Technology Description (CS Sensor)

Kent Optronics, together with its partner Prof. Kevin Kelly at Rice University, has developed a compressive multispectral (MS) and hyperspectral (HS) foveal video sensor[1,2] (CMHFVS) under an SBIR contract. The sensor is a unique state-of-the-art computational imaging system that combines both optical and computational elements with real-time adaptive configurability to address user's needs in challenging multiple-threat and multiple-mission environments.

Compressed sensing is a signal processing technique for efficiently acquiring and reconstructing a signal with faster and far fewer samples than required by the traditional Nyquist-Shannon sampling theory.[3] This alternative approach is based on the principle that, by finding solutions to underdetermined linear systems and through optimization, the sparsity of a signal can be exploited to recover it via using a much smaller volume data stream.

Figure 1 shows a fundamental compressive sensor.[4,5] It combines a micro-controlled mirror array displaying a time sequence of *M* pseudorandom basis images with a single optical sensor to compute incoherent image measurements. By adaptively selecting how many measurements to compute, the design trades off the amount of compression versus acquisition time, rather than the trade-off resolution versus the number of pixel sensors as in conventional cameras. If the single-pixel detector is replaced by a spectrometer, the sensor in the figure becomes a hyperspectral sensor.

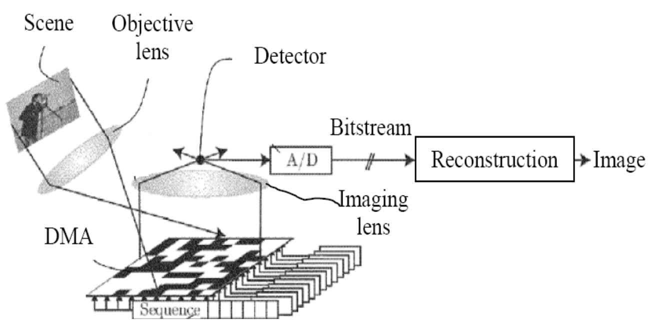

Figure 1. Single-pixel detector based multispectral compressive sensor

Figure 2 illustrates the principle design of our CMHFVS sensor system, where the dashed line enclosed area represents a spectrometer. The objective lens collects and focuses broadband scene light to the digital mirror device (DMD) for spatial coding. The coded light beam is then coupled into the spectrometer. The spectrally dispersed and spatially coded sub-beams from the spectrometer are detected by the one dimensional (1D) linear array whose 2048 pixels output pins are registered to the corresponding wavelengths (λs). The data from the 1D detector pins are reconstructed to generate 4D HS imagery set (x, y, λ, t). The optional 2-D camera is for wide area monitoring and recording of the events during the test and is not used in data reconstruction.

---

[1] "*Compressive Multi-Mission Electro-Optical Sensor System*", Le Li, Yi Yang, Juefei (Jeff) Zhou, Yongmei Li, Kevin F. Kelly, Anthony Giljum, Sanjeev Agarwal, Son Nguyen, SET-265 RSM, "*Compressive Sensing applications for Radar/ESM and EO/IR imaging*", 06-07 May 2019, Salamanca (ESP)

[2] "*Developing, integrating and validating a compressive hyperspectral video imager*", Juefei (Jeff) Zhou, Yi Yang, Le Li, Sanjeev Agarwal, Son Nguyen, Anthony Giljum, Kevin F. Kelly, Proc. SPIE 11423, Signal Processing, Sensor/Information Fusion, and Target Recognition XXIX, 114230V (21 May 2020); doi: 10.1117/12.2560282

[3] https://en.wikipedia.org/wiki/Compressed_sensing#:~:text=Compressed%20sensing%20(also%20known%20as,solutions%20to%20underdetermined%20linear%20systems.

[4] "*Method And Apparatus For Compressive Imaging Device*", Baraniuk et al., United States Patent, 8,199,244 B2, Jun. 12,2012

[5] "*Single-Pixel Imaging via Compressive Sampling*", Marco F. Duarte, et al, IEEE Signal Processing Magazine, p.83, Mar. 2008

The sensor can be designed to operate in an arbitrary spectral band from UV to 12 μm in long wave infrared (LWIR).

