Compressive Multi-Mission Electro-Optical Sensor System

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Outline

- **Incentives & General Approach**
- **Design and Implementation**
- **Sensor System Demonstration**
- **Conclusion Remarks**
- **Acknowledgements**

Motivation & Approach

▪ Motivation

Compressive multispectral and hyperspectral sensor system that is adaptive to configure operational sensing parameters like spatial, spectral and temporal resolution on the fly to enable multi-mission capability.

▪ Technical Approach

- HS sensing: via a spectrometer with a 1-D linear sensor
- Grayscale/MS sensing: processing the HS data & integrating all spectral data into one or selected few image frames
- Spectral fovea: via post HS data processing
- Spatial fovea: high resolution measurements, down-sampling to create foveal pattern followed by reconstruction
- MS sensing (complementary): a 2-D sensor for ROI selection

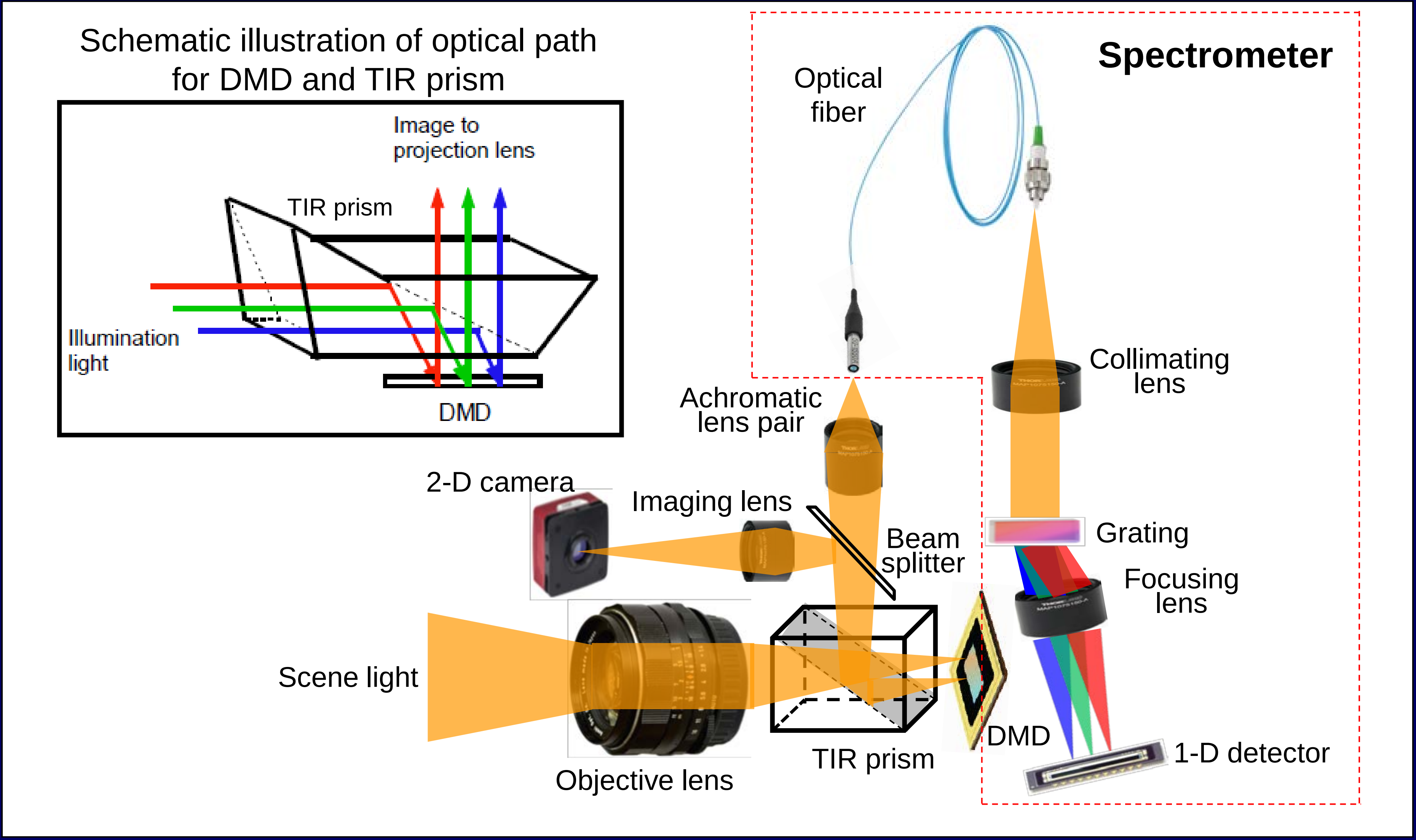
Design & Implementation

Design Specs:

Parameter	Target	Achieved	Remarks
Spectrum (nm)	*400 - 850*	400 - 850	Limited by Spectrometer FX
Spatial resolution	*1x1* to *1024x1024*	*1x1* to *1024x1024*	Spatial foveal; limited by DMD/STOne
Spectral resolution (nm)	*0.8 - 450 nm*	*0.8 - 450 nm*	Spectral foveal; limited by slit width and sensitivity of silicon detector
Frame rate (fps)	*30*	< *30*	
Field of view (deg)	*12.6 x 12.6*	*12.6 x 12.6*	Not optimized
Size (Inch)	12”x8”x8”	12”x8”x8”	Excluding PC
Weight (Lb)	*~2*	*~2*	Excluding PC
Power consumption (W)	≤ *55*	≤ *55*	Excluding PC

