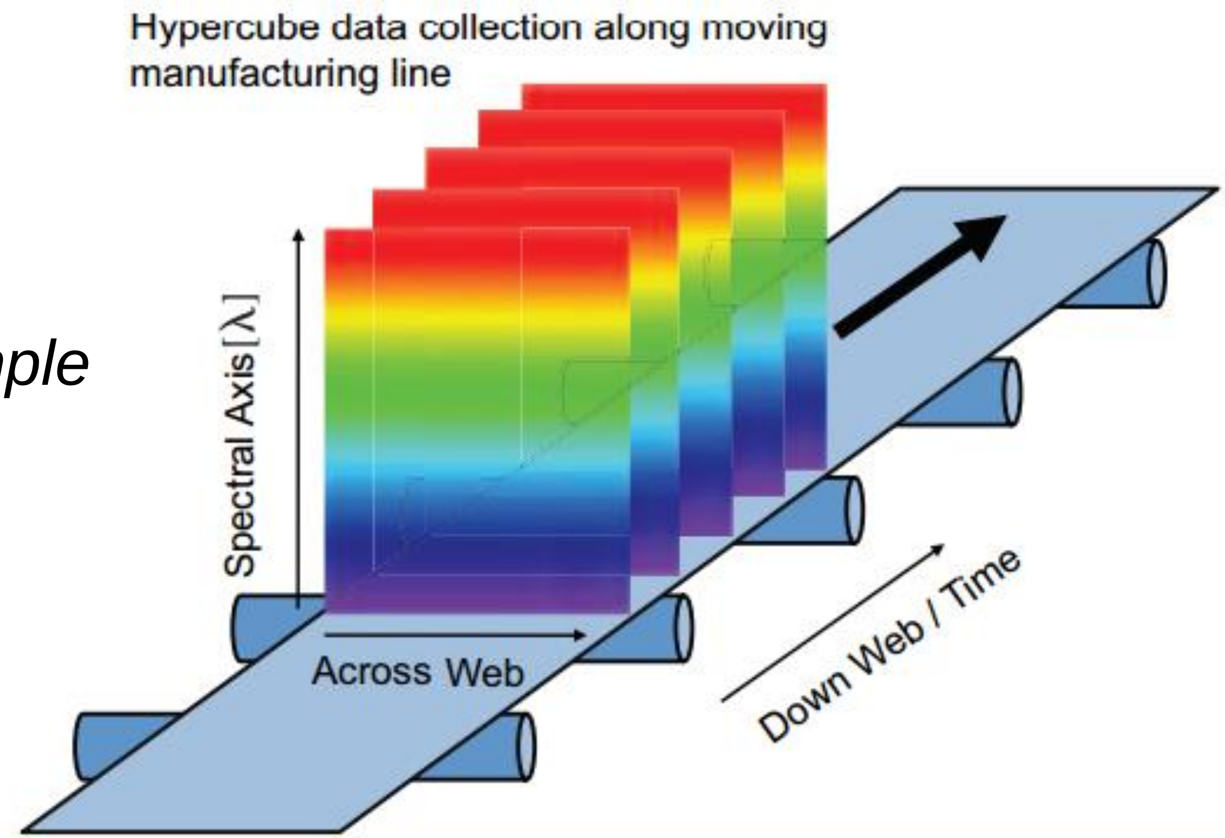


Figure 1. Shows hyperspectral data collection: The system collects a full spectrum for each point on a line across the transdermal web. As the web moves past the camera, the system forms the complete hypercube.

Classification based on scanning process

1. Spatial scan

The system is integrated with a movement mechanism, where either the scene or the camera is moved, so that the acquisition process is done line-by-line sequentially.

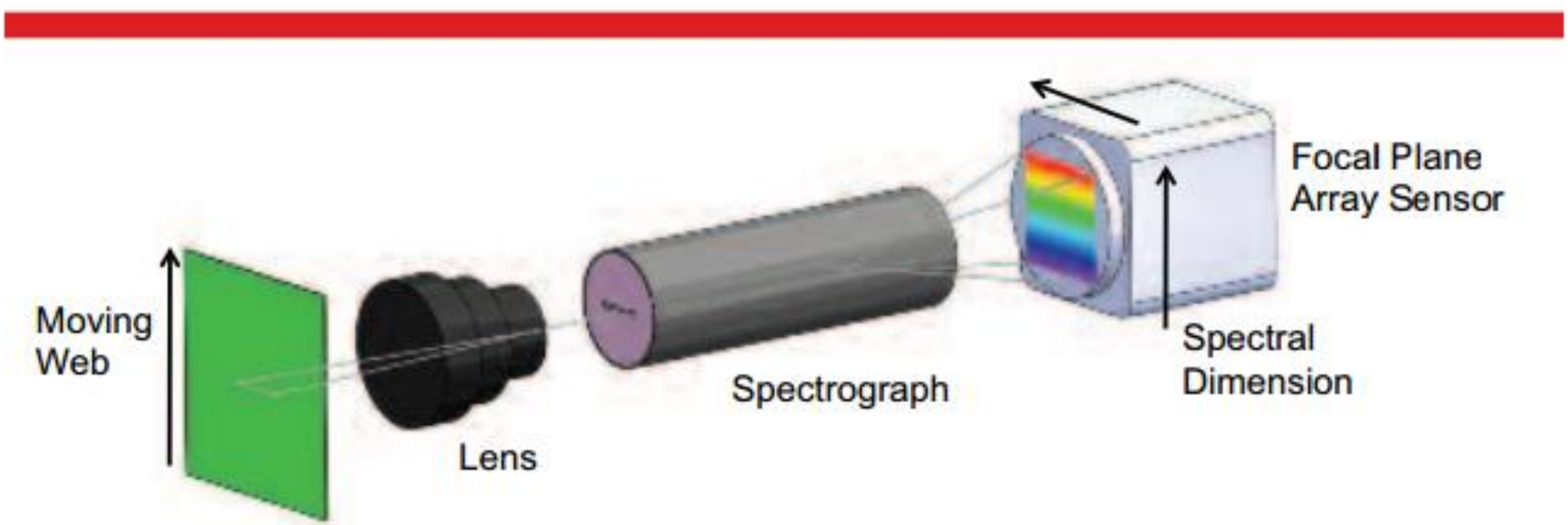


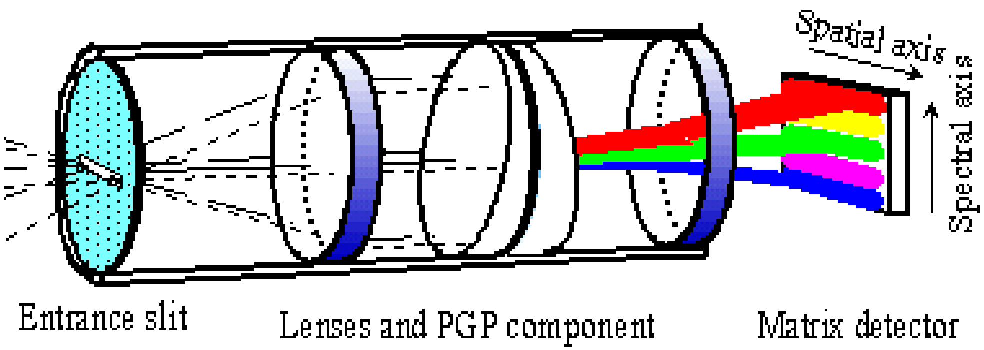
Figure 2. A hyperspectral camera includes a lens, a spectrograph, and a focal plane array sensor.

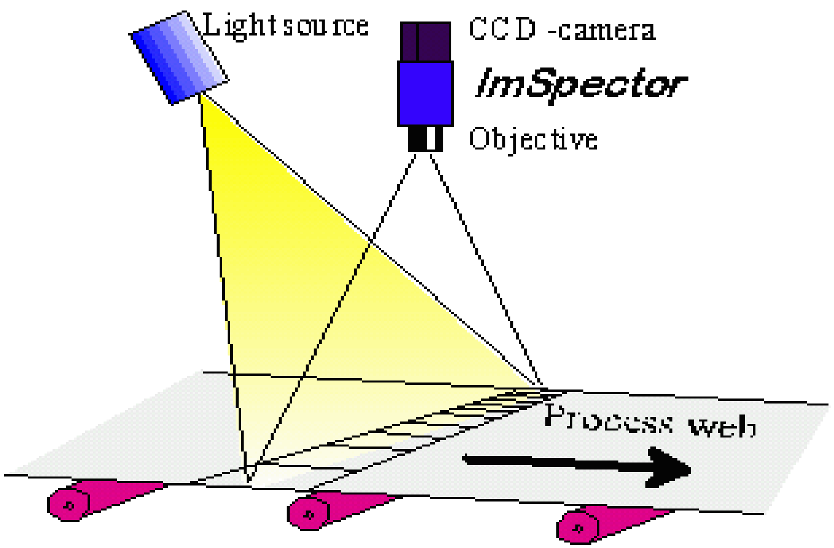
http://www.middletonspectral.com/

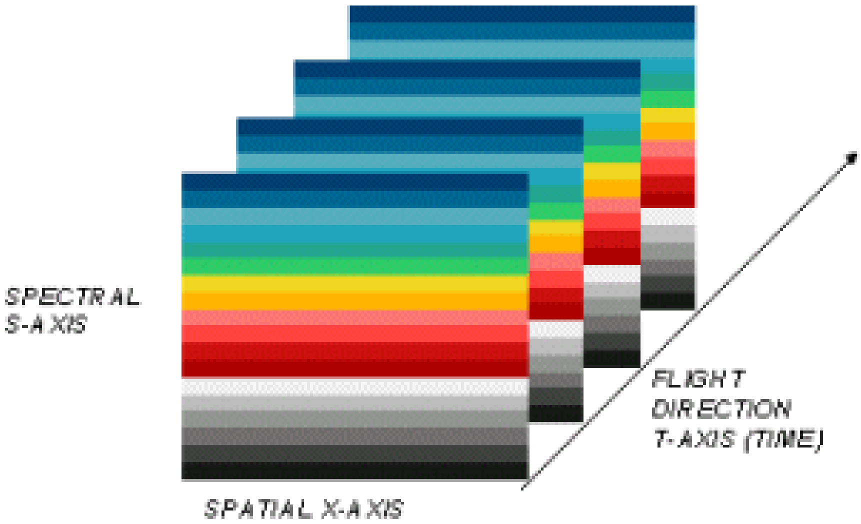
Classification based on scanning process