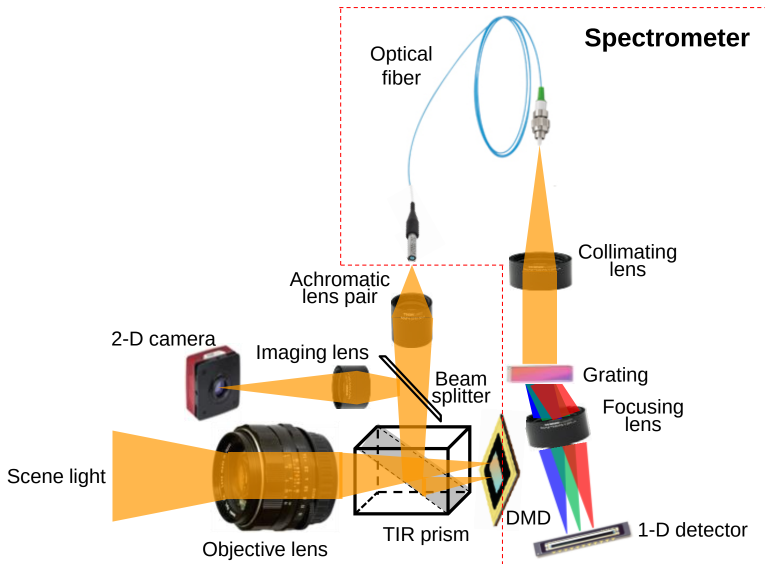

Figure 2. Schematic illustration of the 1st design of the compressive multispectral and hyperspectral sensor (CMHS) system.

Figure 3 shows the fully packaged CMHFVS system with specifications in Table 1.

Figure 3. Photo picture of the packaged CS sensor unit

Table 1. Specifications of the demo CMHS system

Parameter	Target
Spectrum (nm)	*400 – 850*$^{(a)}$
Spatial resolution	1×1 to 1024×1024$^{(b)}$
Spectral resolution (nm)	0.8 - 450 nm
Frame rate (fps)	*30*$^{(c)}$
Field of view (deg)	*Up to 12 × 12*
Size (Inch)$^{(d)}$	12" × 9.5" ×18"
Weight (Lb)$^{(d)}$	*~24*
Power consumption (W)	*≤ 55*

Notes:

[a] --- Other spectra are available under special order, up to 12 μm in long wave infrared (LWIR).
[b] --- Compressed, not full resolution at 1024×1024
[c] --- Compressed video rate
[d] --- The weight and size specs are for generation-1 product, which can be reduced in the future

With the unique algorithm implementation, the sensor exhibits exceptional agility enabling both multispectral (MS) sensing for wide area situational awareness and hyperspectral (HS) sensing for target recognition and identification. The sensor allows configuration of the operational parameters such as spatial, spectral and temporal resolutions based on mission requirements.

The sensor has realized the following key functions:

- Flexible switching between MS and HS sensing modes from a single sensor system;
- Fast sampling rate and imagery display refresh rate;
- Flexible fovea with arbitrary region of interest (ROI) number, size, location, and resolution in both spectral and spatial domains;
- Small foot-print profile in size, weight, and power consumption as well as cost (SWaP-C).

Figure 4 shows a set reconstructed HS images with different spectral resolutions, where the upper row has $\Delta\lambda$ = 10 nm spectral resolution without noise reduction; the middle row has $\Delta\lambda$ = 1 nm resolution with noise reduction; and the lower row has the same $\Delta\lambda$ = 1 nm spectral resolution but without noise reduction, respectively.