Design & Implementation

Hardware Layout:



Design & Implementation

Hardware Description:

•Objective lens (50mm F1.4) collects & focuses broadband scene light on DMD for spatial coding

•The spatially coded light from DMD is fed into the spectrometer optical fiber

•The grating in spectrometer disperses the coded broadband light into spectrally distributed sub-beams

•The sub-beams are detected by the 1D linear array

•The detector output pins are registered to corresponding λs

•The data from the detector pins are then reconstructed to generate 4D HS imagery set (x-y-λ-t)

•The complementary 2-D camera for wide area monitoring

Design & Implementation

Hardware Selection:

- Objective lens: Asahi Pentax Super Takumar 50mm F1.4 lens
- DMD: DLi V9501

Key Features	DLi V9501	Key Features	DLi V9501
Micromirror Array Size	1920 x 1080	Layout	XY Grid
Micromirror Array Diagonal (inch)	0.95	On Board Memory	8 GB DDR3
Micromirror Pixel Pitch (μm)	10.8	Binary Pattern Storage	31,086
Maximum Binary Pattern/Second	17,857	Controller Interface	USB 3.0
Micromirror Tilt Angle (degrees)	+/-12	Window Coating	VIS/UV

- Spectrometer: Ocean-FX

Spectral coverage (nm):	350 - 850
Detector:	1x2048
Spectral resolution (nm):	0.8 (5 μm slit)
Scan rate (Hz):	4,500
Slit (μm):	50, 100, 200, 600 (no slit)

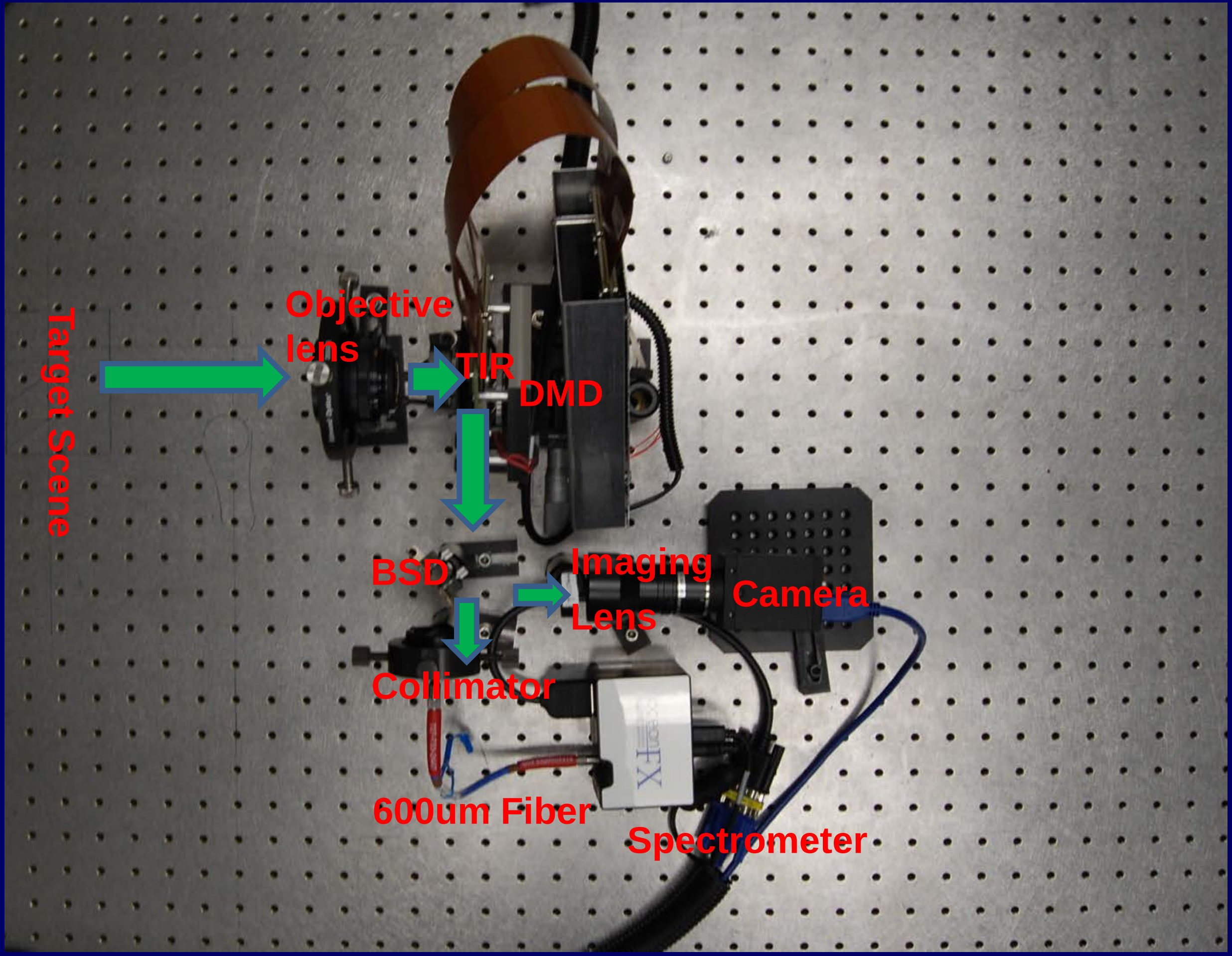
Sensor Demonstration

- Sensor Setup

  Right photo

- Illumination:

  Up to 81k Lux

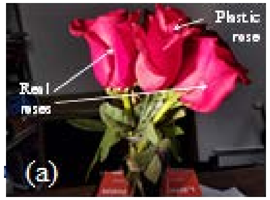


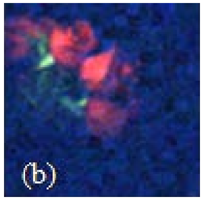
Sensor Demonstration

MS (Grayscale) & HS Sensing:

- One Measurement of Full Spectral Resolution
  - *Measurement condition:* 24,200 Lux illumination level, 300Hz DMD frame rate, 100% sampling rate, 64x64 pixel format

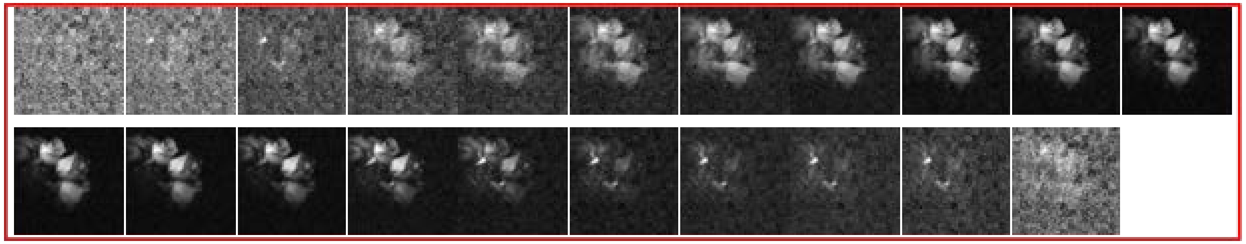
Photo picture of the rose bundle with plastic and real roses





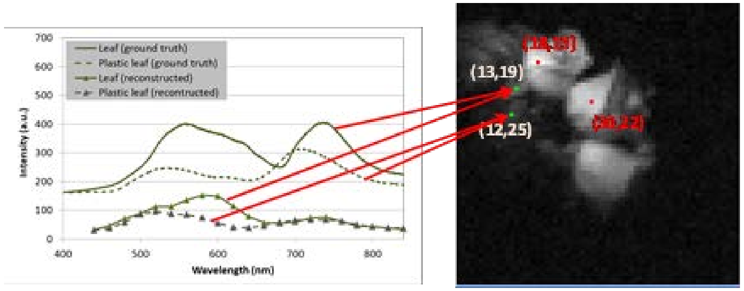
Restored color picture from the hyperspectral image frames based on CIE 1931 color space

440 nm 460 nm 480 nm 500 nm 520 nm 540 nm 560 nm 580 nm 600 nm 620 nm 640 nm

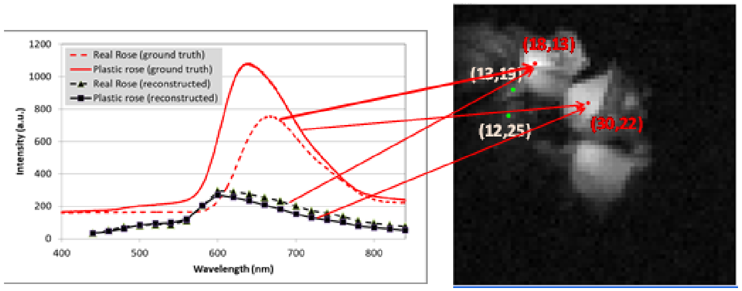


660 nm 680 nm 700 nm 720 nm 740 nm 760 nm 780 nm 800 nm 820 nm 840 nm

Reconstructed HS images of the rose bundle



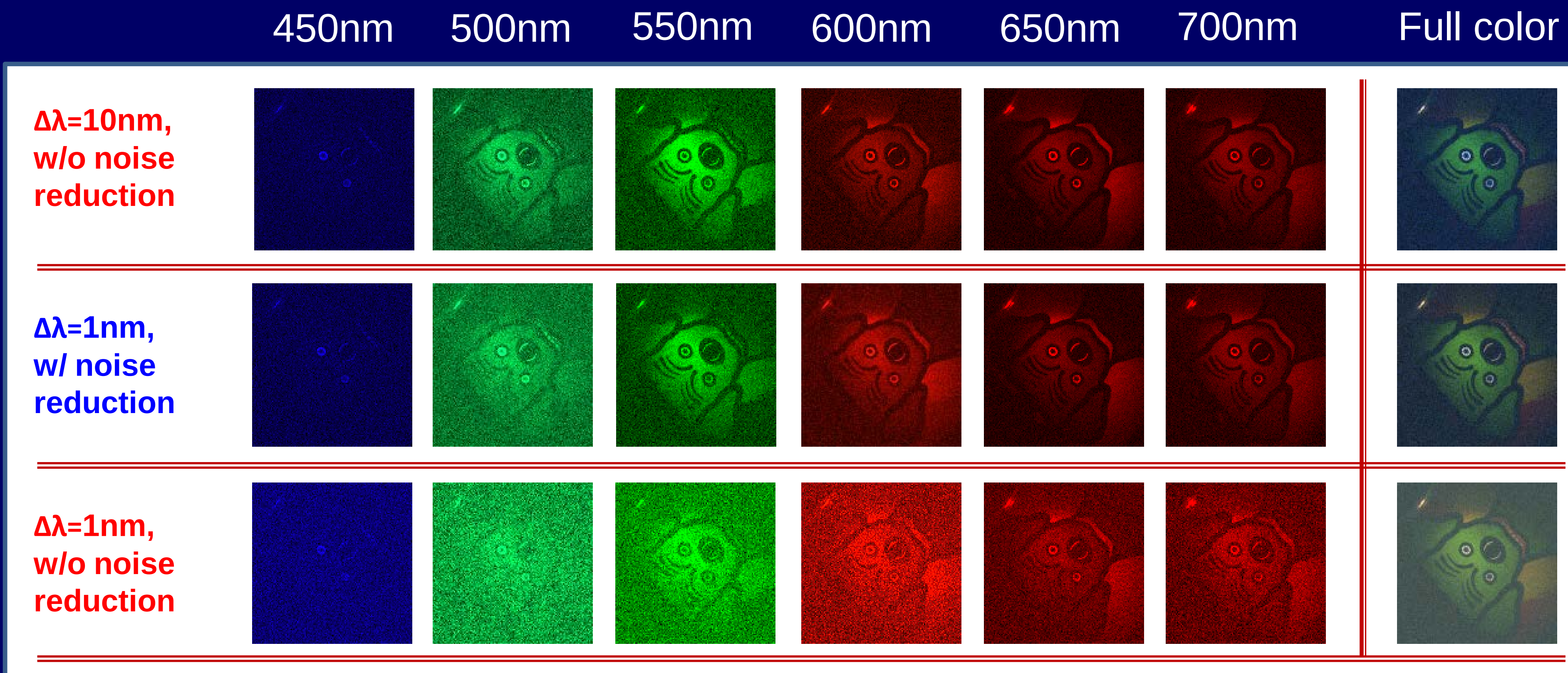
Comparison of spectra of real & plastic leave