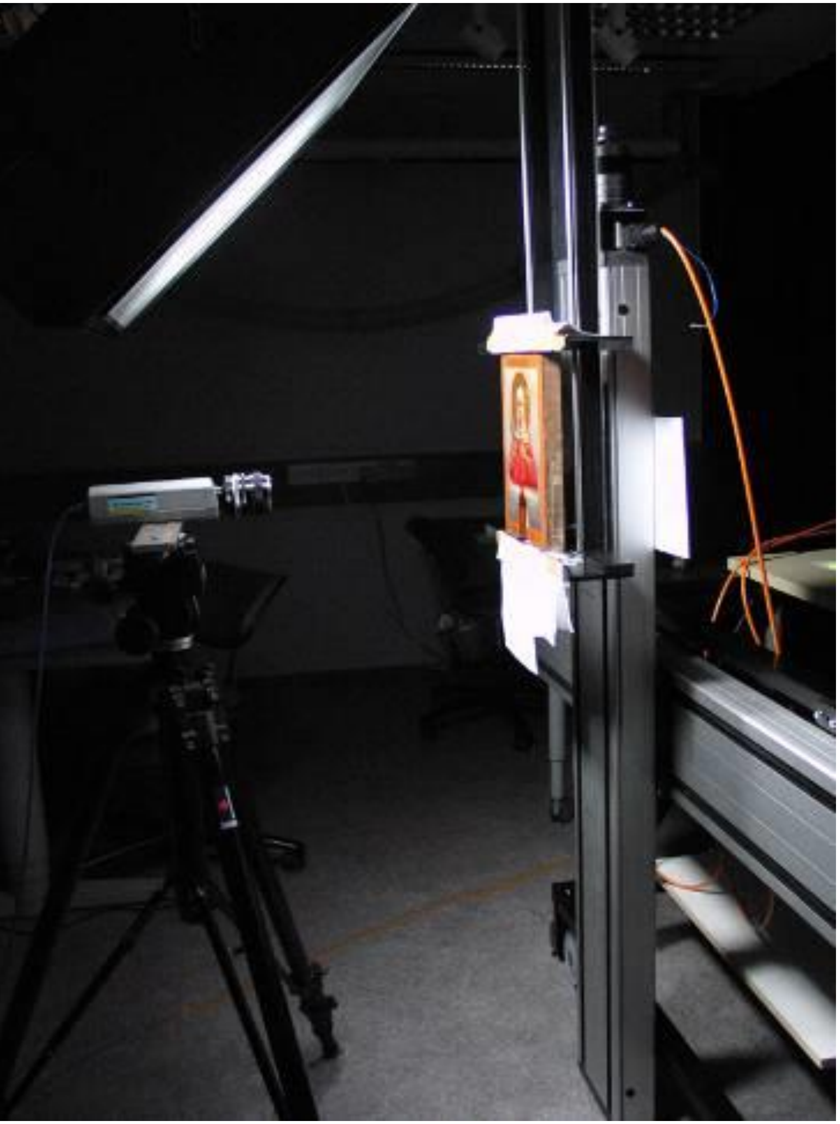
1. Spatial scan

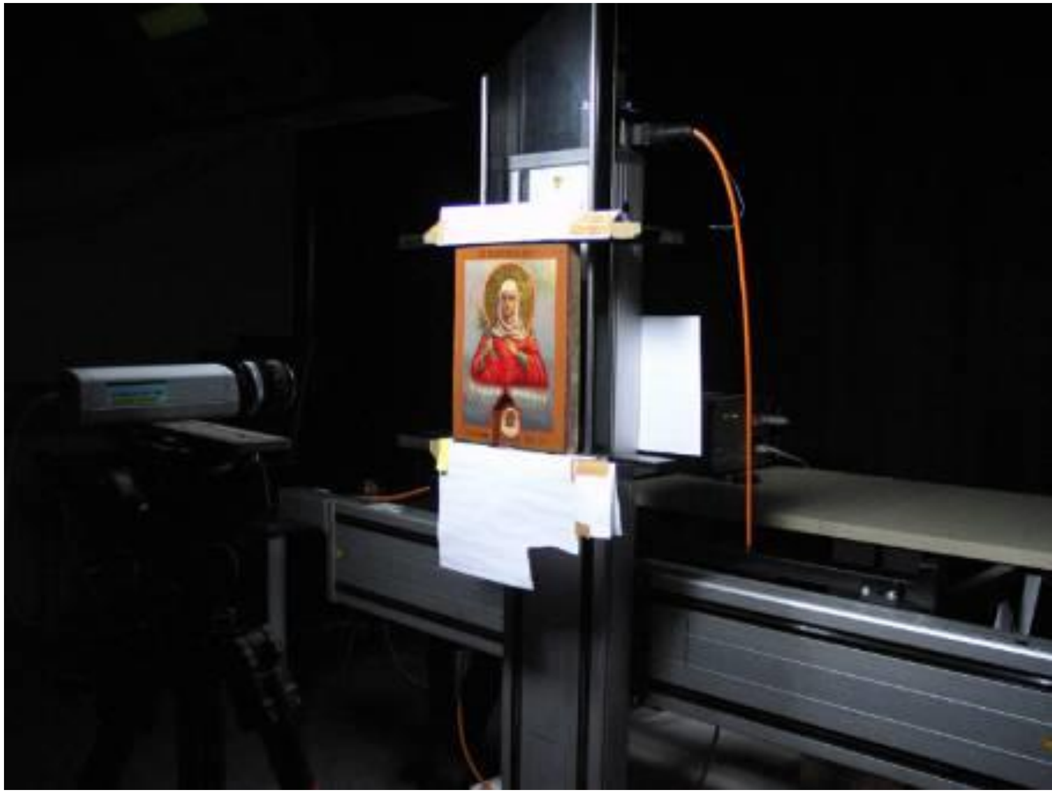
www.specim.fi



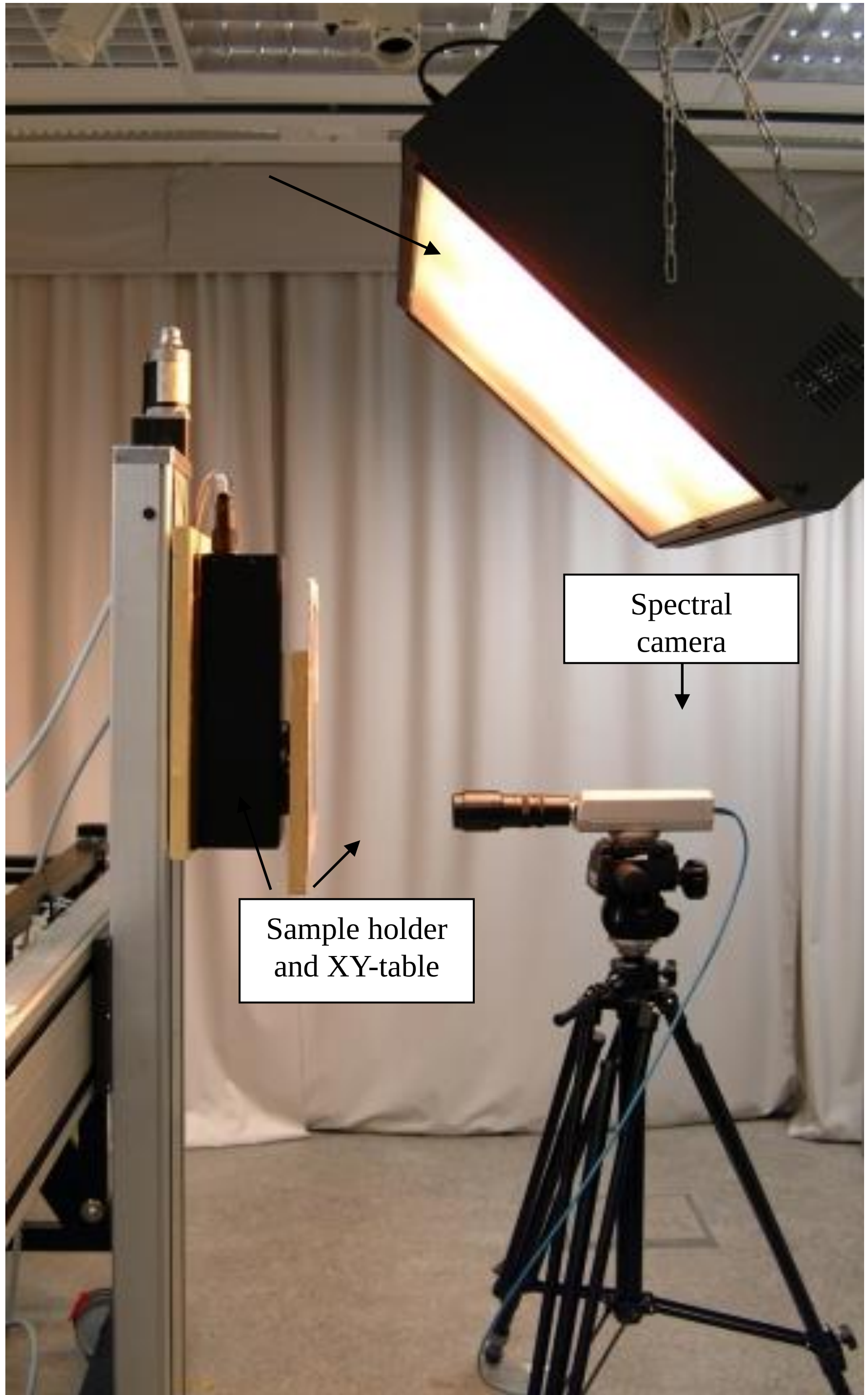








http://ifc.joensuu.fi



http://ifc.joensuu.fi

http://ifc.joensuu.fi

Spectral imaging from 380 nm to 1700nm

http://ifc.joensuu.fi

Classification based on scanning process

1. Spatial scan

A post-processing step is essential where images acquired at each line are properly registered and stitched together to get the full hyperspectral image or spectral cube.

For example:
"Co-aligning aerial hyperspectral push-broom strips for change detection" Ringaby et al. SPIE Vol 7835 (2010)
Martínez et al. (2019). Multifocus HDR VIS/NIR hyperspectral imaging and its application to works of art. *Optics express*, *27*(8), 11323-11338.

Since spatial scan systems usually require mechanical movement and scans line-by-line (or point by point), it requires stabilized mounts and accurate pointing information; otherwise motion artifacts are created.

Therefore this technology is not suitable for very high speed spectral imaging systems!

Classification based on scanning process

1. Spatial scan

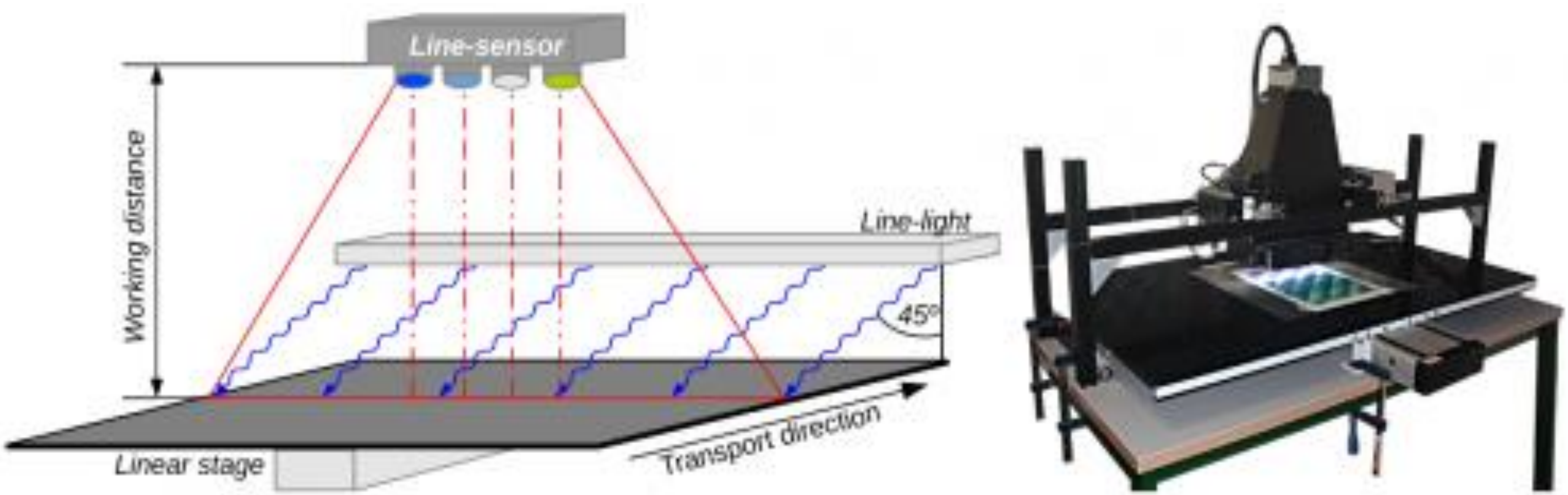
TruePixa from Chromasens?

It is an example of spatial scan?

What is the scanning speed for the TruePixa?

http://www.chromasens.de/en/multi-spectral-camera-truepixa

Any pre-processing? Registration?



(a) (b)

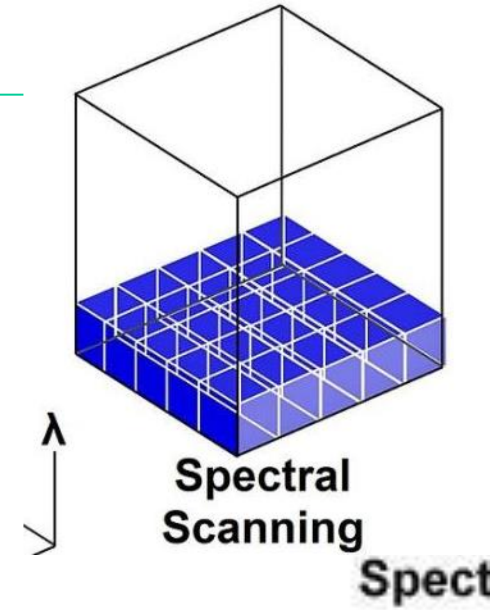
Classification based on scanning process

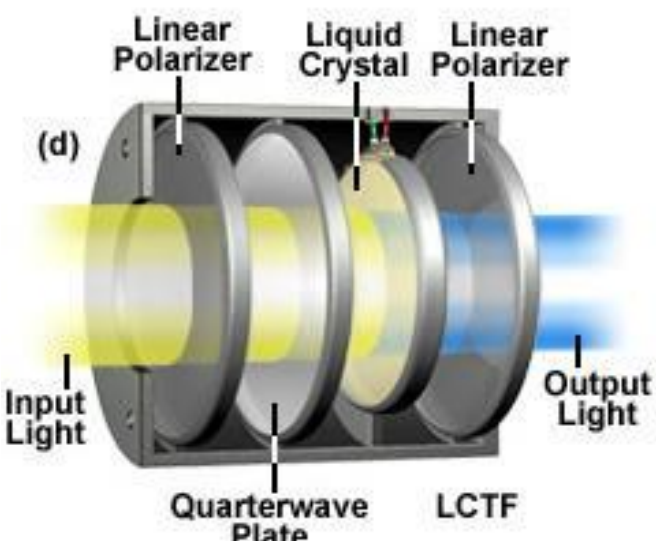
2. Spectral scan (also known as *starring array* technique)

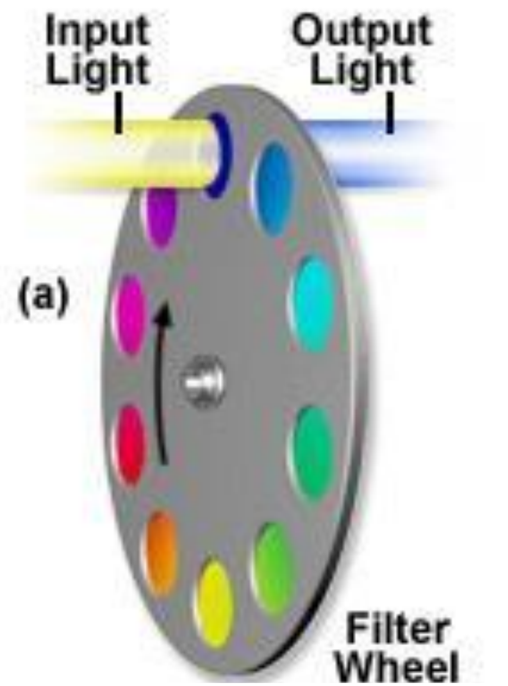
Captures the whole scene at the same time and scan through spectral wavelengths sequentially, one wavelength at a time.

