Surveillance using Hyperspectral, LiDAR and Spectro-Polarimetric Data

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Challenges in Dynamic Imaging Data, Isaac Newton Institute, Cambridge, June 2015
2015 - UNESCO’s International Year of Light & Light Technologies

Overview of **3D, 4D Optical Imaging Data Modalities for Dynamic Surveillance**

1. **Hyperspectral Imaging (HSI)**
2. **Light Detection And Ranging (LiDAR), Fused HSI/LiDAR**
3. **Snapshot HSI and Spectro-Polarimetric Imaging (SPI) - Dynamic HSI and SPI**

Overview of **Projects for US NGA and AFOSR**

**Processing High Dimensional Data taken through Atmospheric Turbulence** - Challenges
Hyperspectral (2D spatial & 1D wavelength) and LiDAR (2D spatial & 1D range) Imaging

- Hyperspectral imaging (HSI) collects information across the visible and IR spectrum for interrogating scenes, wavelengths generally 400 to 2,500 nm. **HSI Video is 4D image tensor.**

- **LiDAR** measures distance by illuminating targets with a scanning laser and analyzing the reflected light. Laser wavelengths vary to suit the target: 5 nm to UV. Very short.

- Fused HSI and LiDAR for enhanced analysis. **Combined laser ranging & object material identification.**
Target placed in scene by sponsor
**Spectro-Polarimetric Imaging (SPI)**

- 3D hyperspectral & 1D polarization. Data is a 4D tensor.
- Spectral traces identify **materials**.
- Polarizations identify **object shapes, metallic surfaces**.
- **Object characterization using spectrally compressive polarimetric image data, funded by AFOSR grant to UNM (Physics), Duke (ECE) and WFU (Math & CS).** **Snapshot spectro-polarimetric cameras** developed at Duke.
- **Snapshot SPI “video” creates a 5D image data tensor.**
Electromagnetic radiation: energy in the form of electromagnetic waves.

Electromagnetic spectrum: the entire family of electromagnetic radiation.

Figure 1: $\lambda$ generally ranges between 400 and 2500 nanometers.
Different materials produce different electromagnetic radiation spectra.

After adjusting for sensor, atmospheric, and terrain effects.
Extract Spectral Signatures (Traces) from HSI to Identify Materials

Figure 2: Illustration High Resolution - Each pixel represents a vector
Some Applications of Hyperspectral Imaging (HSI)

- Environmental remote sensing, e.g., monitoring chemical/oil spills and gas plumes (HSI video)
- Military target discrimination
- Astrophysics
- Sensing for agriculture & food quality and safety
- Biomedical optics, medical microscopy, etc.
- Disaster relief, land/water management
- Tracking and identifying people (HSI video)
- Remote surveillance for defense & security, e.g., imaging a compound in western Pakistan
Recent Remote Sensing Work

NGA Project

- National Geospatial-Intelligence Agency (NGA) Funded Project “Compressive Sensing and Fusion of LiDAR and Hyperspectral Data using Tensor Factorizations”. Boeing and Wake Forest 2011-2013

Hyperspectral

LiDAR
Figure 3: Warfighter NGA application
NGA HSI/LiDAR Project

- Clustering and classification of fused data, and **information-theoretic results**, detecting objects in shadows, etc.
- **3D object shape recognition** for identification and tracking, differentiate people from background.

NGA Campus, near DC
Proposed WFU Project for NGA - Academic Research Program

“Geometric Representation, Processing and Information Optimized Fusion of LiDAR, HSI and Polarimetric Data”

- HSI
- LiDAR
- Polarimetry

Deblurring & Sparse Unmixing → Scale Space 3D Representation → Projection to 2D Image Plane → Target identification

Keypoint Detection & Feature Description → Selective Visualization

Mesh Registration → Scale Invariant target identification

3D Regular Grammars for Shape Retrieval → Bayesian Classification
AFOSR Project

- **Air Force (AFOSR) Funded Project**

**Space Object Identification with Spectral Imagers**

Analysis of reflectance.