Comparison of spectra of real & plastic rose

Sensor Demonstration

HS Reconstruction Image With Various Spectral Band Process



Target captured by Nikon D40
Visible Camera (cropped for comparison purpose)

Sensor Demonstration

HS Reconstruction Image With Various Spectral Band Process

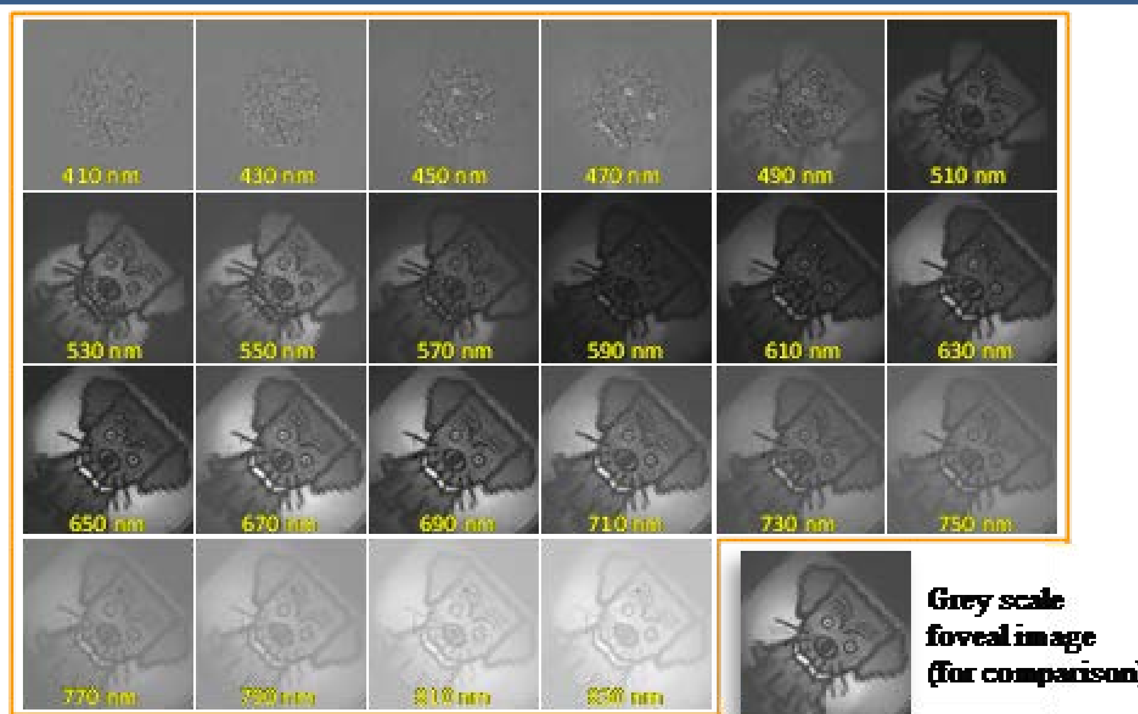
Noise reduction approach: at one λi, average its intensity **I**(λi) over a spectral interval of +/- $\Delta\lambda$ around λi to yield an averaged intensity <**I**>(λi) to replace **I**($\lambda\iota$)

Data acquisition parameters: 24,200 LUX illumination; 500 Hz DMD frame rate; Ocean Optics FX spectrometer; Slit = 100 μm;