Examples: filter wheel,

LCTF, others…







Images from http://www.microscopyu.com/articles/confocal/spectralimaging.html

Classification based on scanning process

2. Spectral scan (also known as starring array technique)

A data cube is built from the images captured sequentially over time.

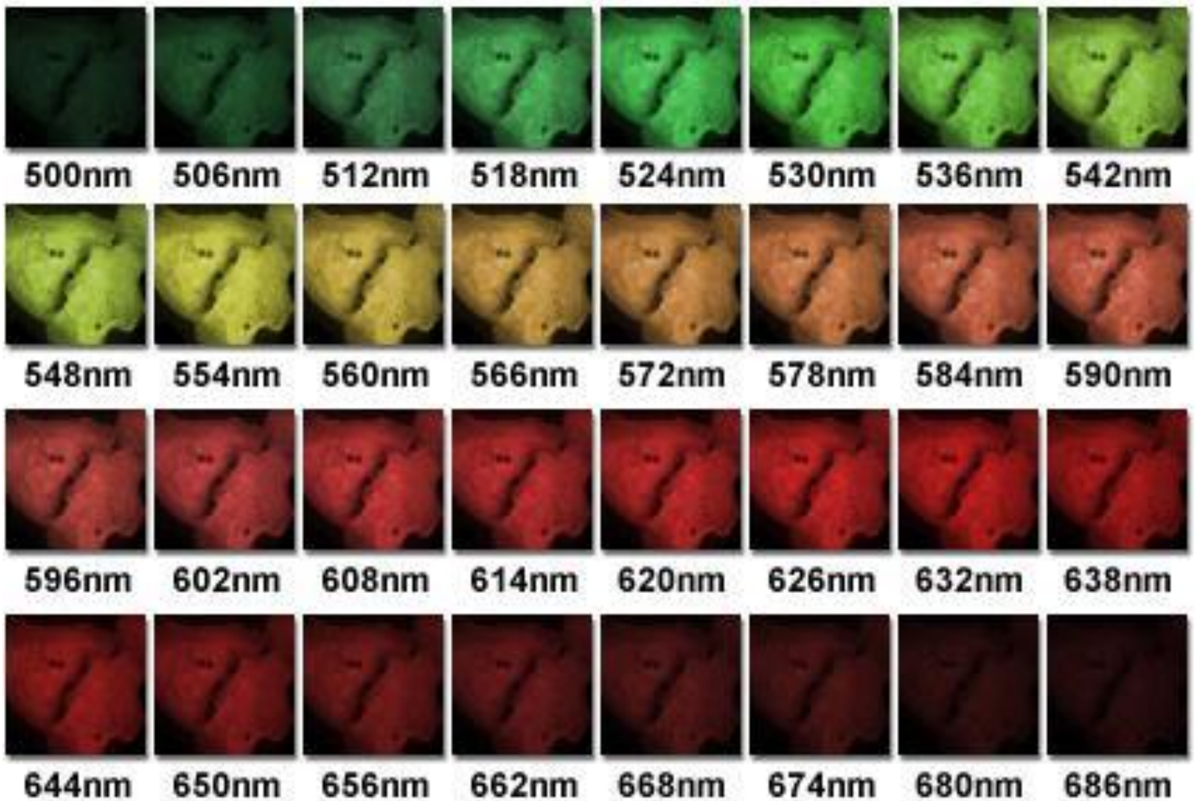


Image from http://www.microscopyu.com/articles/confocal/spectralimaging.html

Classification based on scanning process

2. **Spectral scan** (also known as starring array technique)

- Minimizing the number of actual filters is important to reduce operational costs, acquisition time, and data storage space.
- How to select filters from among a large set of filters?
- The spectral scan can be hyperspectral or multispectral.
- The camera and the sample remain stationary, and the whole sample should be illuminated by an uniform illumination.
- A slight movement can cause spectral smearing.
- The whole sample is under direct heat during the entire measurement.
- Registration of images?

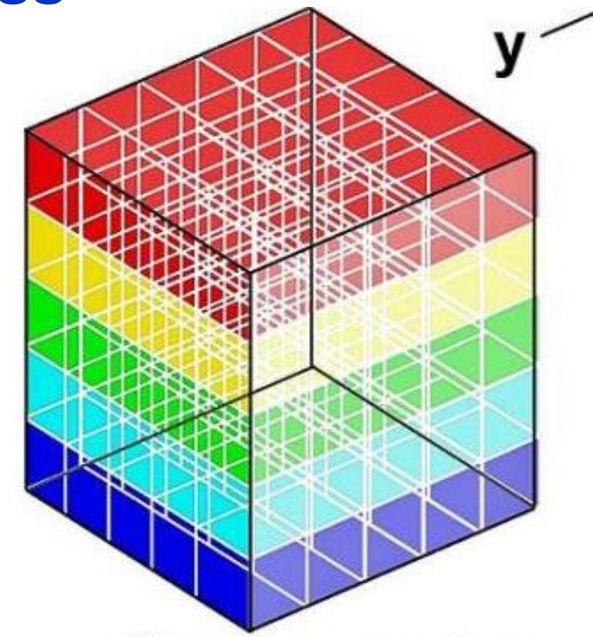
????

????

Classification based on scanning process

3. Snapshot or single shot

- Capturing all the spectral and spatial information at once.
- Which technology?
  - Multi-sensor (i.e. FluxData)
  - Multispectral filter array



Non-scanning (Snapshot)

No motion artifacts
Video
High speed applications

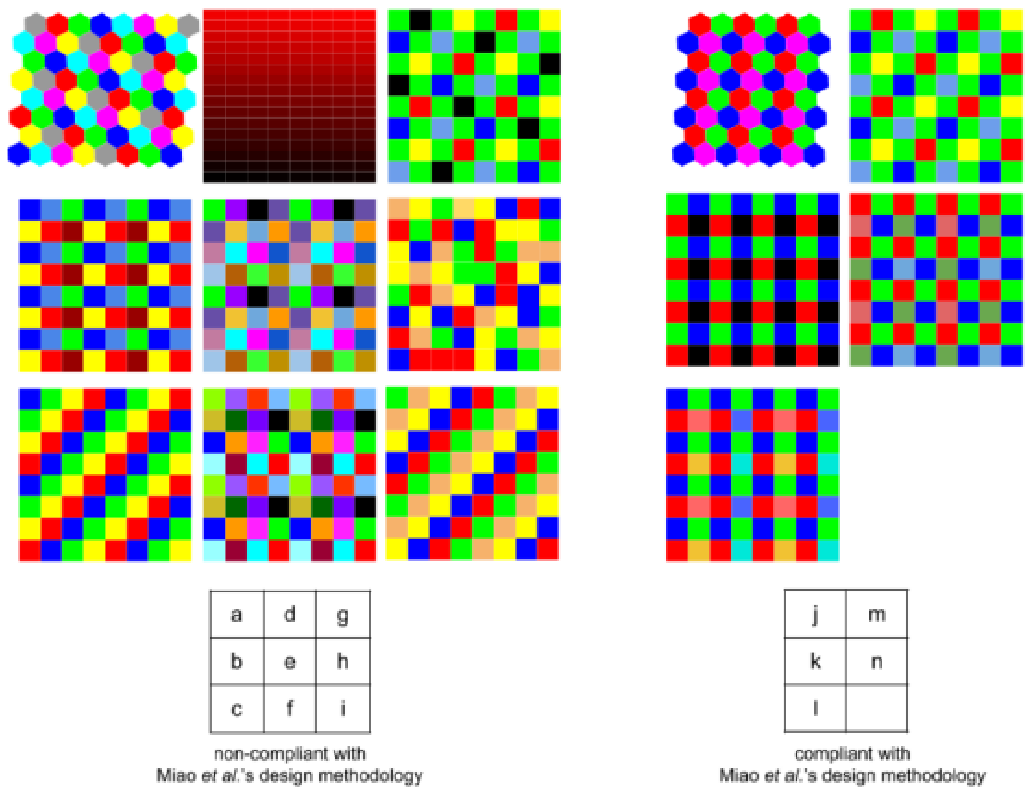
Not yet feasible
Not practical
Not cheaper

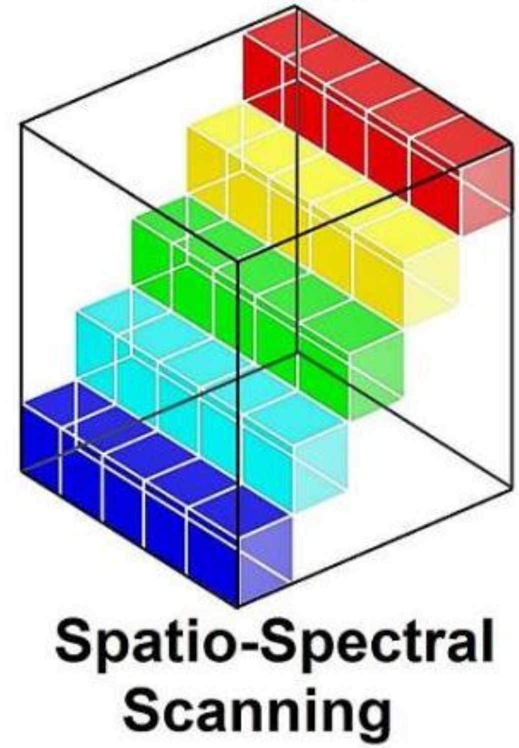
Classification based on scanning process

Multispectral filter array

Figure 7. (**a**) Ramanath *et al.* [32]; (**b**) Brauers and Aach [47]; (**c**) Aggarwal and Majumbar [48]; (**d**) Wang *et al.* [50]; (**e**) Lu *et al.* [52]; (**f**) Sadeghipoor *et al.* [53]; (**g**) Kiku *et al.* [58]; (**h**) Aggarwal and Majumbar [59]; (**i**) Aggarwal and Majumbar [59]; (**j**) Ramanath *et al.* [32]; (**k**) Hershey and Zhang [49]; (**l**) Yasuma *et al.* [55]; (**m**) Monno *et al.* [56], Shrestha and Hardeberg [57].