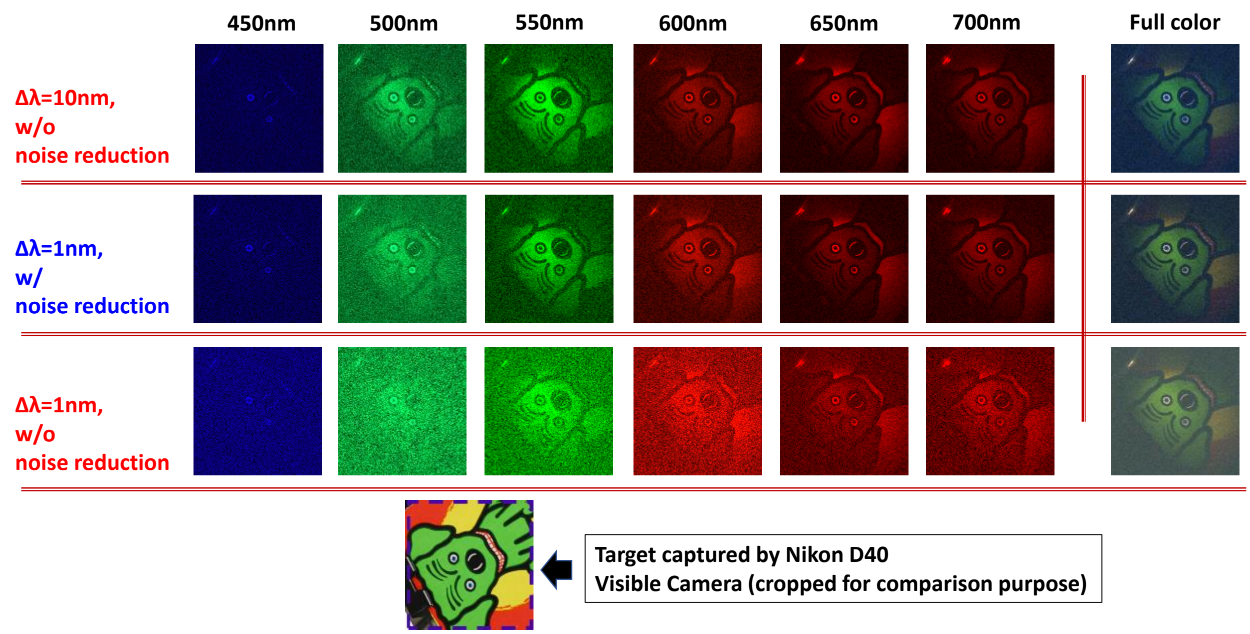

Figure 4. Reconstructed HS images with different spectral resolutions, where the upper row has $\Delta\lambda$ = 10 nm spectral resolution without noise reduction; the middle row has $\Delta\lambda$ = 1 nm resolution with noise reduction; and the lower row has the same $\Delta\lambda$ = 1 nm spectral resolution but without noise reduction, respectively

Figure 5 illustrates the application of our foveated algorithm to compressive video reconstruction of a moving scene. Full resolution in the foveated region is kept at 128×128 spatial equivalent while the remaining image is down sampled to either 16×16 or 32×32 resolution blocks. Depending on the chosen down sampling and percent compression one can adjust the image quality versus the reconstruction speed.

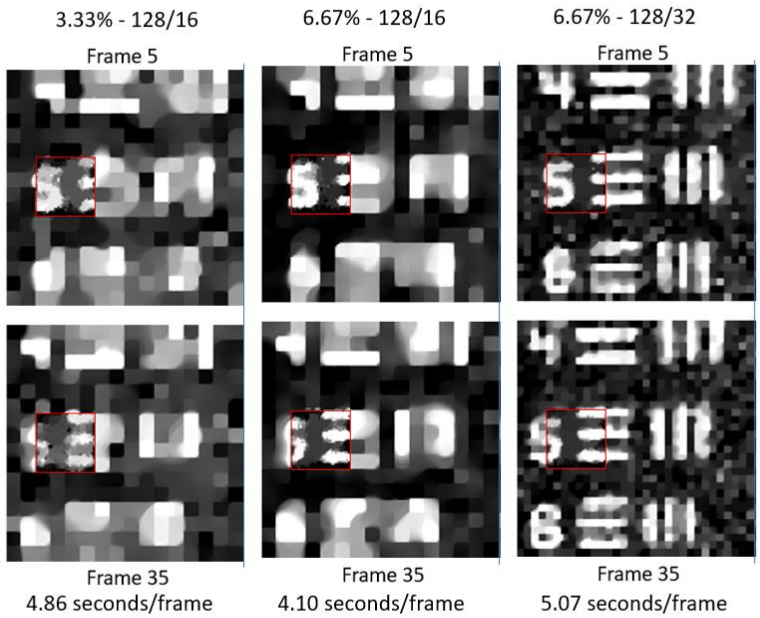

Figure 5. Comparison of down sampling resolution and percent measurement compression in the ability to reconstruct foveated video at full resolution (highlighted by the red box)

Data acquisition time "*t*" is determined by $t = N \times N/f$ where N is the image format and f is the data acquisition frame rate determined by the detector and DMD. The data reconstruction time is solely determined by the computer computation power. Given an exemplary computer power of 4 cores, 3.2 GHz clock frequency, and 32 Gb memory, for 128×128 pixel format, mu = 10 (the parameter embedded in the algorithm solver), and 256 shift, the shortest time is 2.33 sec under 75% sampling rate which involves 16 frames of image per video set.

The sensor can be used as a scientific research backbone platform for facilitating advanced Compressed Sensing, Machine Vision, Deep Learning research, and also a good education platform for college students to study in the field of artificial intelligence (AI). From 2019 when our team together with Prof. Kelly won a STTR contract from the US Air Force, we have started to develop novel deep learning algorithms to perform machine vision tasks such as target recognition and tracking utilizing the direct measurements from the compressive hyperspectral imaging system. By skipping the hypercube reconstruction, this combination of hardware and software will allow a real-time, actionable reaction to the incoming data stream.