Sensor Demonstration

Spatial Foveal HS Imaging

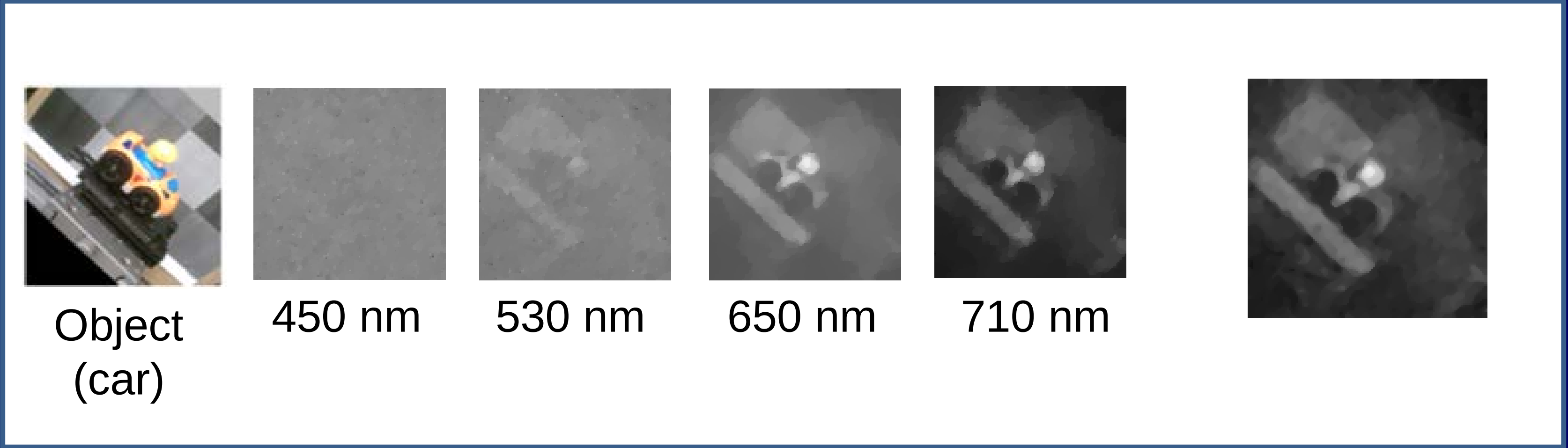
- Data Acquisition
  - *Measurement parameters:* 81,000 Lux illumination, 500 Hz DMD frame rate, 100 μm spectrometer slit opening
  - Image format: 128×128. Spatial fovea (at the center) is obtained with log(z) pattern



Sensor Demonstration

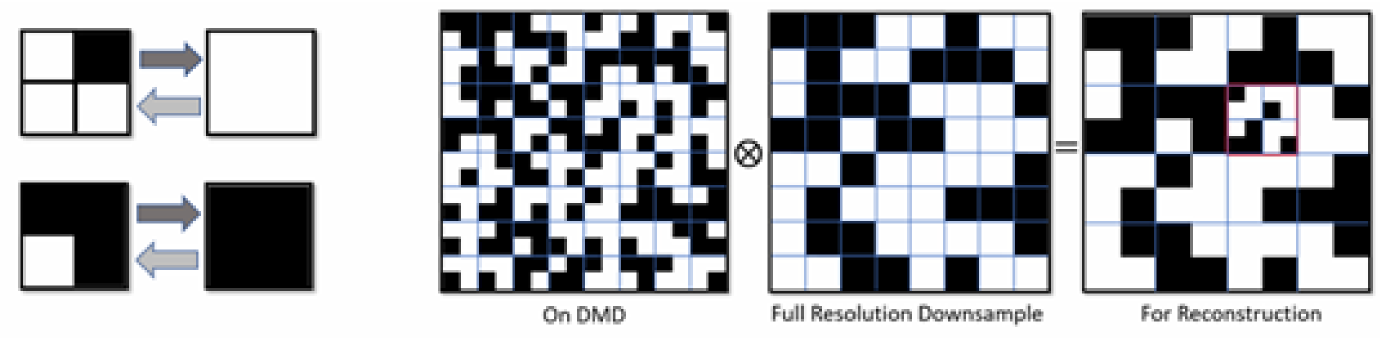
HS Video Acquisition and Reconstruction

- Data Acquisition
  - *Measurement parameters:* 81,000 Lux light illumination, 500Hz DMD frame rate, and 12.5% sampling rate. The object (car) moving speed is ~0.5 inches/second
  - Video image pixel format is 128*128.
  - Data acquisition time t =128*128/500 = 33 sec