MSFA: multispectral filter array

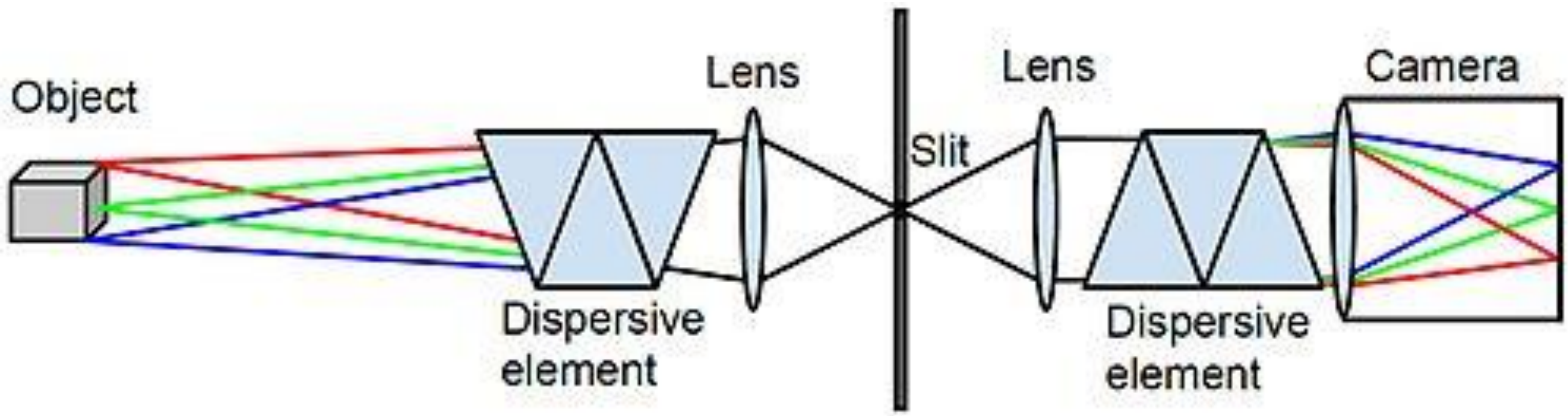




Classification based on scanning process

4. Spatio-spectral scan

Basic slit spectroscope reveals three-dimensional scenes through diagonal slices of hyperspectral cubes
Sascha Grusche



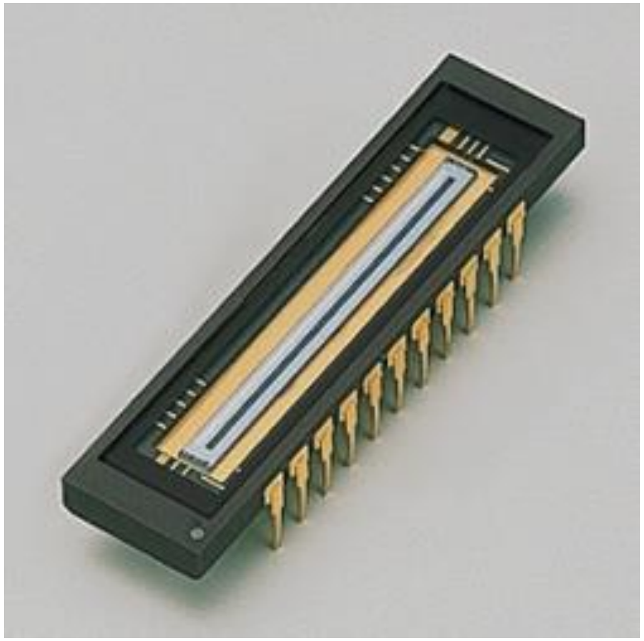
Classification based on the sensor type

1. **Linear array sensor**
2. **Monochrome matrix sensor**
3. **Color matrix sensor**
4. **Multispectral matrix sensor**
5. **Multiple matrix sensor**
6. **Tunable sensitivity matrix sensor**

Classification based on the sensor type

1. Linear array sensor

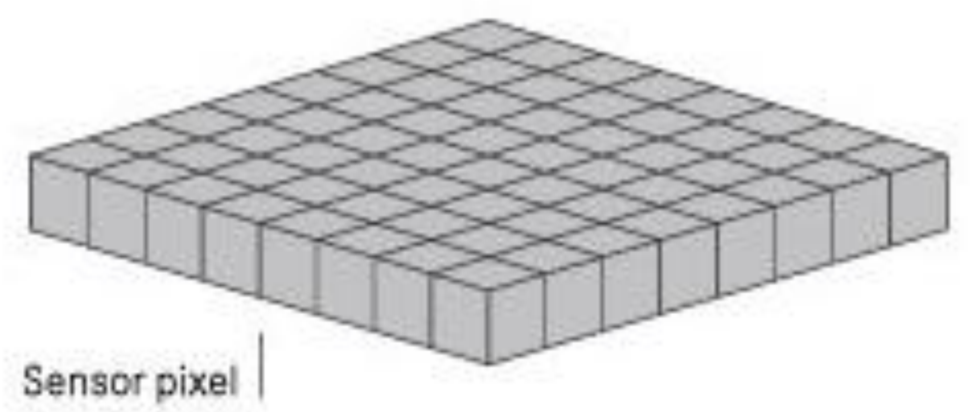
- Used in the pushbroom imaging systems
- How is the sensor of the Chromasens TruePixa device?



Classification based on the sensor type

2. Monochrome matrix sensor

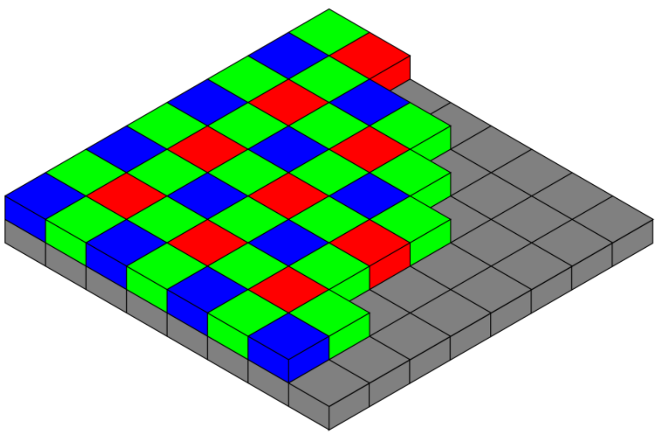
- 2D matrix form. No Bayer filter on top



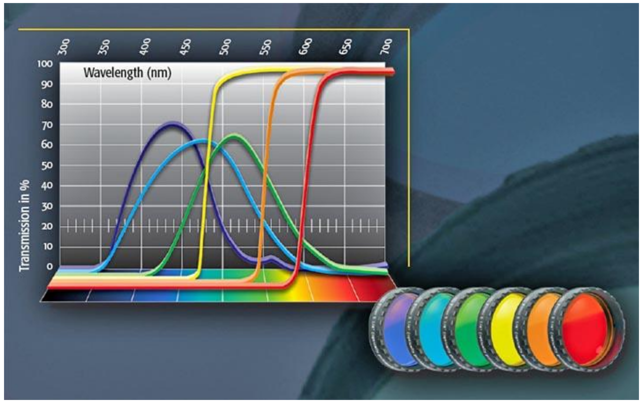
Classification based on the sensor type

3. Color matrix sensor

- RGB sensor + n color filters = 3n+3 camera responses
- “Theoretically” a 3n+3 channel multispectral image



+



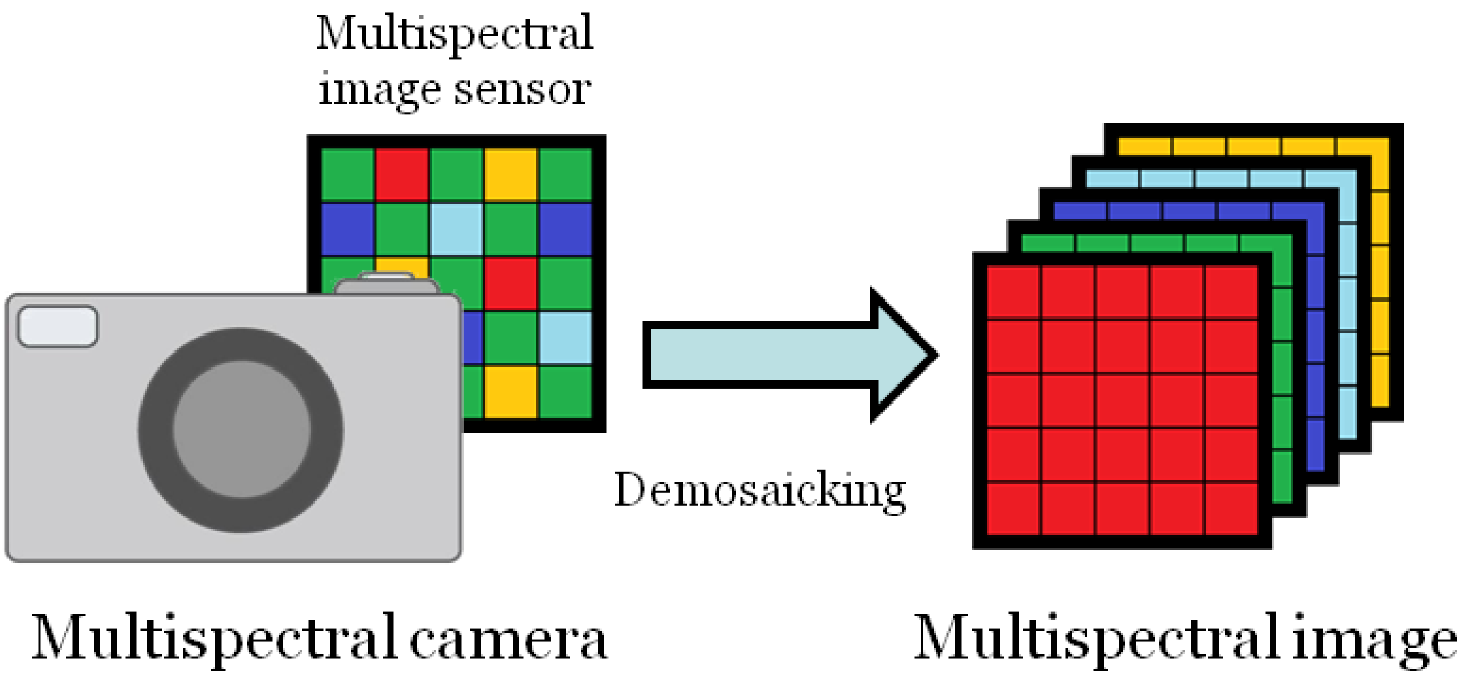
Available technology
Cheap technology
Not specialized

Demosaicing

Classification based on the sensor type

4. Multispectral matrix sensor

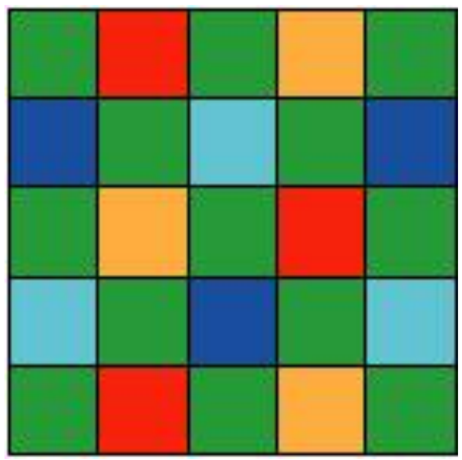
- CFA technology: 3 color filters
- MSFA: multispectral filter array
- MCFA: multispectral color filter array
- SFA: spectral filter array



Classification based on the sensor type

4. Multispectral matrix sensor

- Allows a spectral image in a single shot
- A topic still under research



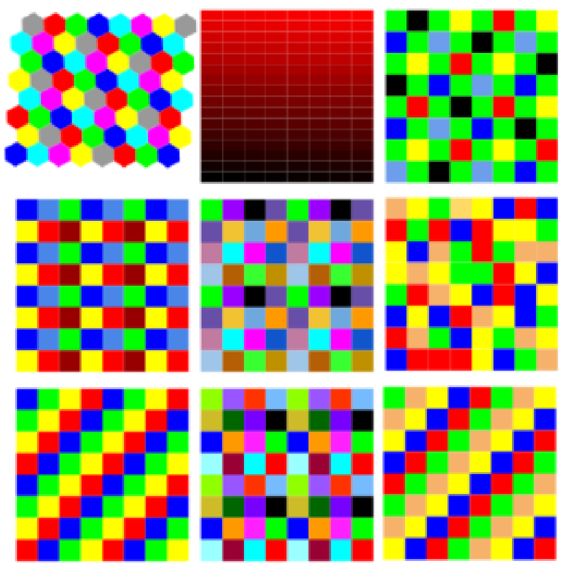
Promising technology

Demosaicing
Not available
Not cheap

Classification based on the sensor type

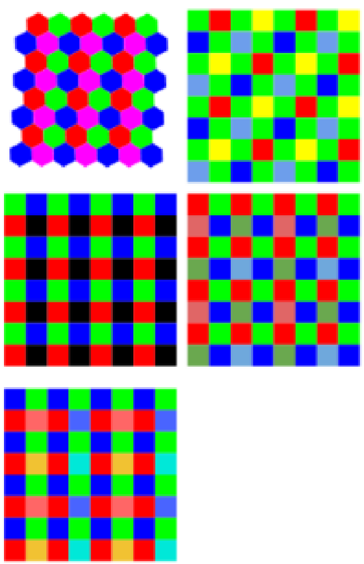
4. Multispectral matrix sensor

Figure 7. (**a**) Ramanath *et al.* [32]; (**b**) Brauers and Aach [47]; (**c**) Aggarwal and Majumbar [48]; (**d**) Wang *et al.* [50]; (**e**) Lu *et al.* [52]; (**f**) Sadeghipoor *et al.* [53]; (**g**) Kiku *et al.* [58]; (**h**) Aggarwal and Majumbar [59]; (**i**) Aggarwal and Majumbar [59]; (**j**) Ramanath *et al.* [32]; (**k**) Hershey and Zhang [49]; (**l**) Yasuma *et al.* [55]; (**m**) Monno *et al.* [56], Shrestha and Hardeberg [57].