*Figure*: Reflectance of an object pixel results from additive reflectance of its constitutive elements.
Figure 4: Application: Satellites & Large Debris Objects Around Earth. (About 1000 active satellites to maintain, 5% of space objects to monitor - international cooperation, huge expenditures)
Current DOD/NASA Imaging of Space Objects

- Current “operational” capability for spectral imaging of space objects – imaging and non-imaging

- Panchromatic images

- Non-imaging spectra

Figure 5: Space object identification.
Space Situational Awareness (SSA) by Monitoring Space Objects

- ‘Listen’ (laser enabled vibrometry)
- ‘Smell’ (chemical sensing with spectral imaging)
- ‘Touch’ (scatterometry/polarimetry for surface texture information)
- ‘See’ (by sequential speckle <video> imaging)
- ‘Object Laser Ranging’ (Ground based LiDAR)
- ‘Characterize Materials’ for SOI (hyperspectral imaging) (polarimetric imaging)

Figure 6: Methods for monitoring space objects (satellites).
• “Statistical Image Analysis and Applications to High Dimensional Imaging for Improved SSA,” 2015 - 2018.

• To develop algorithms and statistical performance metrics as design tools for range-integrated high dimensional object tracking systems.

A US Air Force Observatory on Haleakala in Maui
Turbulence

Image contains sketch by Leonardo da Vinci, along with a remarkably modern description: “the smallest eddies are almost numberless, and large things are rotated only by large eddies and not by small ones.” Called phenomena “turbolenza”, leading to modern word turbulence.
Atmospheric Turbulence

Later, Galileo, 1564-1642, knew effects of atmospheric turbulence on telescopes. Modern mathematical models developed by:

(a) Th. von Karman, 1881-1963  
(b) Andrey Kolmogorov, 1903-1987
Tracking Objects Using “Snapshot” Spectro-Polarimetric Imaging (Snapshot SPI)

- Compressive Sensing from Snapshot HSI-Polarization Imaging
- Prototype polarimetric coded aperture snapshot spectral camera designed at Duke in AFOSR project joint with: D. Brady (ECE, Duke), S. Prasad (Physics, UNM).
- Prototype polarimetric spatial light modulator (SLM) snapshot spectro-polarimetric camera.

HSI and 4 polarization channels. All the PSFs are wavelength and diffraction blur dependent.

- Data reconstruction and joint deblurring for removing atmospheric turbulence, as well as feature extraction.
How HSI works

Dispersion of light through a prism

Spectrum divided into discrete bands

Record the intensity values for each band

Spectrum Band Intensity Values
Figure 8: There are numerous ways to capture HSI, almost all of which are temporal. **However,** new snapshot imagers provide method of capturing hyperspectral images during a single integration time of a detector array.
Coded Aperture Snapshot Spectral Compressive Sensor

\[ g(x, y) = \int_{\lambda} C_\lambda(x, y)f(x, y, \lambda)d\lambda + \epsilon_\lambda(x, y). \]

- Dave Brady et al., Duke U., part of AFOSR SOI project.
Spectro-Polarimetric Compressive Sensing - Enables HSI Video Imaging

• Spatial Light Modulator (SLM)-based - snapshot spectro-polarimetric imager forward model.

\[ g(x, y) = \int_\lambda C_\mu(x, y, \lambda)[h(x, y, \lambda) \ast f_\mu(x, y, \lambda)]d\lambda + \epsilon_{\lambda,\mu}(x, y). \]

\( C = \) system function, \( \mu = \) linear polarization variable, \( \lambda = \) wavelength, \( h = \) PSF system function, solve inverse problem for \( f \).

• Applied to surveillance through atmospheric turbulence, as part of UNM, Duke, WFU project.