Sensor Demonstration

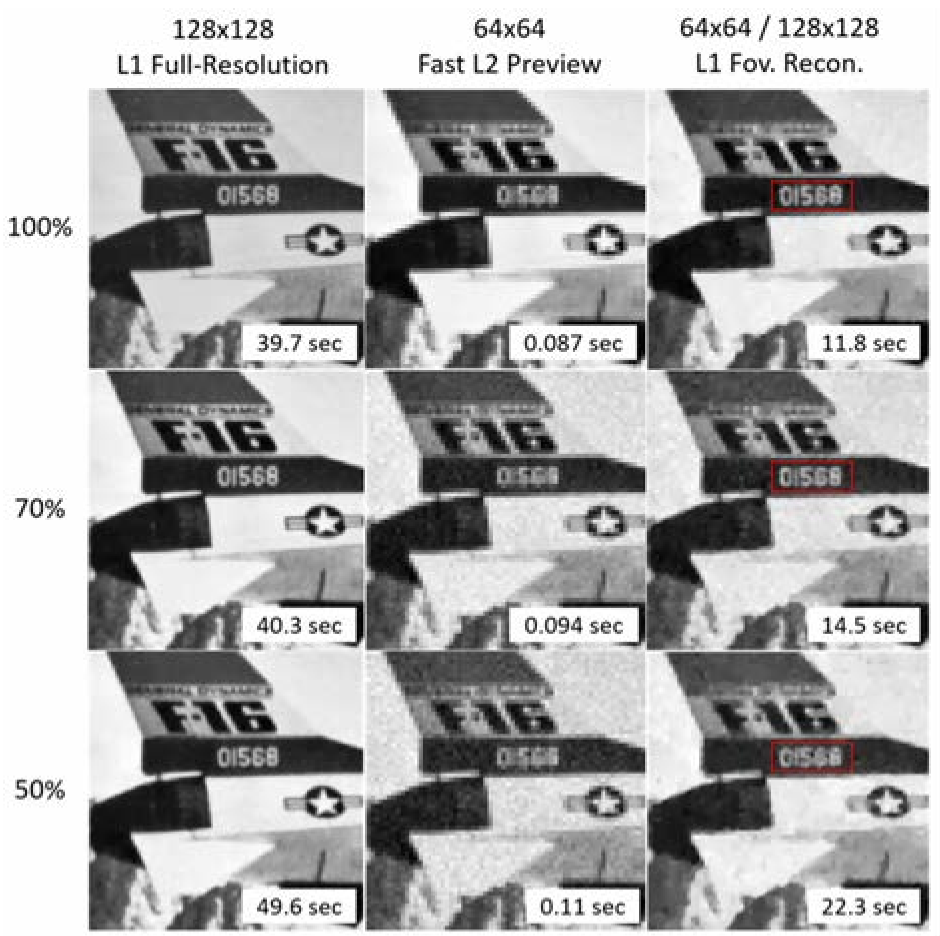
Spatially Foveated Grayscale Video Image Acquisition and Reconstruction



Schematic on the left: upsampling/downsampling kernel property inherent in the STOne transform through nested embedding. On the right: foveated reconstruction by combining the low and high resolution patterns input into the solver while still utilizing the full high resolution patterns in acquisition.

Sensor Demonstration

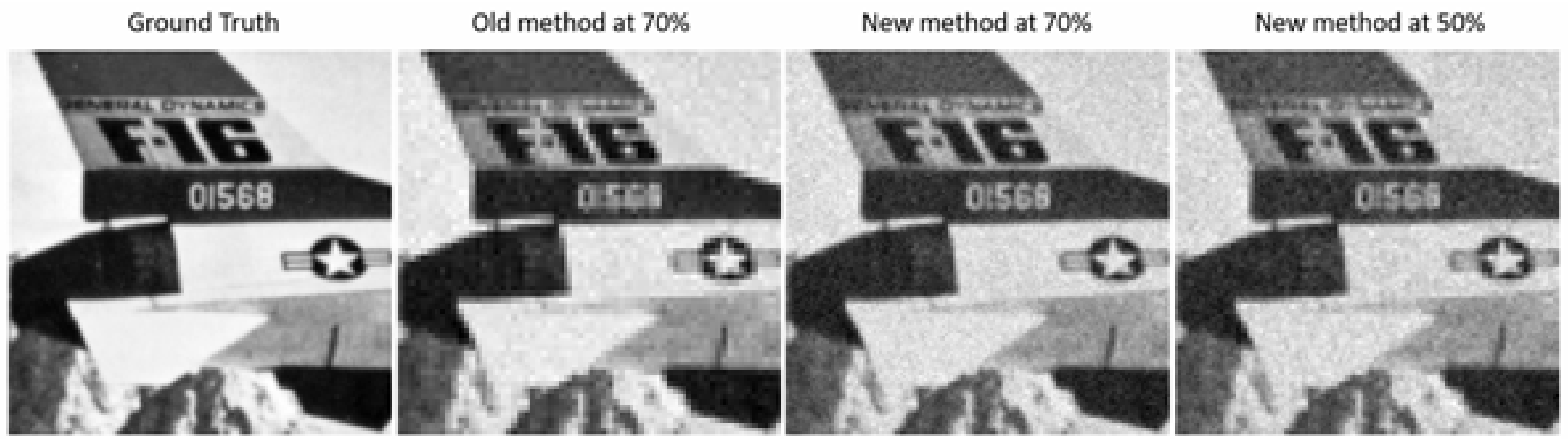
Spatially Foveated Grayscale Video Image Acquisition and Reconstruction



(Left) L1 reconstruction of test image using the full high resolution STOne patterns in the solver as a function of compression. (Middle) L2 reconstructed preview generated at full resolution with old method. (Right) L1 reconstruction using foveated STOne patterns with full resolution region highlighted in red. Inset within each image is the reconstruction time required for each process