a	d	g
b	e	h
c	f	i

non-compliant with
Miao *et al.*'s design methodology



j	m
k	n
l	

compliant with
Miao *et al.*'s design methodology

Classification based on the sensor type

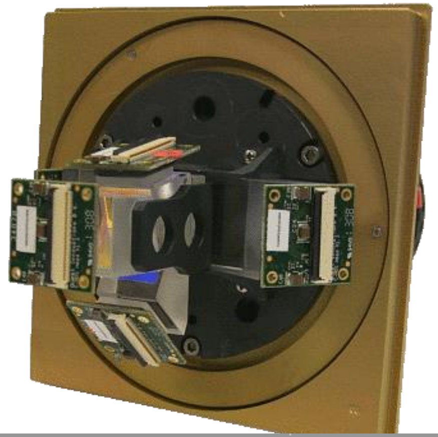
5. Multiple matrix sensors

- More than one sensor
- Light is splitted

As of August 2008 Quest Innovations has released world's first Multi-Spectral Scalable **5 channel camera**. This camera is the first in a line of Multi-Spectral camera products based on Quests smart camera platform, allowing on board processing on all available data channels

Classification based on the sensor type

5. Multiple matrix sensors



www.quest-innovations.com

The condor-1000 MS-5 is the most advanced high tech multi-spectral imaging system available worldwide in the market today. State of the art optic solutions combined with the latest in CMOS technology and the latest electronic developments are used in developing this camera system. With a spatial resolution of 1280x1024 at 10 bits per pixel and 5 image sensor this system generates over 150 frames per second in parallel. Processing this data online is an enormous task. On board processing is available to allow signal processing per optical channel to process images on the fly. Several interfaces are available, for full data transfer an Optical Fiber or CameraLink interface is available, for reduced load and framerate a GigE interface is available.

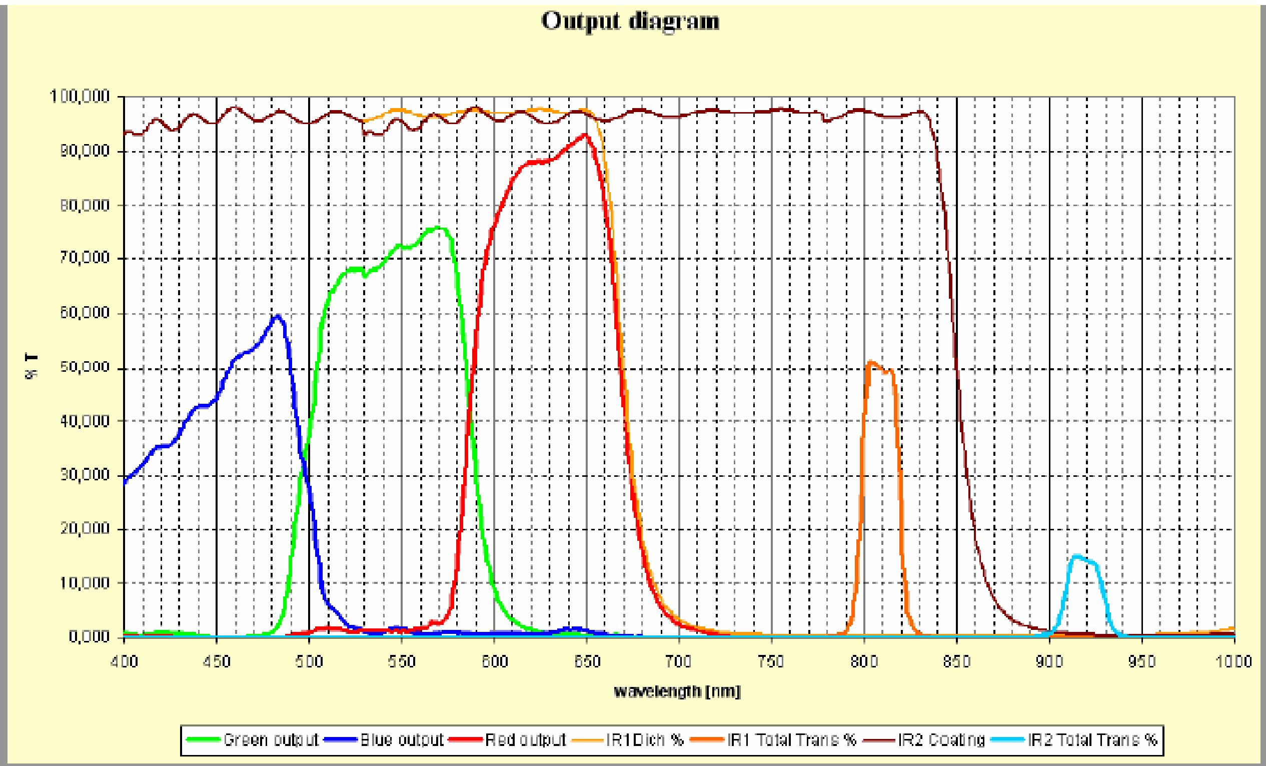
Key Features

- 5 Parallel optical acquisition channels
- 5 CMOS Sensors
- 150 Frames/second
- 210 Mbytes/second of data
- Individual Sensor control
- Parallel Sensor Synchronization
- Global and Rolling shutter
- Separate Integration time per image sensor
- 5 x 32-Bit processors optional
- 5 x Multi-Pixel Co processors optional
- Enhanced NIR efficiency
- Several Interfaces
  - Optical Fiber
  - CameraLink
  - GigE

Classification based on the sensor type

5. Multiple matrix sensors

www.quest-innovations.com



The condor multi-spectral imager is available with in different spectral response curves. Shown is a standard spectral response curve for medical applications with 3 standard RGB spectral regions and 1 IR region surrounding 810 nm and one spectral region surrounding 910 nm.

Classification based on the sensor type

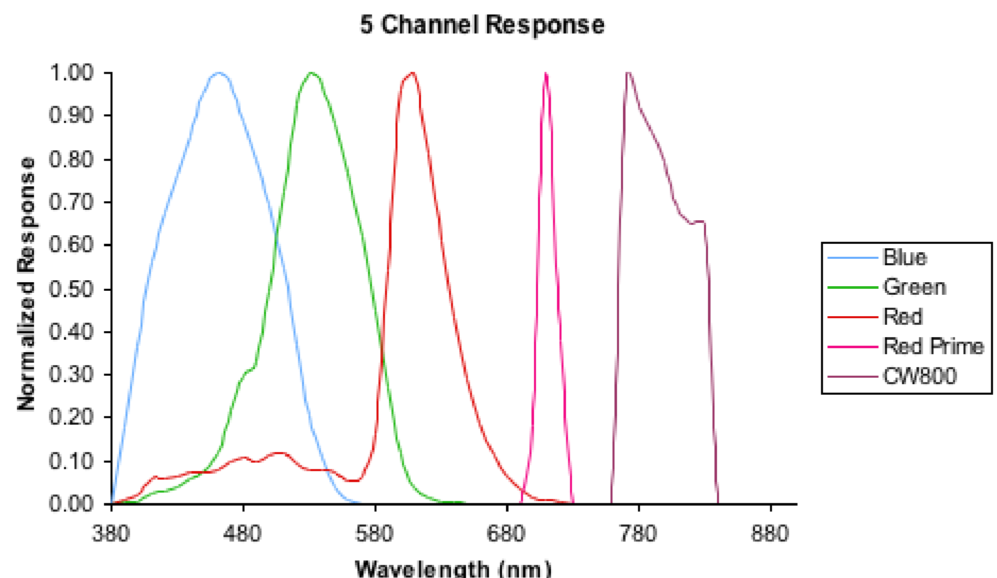
FluxData Incorporated

5. Multiple matrix sensors

The FluxData FD-1665 series of 3CCD cameras provides the advantage of 3 unique CCD cameras with a single lens. Users can select from FluxData's pre-configured **7, 5, or 3** channel camera or configure a custom 3CCD camera **with their own specified spectral bands**. The FD-1665 is offered in a range of resolutions from 1.4MP, 2MP and 5MP x 3CCD

The FD-1665 5 Channel Camera

The 5 channel FD-1665 is configured with one RGB bayer sensor and two monochrome sensor with any customer specified bands.



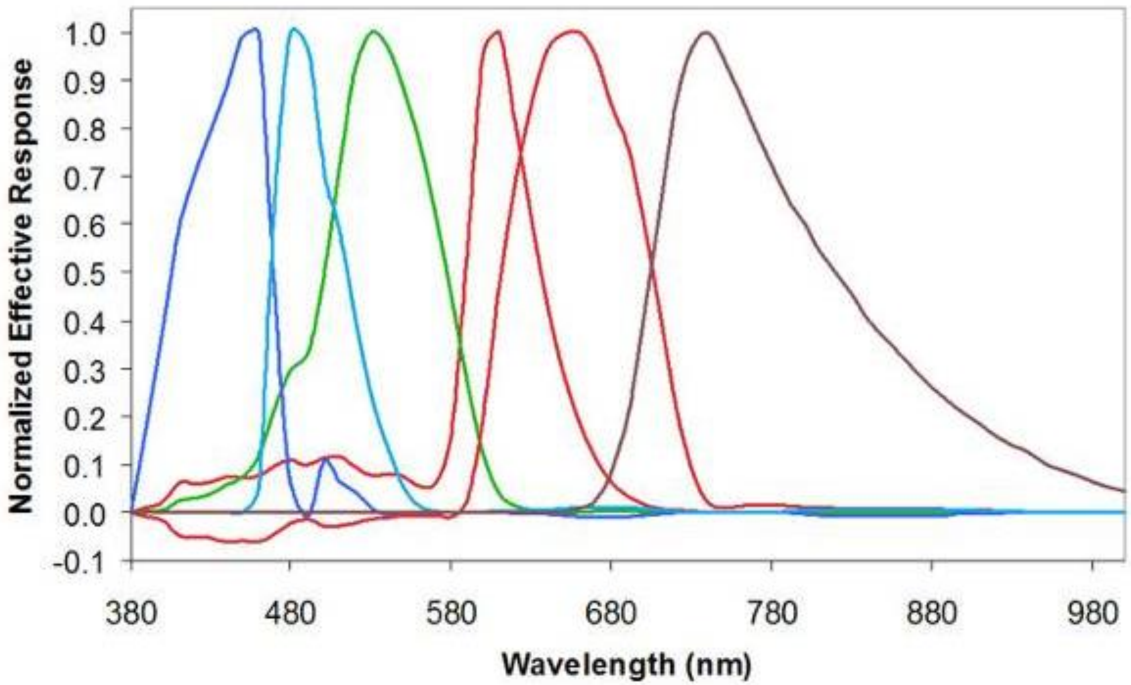
Classification based on the sensor type

5. Multiple matrix sensors

FluxData Incorporated

The FD-1665 7 Channel Camera

The preconfigured FD-1665 provides two color sensors with the second sensor having the RGB shifted. The combination of the two color imaging arrays provide for superior spectral color imaging. The third channel senses the Near Infrared Region (NIR) from 700-1000 nm. The NIR region can be used to discriminate different properties of materials i.e., defects, integrity, inconsistency, and detection of man made vs natural made materials.