Spatial Light Modulator (SLM)-Based Imaging

Segmentation model:

\[ f(x, y, \lambda) = \sum_{i=1}^{m} s_i(\lambda)u_i(x, y). \]

Resulting system forward model:

\[ g(x, y) = \int_{\lambda} C_\lambda(x, y)[h^\phi(x, y) * \sum_{i=1}^{m} s_i(\lambda)u_i(x, y)]d\lambda + \epsilon_\lambda(x, y). \]

Knowns: coded, blurred image \( g \), and imaging system operator \( C \).

Unknowns: phase function \( \phi \) (in terms of the OPD), spectral signatures \( s_i \), and support functions, \( u_i \).

Approach: estimate the optical path difference function (OPD) first using a HSI of a laser guide star, then classify features of object.
• Assume the OPD is known as the estimated $\hat{\phi}$ from Berisha, Nagy, Ple. 2015 so each PSF $h_\lambda$ is available. We estimate support functions $u_i$ and spectral signatures $s_i$.

$$J(u, s) = \frac{1}{2} \left\| \int_\lambda C_\lambda(x, y) \left[ h_\lambda(x, y) \ast \sum_{i=1}^m s_i(\lambda)u_i(x, y) \right] - g(x, y) \right\|_2^2$$

$$+ \alpha \sum_{i=1}^m \int_{\mathbb{R}^2} \sqrt{\nabla^2_x x_i + \nabla^2_y y_i} + \frac{\beta}{2} \sum_{i=1}^m \int_\lambda \|s_i(\lambda)\|_2^2,$$

where we use total variation regularization for $u_i$ and Tikhonov for spectral signatures $s_i$.

• Solve inverse problem for $u_i, s_i$ using ADMM.
Sample Test Results by Duke graduate student TH Tsai

Schematic of compressive snapshot SPI

- Spatial light modulator (SLM) is from Holoeye Photonics and uses a liquid-crystal-on-silicon modulator.
System modulates 4D tensor array images onto a 2D detector (matrix). Reconstruct 4 linearly polarized images.
(a) Unpolarized reference in RGB.
(b) Compressed spectro-polarimetric measurement.
(c) - (f) Reference polarized image channels in RGB.
(g) - (j) Reconstructions from (b), pseudo color.
Atmospheric Turbulence Effect on Optical Images

Recent video: The Unexpected Math behind Van Gogh’s “Starry Night” by Natalya St. Clair: http://youtu.be/PMerSm2ToFY

- Variations in the index of refraction cause the plane optical wavefront from objects to be distorted. Caused by variation of air temperature in eddies and air currents.
- In surveillance for space situational awareness, resolution of all ground-based telescopes is severely limited by turbulence.
- Can also cause extreme blurring in ground-level (horizontal) imaging.
Imaging Through Atmospheric Turbulence - Estimating a PSF for Deconvolution

- Ground-level turbulence - video imaging illustration 1km distance.

(a) Image taken in early morning
(b) Afternoon image through turbulence.

Active research topic: e.g., Zhu and Milanfar, 2012-13. Lou, Kang, Soatto, Bertozzi, 2013. Others ...

Methods generally based on selecting “lucky frames”, patches, image registration, fusion, segmentation etc.
Figure 9: Space object imaging from AFOSR Project
Atmospheric Turbulence

Galileo, 1564-1642, knew effects of atmospheric turbulence on telescopes. Modern mathematical models developed by:

(a) Th. von Karman, 1881-1963  (b) Andrey Kolmogorov, 1903-1987
German physicist Ernst Abbe realized the resolution of an imaging instrument is constrained by the wavelength of light used, and the aperture of its optics.

Resolution (detail an image holds) is proportional to the size of its aperture, and inversely proportional to the wavelength of the light being observed: $\text{Res} \approx \frac{d}{\lambda}$. - opposite to the effect of atmospheric turbulence. Resolution also affected by blur & noise.

We estimate wavelength dependent PSFs for HSI.
Imaging Through Atmospheric Turbulence - Estimating a PSF, or PSFs, for Deconvolution


AMOS sensors can collect simultaneously from visible to LWIR.