Sensor Demonstration

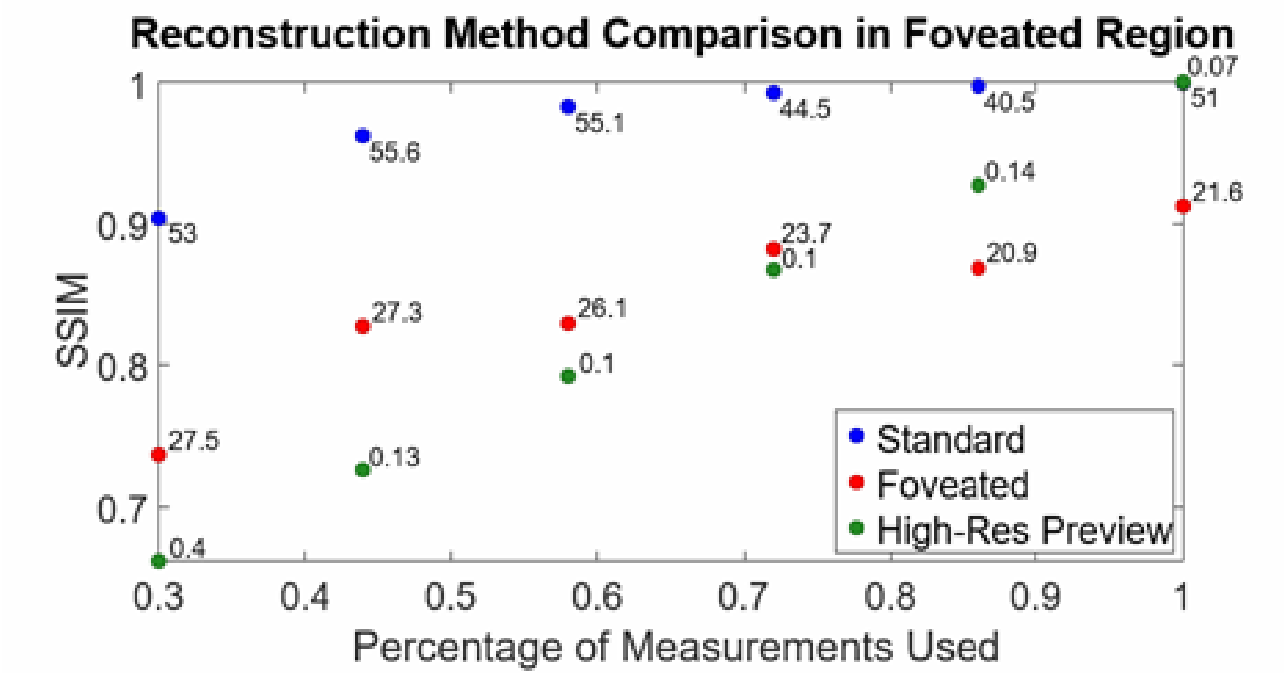
Spatially Foveated Grayscale Video Image Acquisition and Reconstruction



Test images of the new L2 STOne method as a function of compression in comparison to the old method

Sensor Demonstration

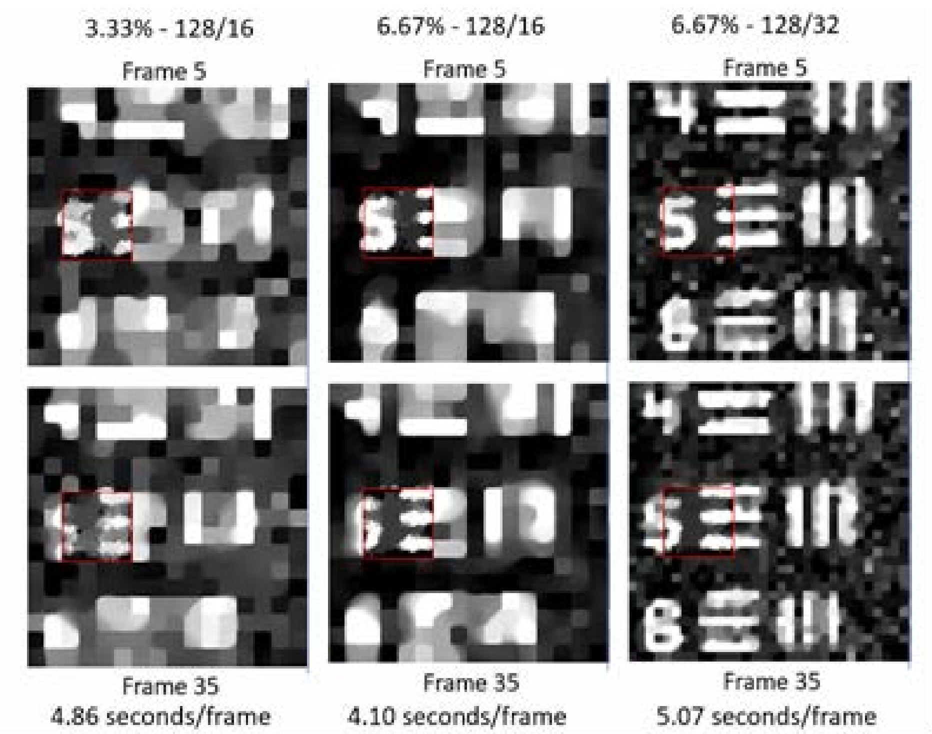
Spatially Foveated Grayscale Video Image Acquisition and Reconstruction



Plot comparing the SSIM over the foveated portion of the image for full L1 reconstruction (blue), foveated STOne L1 (red), and new STOne L2 previews (green) as a function of measurement percentage with reconstruction time in seconds on a PC at each point

Sensor Demonstration

Spatially Foveated Grayscale Video Image Acquisition and Reconstruction

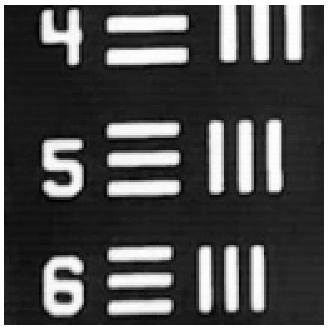


Comparison of downsampling resolution and percent measurement compression in the ability to reconstruct foveated video at full resolution (highlighted by the red box)