Classification based on the sensor type

5. Multiple matrix sensors

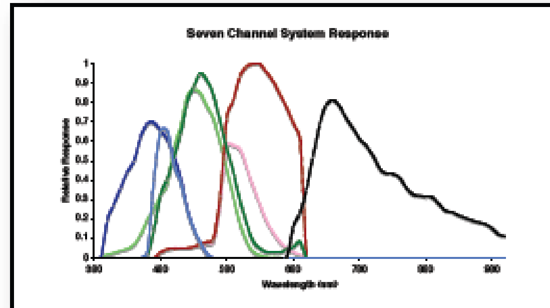
FluxData Incorporated

Specifications

Image Device	3 x 2/3-inch Interline Transfer CCD
Sensor Size	*See Table 1*
Pixel Size	*See Table 1*
Pixel Depth	12 bit ADC
Frame Rate	*See Table 1*
Image Data Format	Y8, Y16 (all models), RGB, YUV411, YUV422, YUV444, 8-Bit and 16-Bit raw Bayer data (color models)
Video Data Output	8,16 and 24 bit digital data
Digital Interface	3 x IEEE-1394a* (6 pin)
Lens Mount	Nikon F-Mount
Electronic Shutter	Automatic / manual / one-push modes, programmable via software 1µsec - 65sec
Gain Selection	0dB to 24dB in 0.04dB increments
General Purpose I/O Port	12-pin Hirose GPIO connector
External Trigger	Mode 0, 1, 2, 3, 4, 5,12,13, 14 and 15
Operating Temperature	0-40° C
Voltage Requirement	8-32V, via the IEEE-1394a interface or Hirose 12-pin GPIO connector trigger
Power Consumption	8VDC ~30VDC, 840mA 12V DC (10W)
Weight	1.8 kg

* 1394b Option Available July 2008

Example System Responses



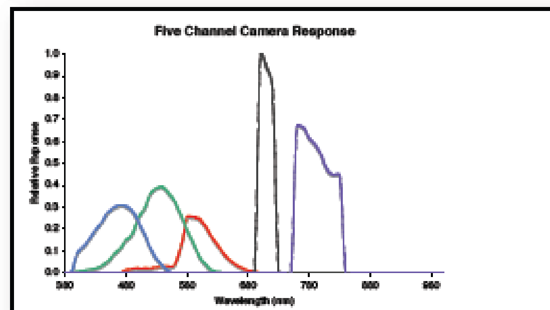


Table 1 - Sensor Options

	4.2 MegaPixel	6.0 MegaPixel	15 MegaPixel
Sensor	Sony ICX285 AL/AQ	Sony ICX274 AL/AQ	Sony ICX625 AL/AQ
Resolution	1384 x 1086	1624 x 1224	2448 x 2048
Pixel Pitch	6.45 micron	4.4 micron	3.45 micron
Frame Rate	20	16	15

Dimensions

Classification based on the sensor type

5. Multiple matrix sensors

- More than one sensor
- Light is splitted

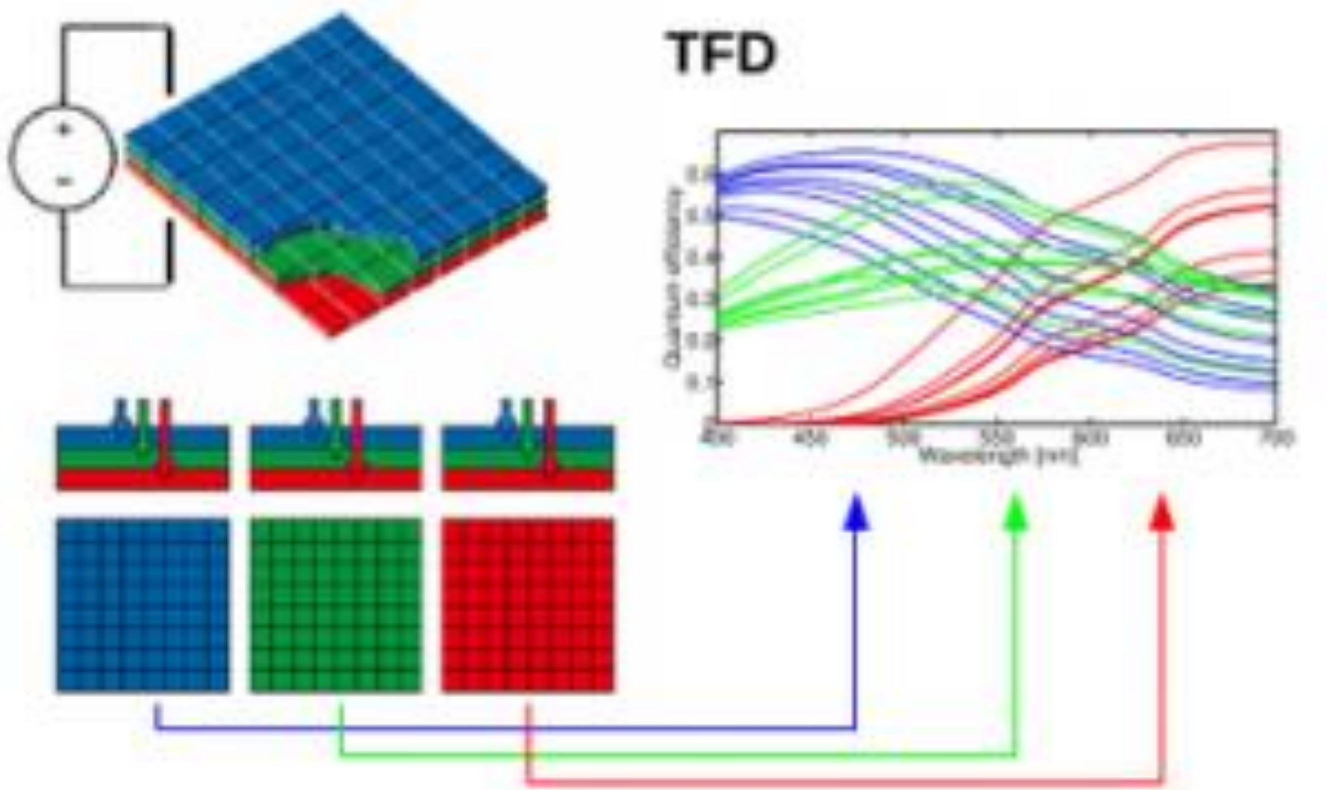
Theoretically nice

Very expensive
Complex
Heavy optics

Classification based on the sensor type

6. Tunable sensitivity matrix sensor

- TFD: Transverse Field Detectors
- "*Combining Transverse Field Detectors and Color Filter Arrays to improve multispectral imaging systems*", **Applied Optics**, vol. 53, N. 13, pp. C14-C24 (2014)



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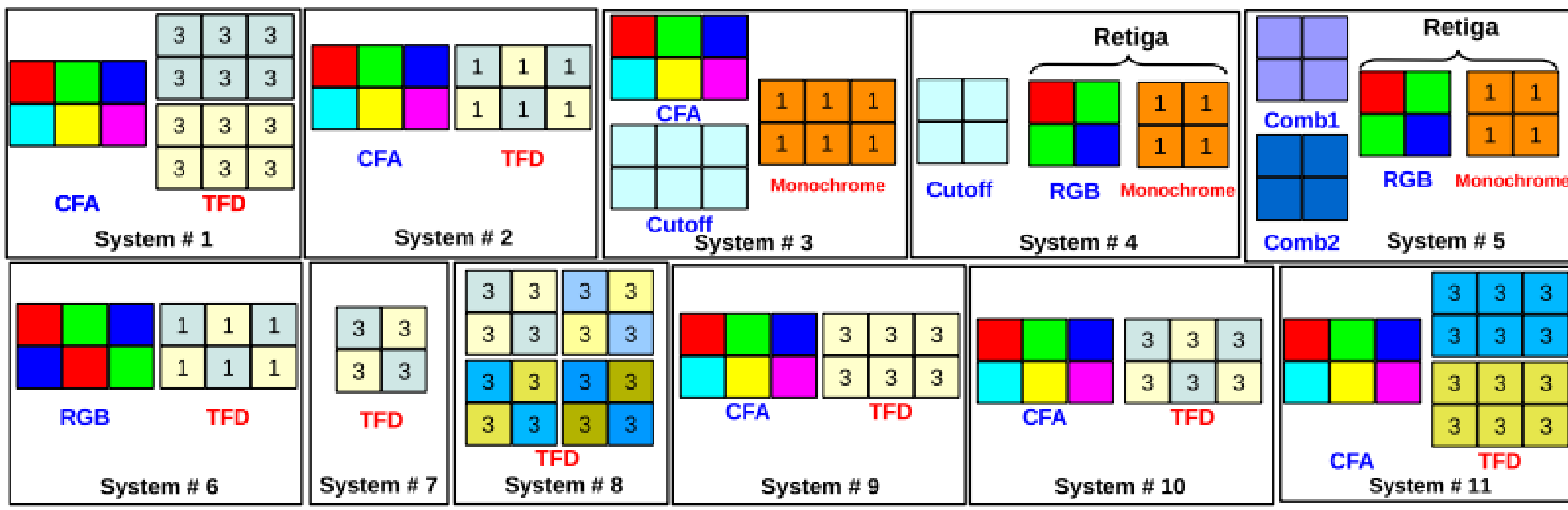


Fig. 1. Schemes for the 11 system configurations studied. Filter layer with blue caption, sensing layer with red caption. The number in each pixel determines the number of channels retrieved in one shot out of it.

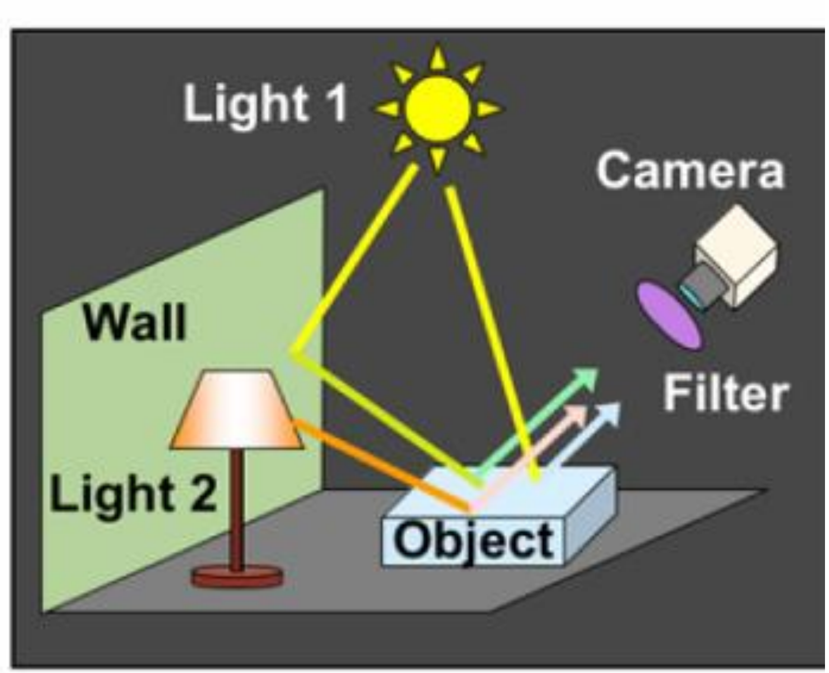
Classification based on types of illumination

1. **Passive illumination**
2. **Active illumination**

Classification based on types of illumination

1. Passive illumination

Single known light source to illuminate the scene during the acquisition process

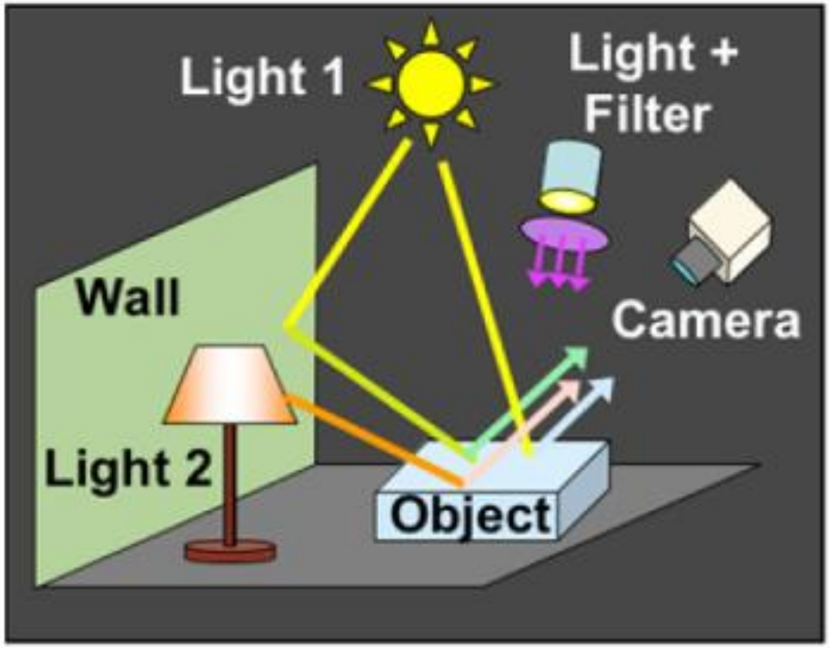


Classification based on types of illumination

2. Active illumination

Instead of separating the reflected light radiance, a number of narrow band illuminations in a certain wavelenght range is used.

Images are captured by illuminating the scene with each of these narrow band illuminations one at a time.