Berisha, Nagy, Plemmons 2015. Others ... Methods based on gradient & phase estimation leading to a PSF, turbulence modeling.
The image acquired at wavelength $\lambda$ can be represented as

$$g_\lambda(x, y) = h_\lambda(x, y; \phi) \ast f(x, y, \lambda) + \epsilon_\lambda(x, y),$$

where the blurring kernel, with diffractive scaling included, is

$$h_\lambda(x, y; \phi) = \left(\frac{\lambda_0}{\lambda}\right)^2 h_0\left(\frac{\lambda_0}{\lambda}x, \frac{\lambda_0}{\lambda}y; \phi\right),$$

with $\lambda_0 =$ reference baseline wavelength, and

$$h_0(x, y; \phi) = \left|\mathcal{F}^{-1}\left(pe^{i\phi}\right)\right|^2,$$

and where the wavefront phase $\phi = \frac{2\pi}{\lambda} \times \text{OPD}$. 

- **OPD** is the optical path difference function, i.e. the optical phase shift in passage through turbulent atmosphere.
HSI Unmixing/Deblurring: Wavelength Dependent PSFs

Solve the deblurring and sparse hyperspectral unmixing inverse problem of the form

\[
\min_{X \geq 0} \frac{1}{2} \| HXM - G \|_F^2 + \mu_1 \| X \|_1 + \mu_2 \text{TV}(X)
\]

- \( H \in \mathbb{R}^{N_p \times N_p} \) is a block diagonal PSF system matrix, with blocks \( h_\lambda \) constructed using HSI image of laser guide star.
- \( \mu_1, \mu_2 \) are two regularization terms used to control the importance of the sparsity and total variation. ADMM applied to compute \( X \).


Figure 11: Space object imaging - HST image wavelength 575 nm.
### Test Results: Simulated Data for HST Satellite - Materials from NASA Database

<table>
<thead>
<tr>
<th>Material</th>
<th>Color</th>
<th>Constituent Endmembers</th>
<th>Frac. Abun. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material 1</td>
<td>green</td>
<td>Aluminum</td>
<td>37</td>
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<tr>
<td>Material 2</td>
<td>light grey</td>
<td>black rubber edge</td>
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<tr>
<td>Material 3</td>
<td>red</td>
<td>copper stripping</td>
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<td>dark gray</td>
<td>honeycomb side</td>
<td>4</td>
</tr>
<tr>
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<td>bolts</td>
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<tr>
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<td>solar cell</td>
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</tr>
<tr>
<td>Material 7</td>
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<td>glue</td>
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<tr>
<td>Material 8</td>
<td>white</td>
<td>Hubble honeycomb top</td>
<td>7</td>
</tr>
</tbody>
</table>
Blurred - von Karman Model for At. Turb., SNR 20
Some Reconstructed Fractional Abundance Maps
Some Reconstructed Material Spectral Signatures

True material spectral signatures: − Computed spectral signatures: −.
Overview of optical imaging data modalities for dynamic surveillance.

Overview of our projects - NGA & AFOSR, recent and new.

Compressive snapshot HSI - enables HSI video for object tracking and identification.

SLM-based spectro-polarimetric imaging - Adds polarization channels useful in identifying object shape and surface properties.

Prototype camera systems and test results.

Topics in Current Work

- Mathematical design tools for range-integrated high-dimension object tracking systems, including 3D, 4D imaging using rotating HSI PSFs, dynamic surveillance for current Air Force (AFOSR) project.

- LiDAR, HSI and polarimetric imaging surveillance technologies, with video. Proposed National Geospatial-Intelligence Agency (NGA) Project.

Final thoughts, inspired by Sigfried Russwurm at Siemens. “We might keep in mind that it’s not always data volume but the content and algorithms for processing data that are crucial.”
Thank You!

Papers available at: http://users.wfu.edu/plemmons/