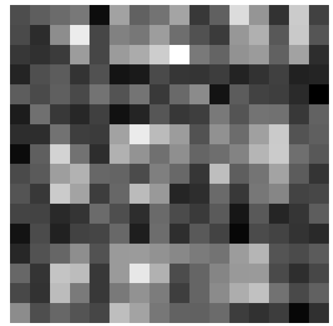
Sensor Demonstration

Spatially Foveated Grayscale Video Image Acquisition and Reconstruction

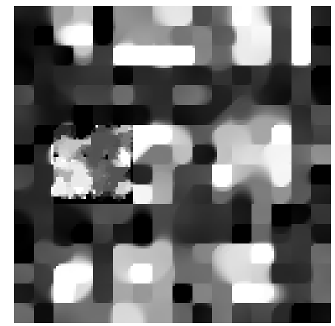
Ground Truth



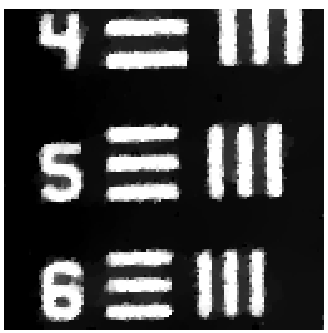
16x16 L2, < 1 sec.



16/128, 282 sec.

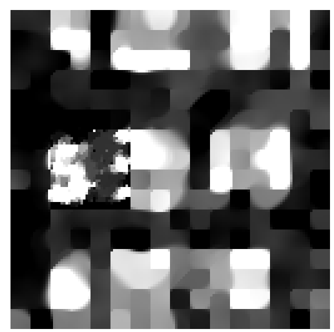


3.33%



Full-Res, 346 sec.

6.67%



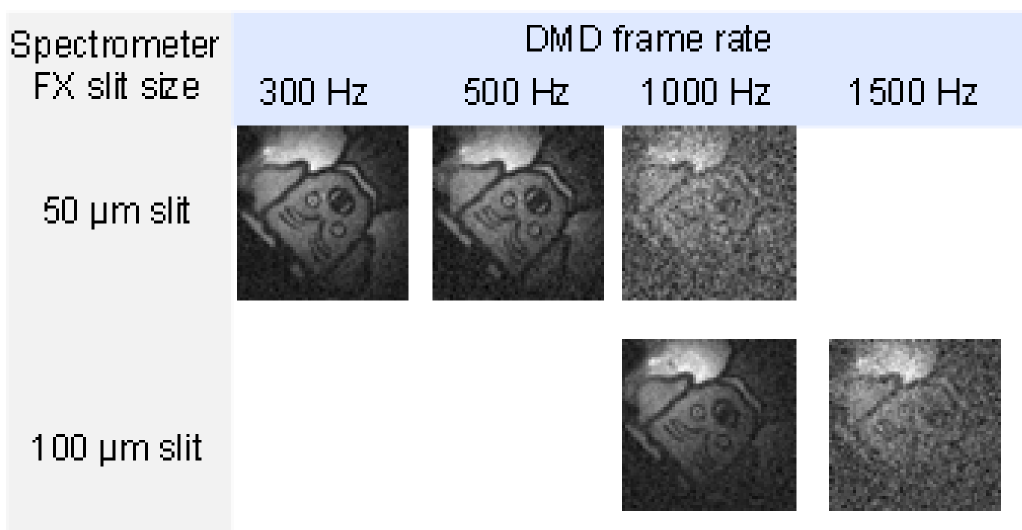
16/128, 238 sec.

32/128, 294 sec.

Comparison of downsampling resolution and percent measurement compression in the ability to reconstruct foveated video

Data Acquisition Time

- Data acquisition: t = N×N/f, N is the image format and f is the DMD frame rate. For N=128 & f=17,857 Hz, t = 128×128/17857 = 0.92 sec
- Data acquisition time is affected by the sensor integration time which affect DMD frame rate
- Current frame rate limited to 1000Hz => acquisition time of ~16sec for 128x128 hyperspectral data cube
- 17.4 minutes for 1024x1024 hyperspectral data cube



Reconstruction Time

- Data re-construction time: computer power of 4 cores, 3.2 GHz clock frequency, and 32 Gb memory. For parameter "mu" = 10, the clocked reconstruction time for generating grayscale (MS) video as shown in next

Sampling rate (%)	Frame	Binning time (s)	Reconstruction time (s)	Converting time (s)	Elapsed time (s)
75.0%	16	0.01	1.8	0.0040	2.33
62.5%	24	0.007	3.2	0.0030	3.84
50.0%	32	0.013	4.8	0.0070	6.13
43.1%	36	0.008	7.4	0.0046	8.4
37.5%	40	0.009	10.0	0.0049	11.2
12.5%	56	0.014	30.5	0.0117	32.14
Note	Frames per video set		Per video set	Input data to image data	Total time per video set

- *Can be improved with the increase of the computation power*

Conclusion

- The specific sensor design enables flexible functions of: Grayscale, MS, HS, spatial fovea, spectral fovea, MS/HS video, switching between MS & HS sensing
- Self-similarity of STOne pattern enables efficient (L2) reconstruction of image and video data at different spatial and temporal resolution
- ROI foveation achieved during reconstruction
- Significant challenges remain to be addressed:
    - Hyperspectral video rates limited by DMD and sensor frame rate
    - Better optical/system architectures needed to improve optical efficiency/light sensitivity
    - Computationally expensive reconstruction

Acknowledgement

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- *This work is supported by the contract:* **W909MY-17-C-0006** under US Army SBIR Program