Classification based on types of illumination

2. Active illumination

Fig. 13 An hypothetical multi-flash system. The flash works in conjunction with the camera continuous shooting mode to capture three images, each with different added illumination

Multi-Spectral Imaging by Optimized Wide Band Illumination (2010), International Journal of Computer Vision

Cui Chi · Hyunjin Yoo · Moshe Ben-Ezra

Classification based on types of illumination

2. Active illumination

With laser sources:
Active spectral imaging, Melissa Nischan Rose Joseph Justin Libby, 2003, Rochester Institute of Technology

Classification based on types of illumination

2. Active illumination

With programmable light source

Spectral imaging with a programmable light source Tominaga, Shoji; Horiuchi, Takahiko; Kakinuma, Hirokazu; Kimachi, Akira Source: Color and Imaging Conference, 17th Color and Imaging Conference Final Program and Proceedings, pp. 133-138(6)

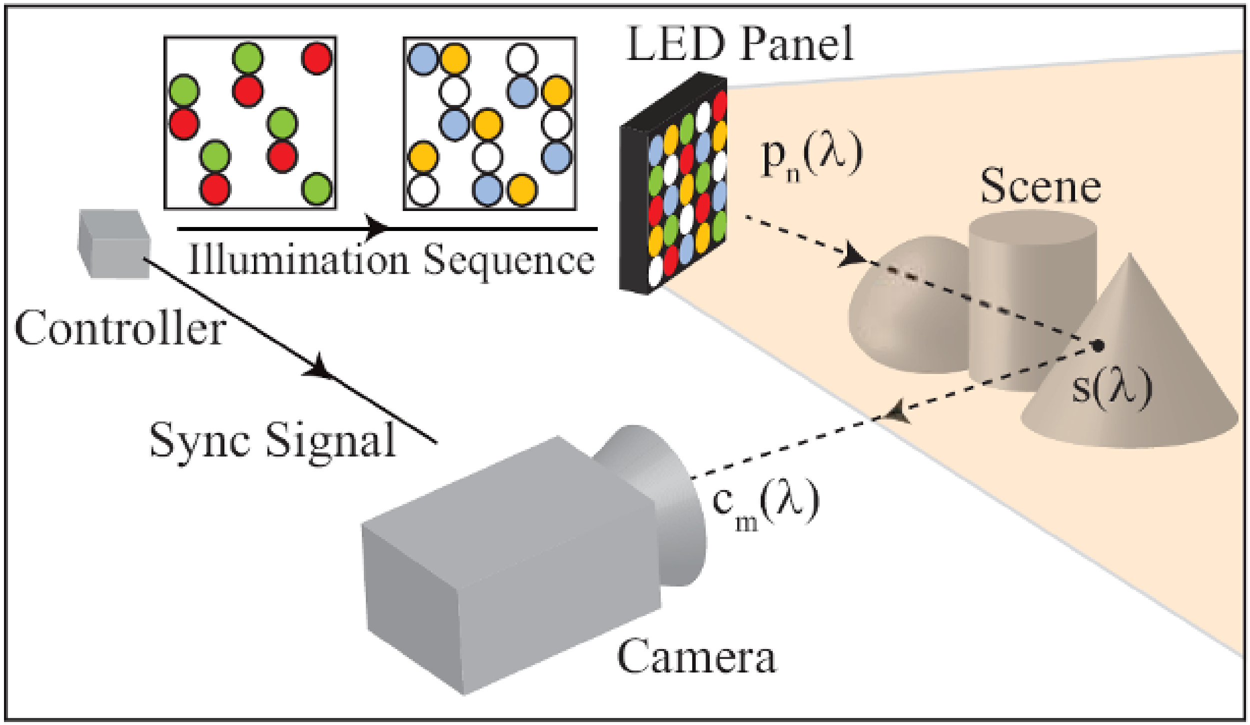
Classification based on types of illumination

2. Active illumination

LEDSI: LED illumination based spectral imaging

Multispectral Imaging Using Multiplexed Illumination (2007)
Jong-Il Park, Moon-Hyun Lee, Michael D. Grossberg, and Shree K. Nayar

The spectrum of the illumination can be modulated temporally, to provide a multispectral light source.



Classification based on types of illumination

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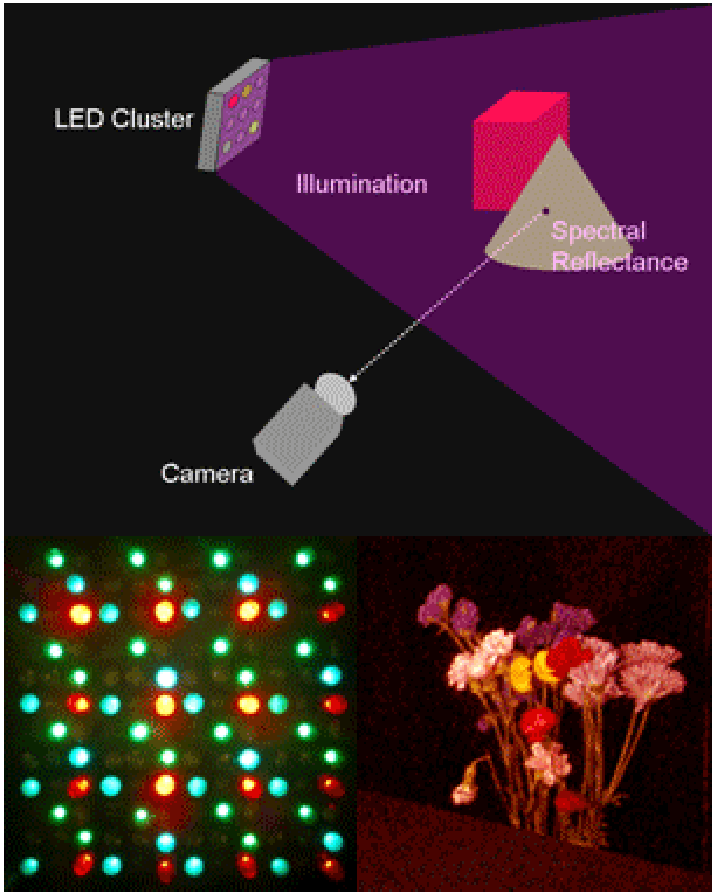
Multispectral Imaging Using Multiplexed Illumination (2007)

Jong-Il Park, Moon-Hyun Lee, Michael D. Grossberg, and Shree K. Nayar



Multispectral Imaging Using Multiplexed Illumination (2007) Park et al.
It is easier to create an illumination source with rapidly changing spectra than a camera with rapidly changing spectral sensitivity

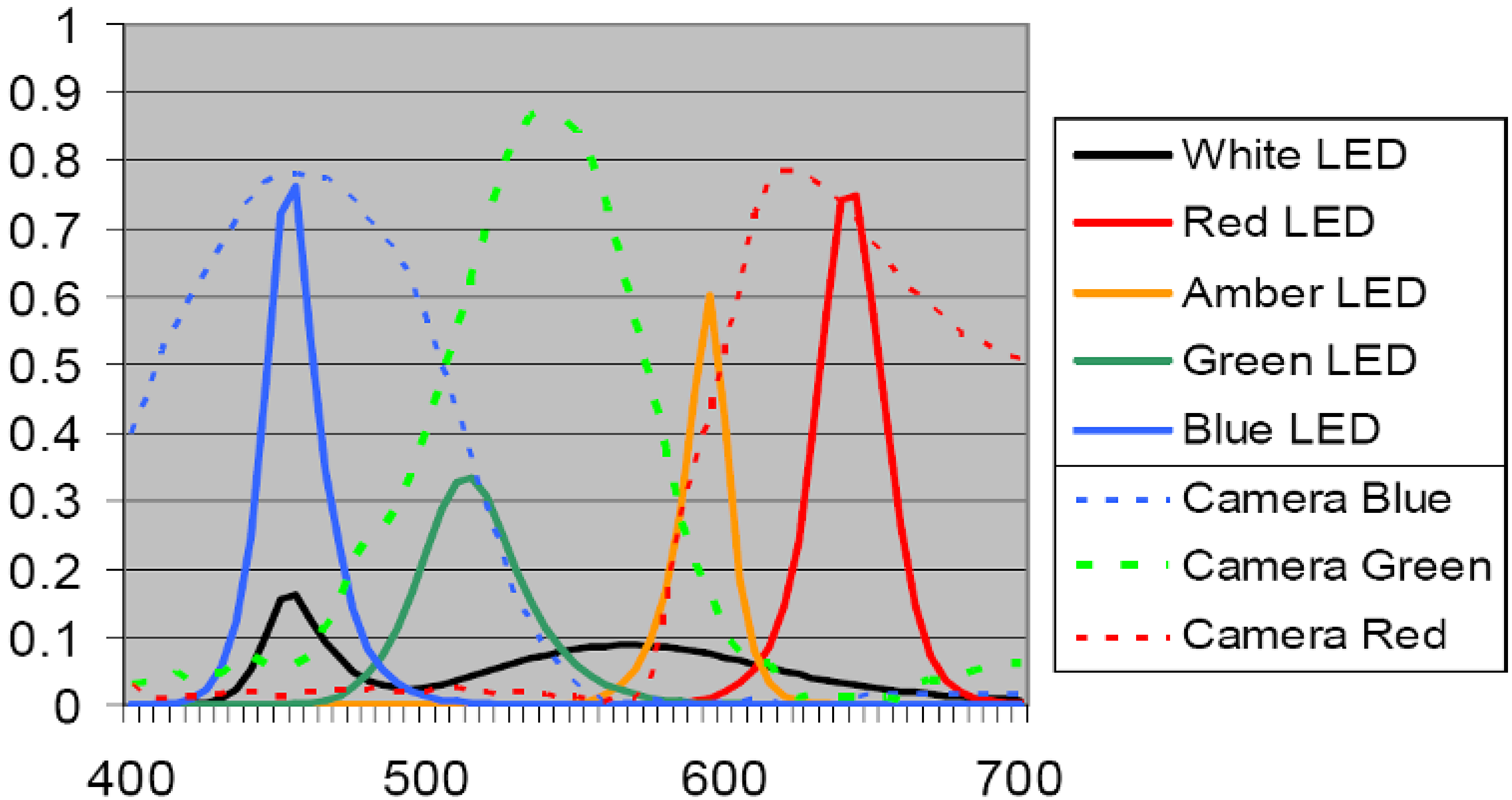


Figure 2. The spectra of the 5 types of LEDs (solid lines) and the spectral responses of the three color channels of the PointGrey Dragonfly Express camera (dashed lines) used in our system.

Multispectral Imaging Using Multiplexed Illumination (2007) Park et al.

M camera channels
N different illuminations → MxN effective channels

increases the number of independent measurements with a minor increase in system complexity

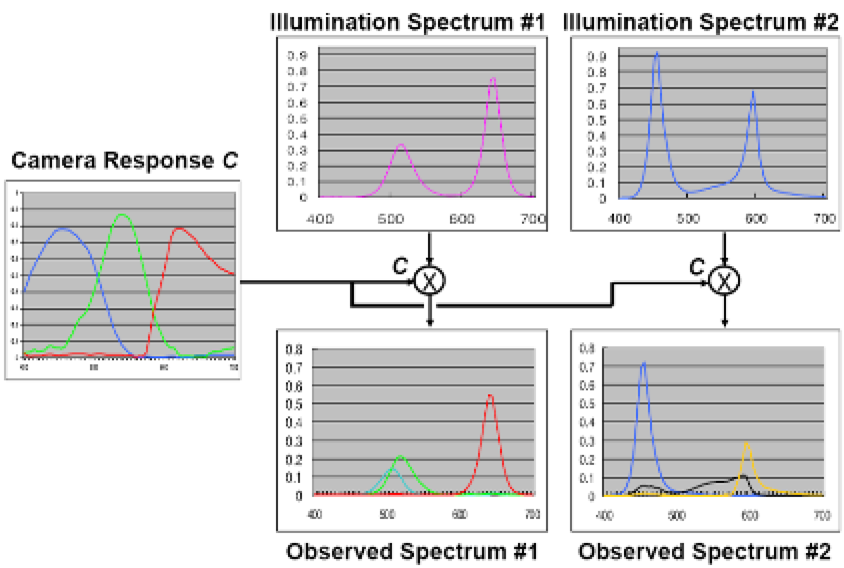


Figure 3. Spectra of an optimal pair of multiplexed illuminations and the corresponding spectra sensed by the color camera.

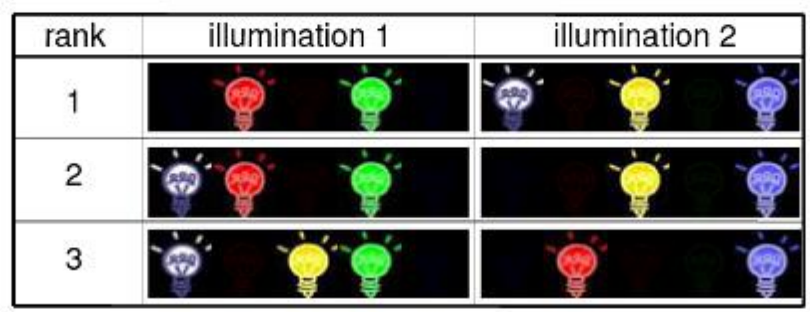


Figure 4. The highest ranking 2-frame multiplexed illuminations (using 5 types of LED sources) found by the optimization algorithm.

Multispectral Imaging Using Multiplexed Illumination (2007). Park et al.

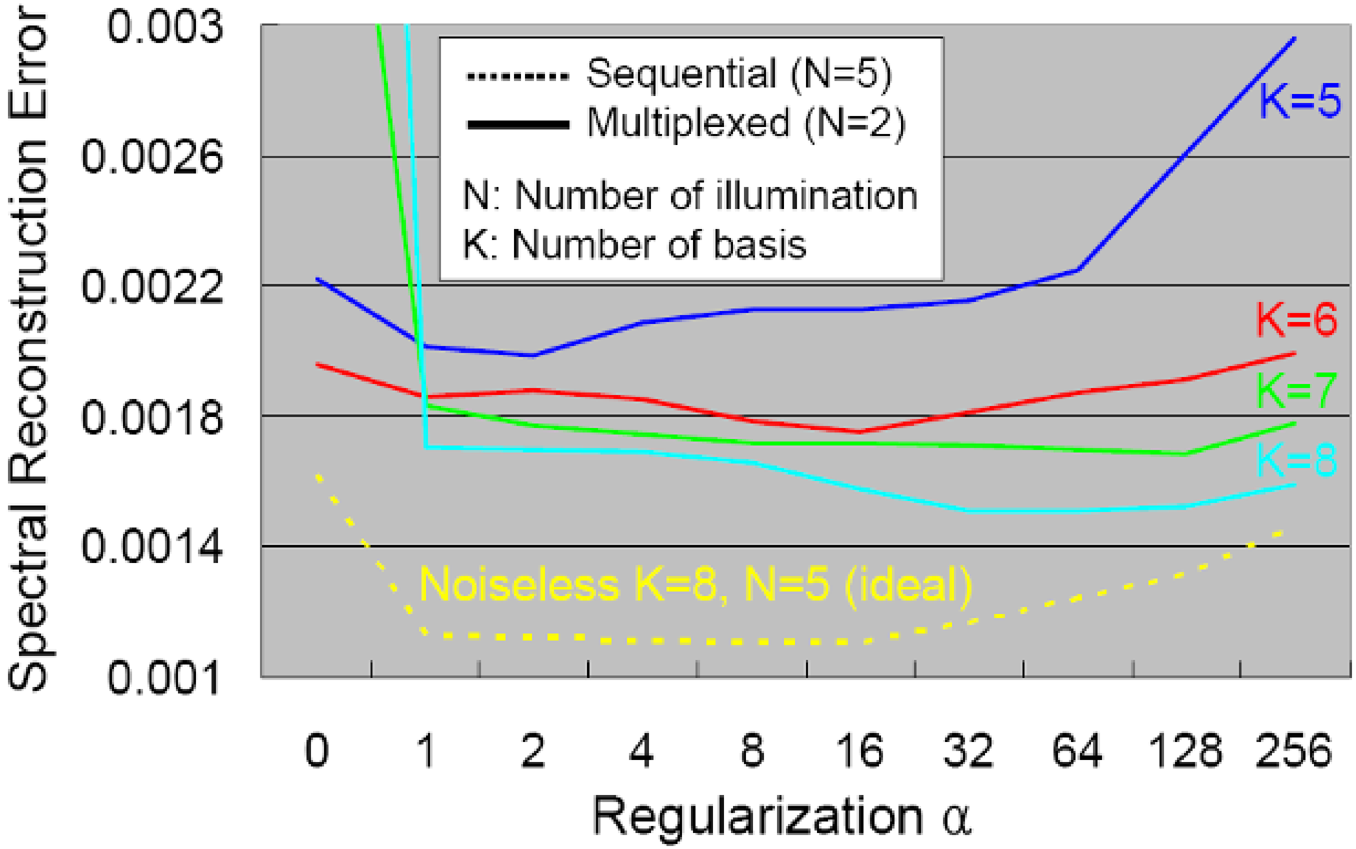


Figure 5. Simulation results that show how the spectral reconstruction error varies as a function of the smoothness parameter α, for different numbers K_s of basis functions. With just two multiplexed illuminations, we can get a spectral reconstruction error that is close to what can be achieved with sequential illumination and noiseless measurements (the lowest curve).

Multispectral Imaging Using Multiplexed Illumination (2007). Park et al.

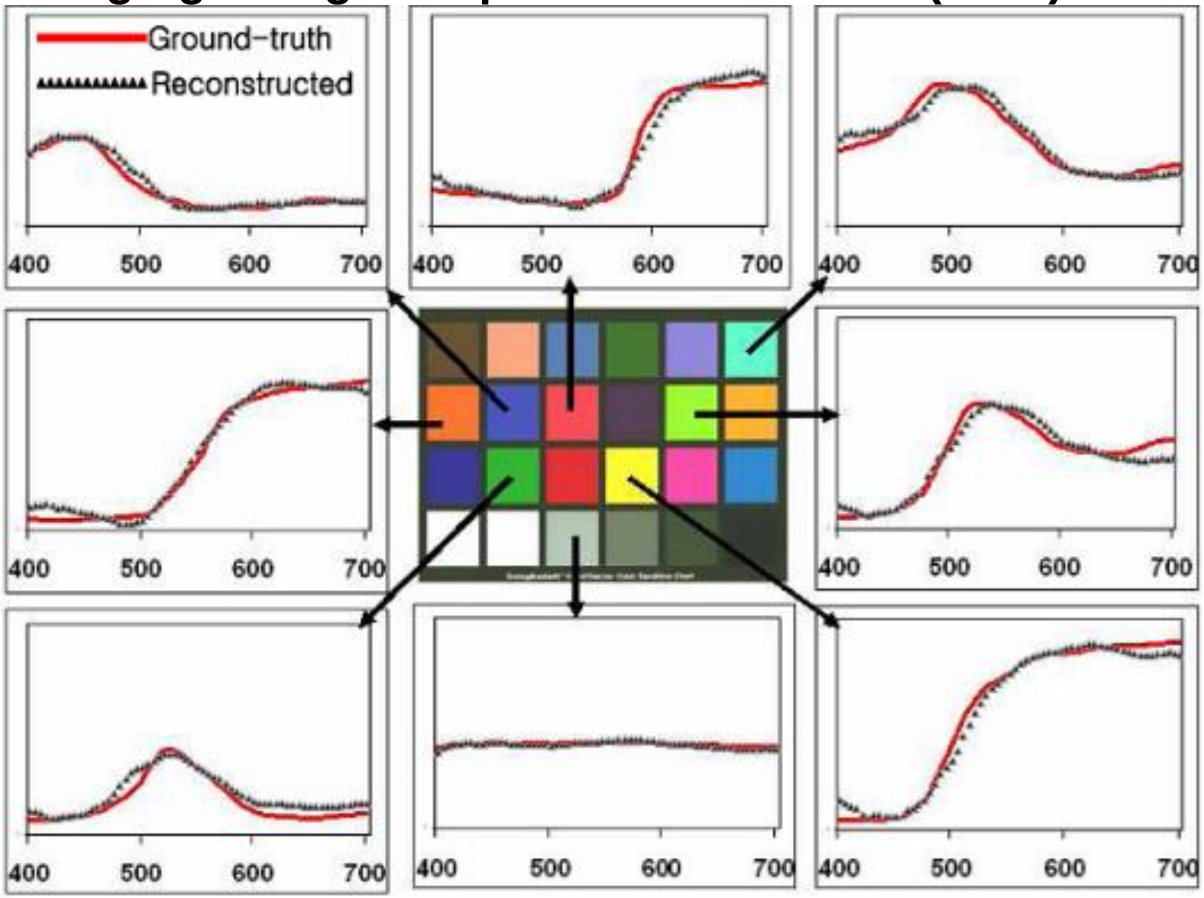


Figure 7. Spectral reflectances of color chips on the Macbeth chart measured using multiplexed illumination. The measured spectra are shown as dotted black lines and the actual spectra (ground truth) are shown as red solid lines.

There exist no methods for capturing multispectral videos in real time.

http://www.cs.columbia.edu/CAVE/projects/multispectral_imaging/

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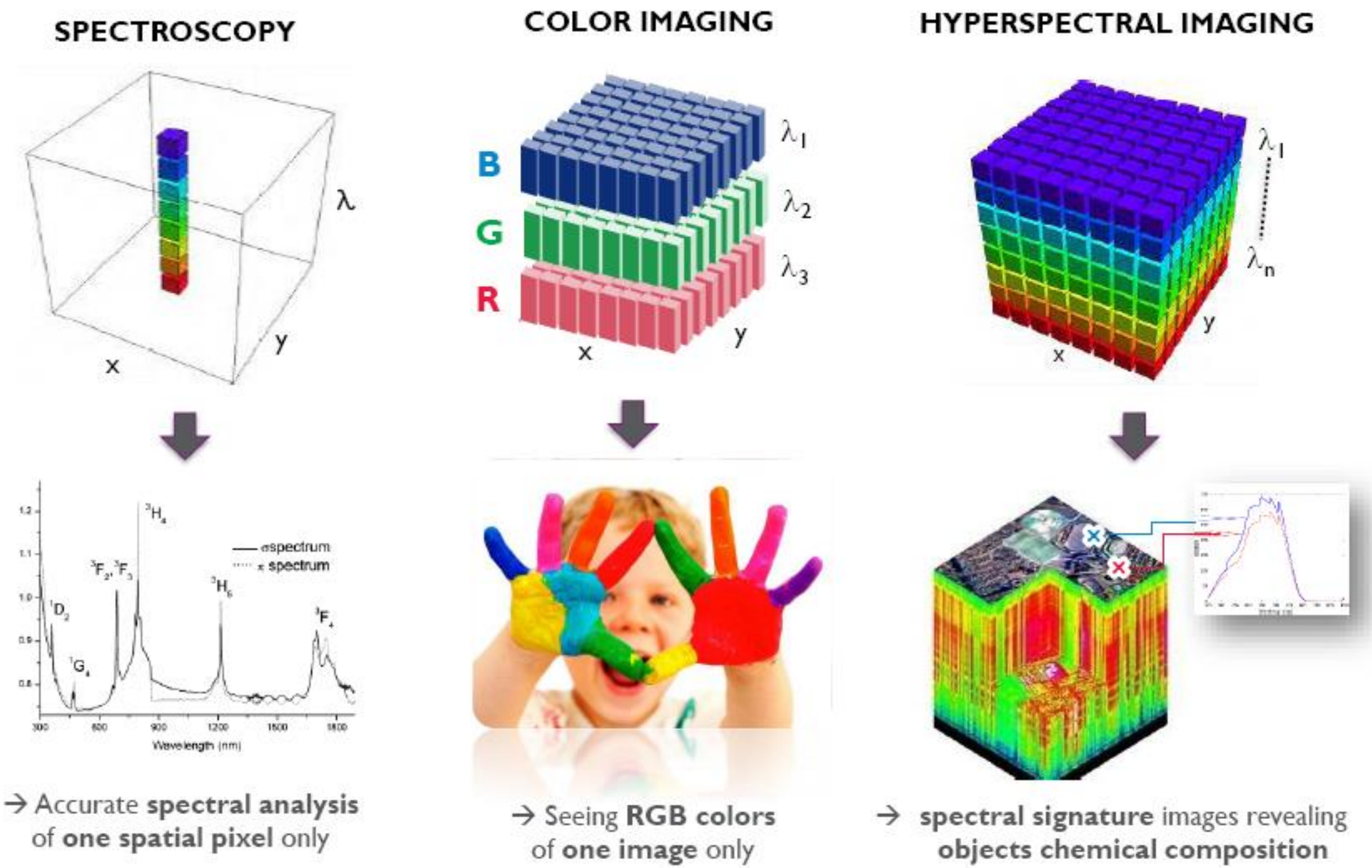

From www2.imec.be/be_en/home.html

Considerations for multispectral systems:

Considerations for multispectral systems:

a. Spectral range
b. Spectral resolution
c. Spatial resolution
d. Indoor / Outdoor
e. Illumination
f. Exposure time
g. Selection of sensors
h. Selection of optics
i. Selection of filters
j. Selection of training set
k. Selection algorithm
l. Calibration
m. Noise
n. Evaluation of quality
o. Budget
p. Etc, etc.…

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