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# Snapshot hyperspectral fovea vision system (HyperVideo)

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## ABSTRACT

The development and demonstration of a new snapshot hyperspectral sensor is described. The system is a significant extension of the four dimensional imaging spectrometer (4DIS) concept, which resolves all four dimensions of hyperspectral imaging data (2D spatial, spectral, and temporal) in real-time. The new sensor, dubbed "4×4DIS" uses a single fiber optic reformatter that feeds into four separate, miniature visible to near-infrared (VNIR) imaging spectrometers, providing significantly better spatial resolution than previous systems. Full data cubes are captured in each frame period without scanning, i.e., "HyperVideo". The current system operates up to 30 Hz (i.e., 30 cubes/s), has 300 spectral bands from 400 to 1100 nm (~2.4 nm resolution), and a spatial resolution of 44×40 pixels. An additional 1.4 Megapixel video camera provides scene context and effectively sharpens the spatial resolution of the hyperspectral data. Essentially, the 4×4DIS provides a 2D spatially resolved grid of 44×40 = 1760 separate spectral measurements every 33 ms, which is overlaid on the detailed spatial information provided by the context camera. The system can use a wide range of off-the-shelf lenses and can either be operated so that the fields of view match, or in a "spectral fovea" mode, in which the 4×4DIS system uses narrow field of view optics, and is cued by a wider field of view context camera. Unlike other hyperspectral snapshot schemes, which require intensive computations to deconvolve the data (e.g., Computed Tomographic Imaging Spectrometer), the 4×4DIS requires only a linear remapping, enabling real-time display and analysis. The system concept has a range of applications including biomedical imaging, missile defense, infrared counter measure (IRCM) threat characterization, and ground based remote sensing.

**Keywords: Hyperspectral, imaging spectrometer, real-time, target detection, biomedical imaging.**

## 1. INTRODUCTION

Hyperspectral imaging systems capture spectral and spatial information with the resulting data product being a "data cube" consisting of a two dimensional (2D) spatial image with spectra at each pixel. Typical hyperspectral systems utilize some form of scanning to build up a data cube over multiple camera frames, and thus do not have the ability to temporally resolve dynamic events. For example, many systems utilize tunable filters[1] or laser illumination[2] to scan over the spectral dimension, or alternatively image only a spatial slice of the cube at one time with scanning over the spatial dimension using platform motion or a rotating mirror[3].

In this paper, we describe a hyperspectral system which captures a full image cube with each camera frame, (i.e., there is no scanning); such systems are often referred to as "snapshot" sensors. We also refer to this concept as "HyperVideo", since the resulting data product is a video stream of data cubes captured at the frame rate of the focal plane array used.

OptoKnowledge has previously developed several HyperVideo systems using fiber optic bundles that reformat a 2D spatial image into a 1D array for input to a spectrometer, see Figure 1. We call such a sensor a four-dimensional imaging spectrometer[4] (4DIS), since it is capable of resolving two spatial dimensions, as well as both spectral and temporal dimensions, see Figure 2. Systems have been developed for different spectral ranges including visible to near infrared (VNIR: $\lambda \sim 0.4$ to 1.0 μm), short-wave infrared (SWIR: $\lambda \sim 1.0$ to 2.5 μm), mid-wave infrared (MWIR: $\lambda \sim 1.8$ to 5.0 μm), and dual MWIR/LWIR (3 to 5 μm and 6 to 10 μm). Different temporal resolution systems have also been developed, including one model[5] that utilizes a high-speed camera capable of capturing full image cubes at the rate of 100,000 Hz.

To obtain adequate signal to noise, and due to the finite number of pixels on a focal plane array, snapshot hyperspectral sensors necessarily make a trade-off in the resolution of the various dimensions of data. The 4DIS concept compromises

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spatial resolution, but maintains relatively high spectral and temporal resolution. In this paper, we describe a new advanced 4DIS system that addresses the relatively low spatial resolution in two ways: (1) it combines the output from multiple imaging spectrometers to increase the number of spectrally resolved pixels, and (2) it utilizes an integrated context camera to effectively increase the spatial resolution of a fused data product.

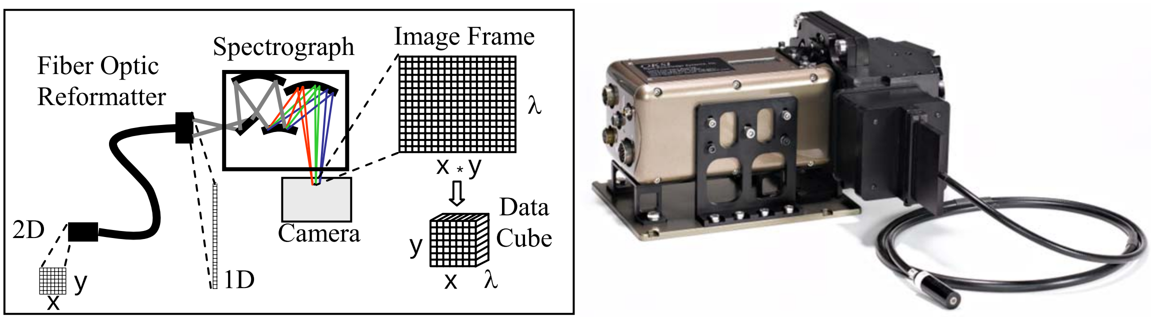


Figure 1. Optical schematic of 4DIS HyperVideo concept, along with a picture of a previously developed 4DIS sensor.

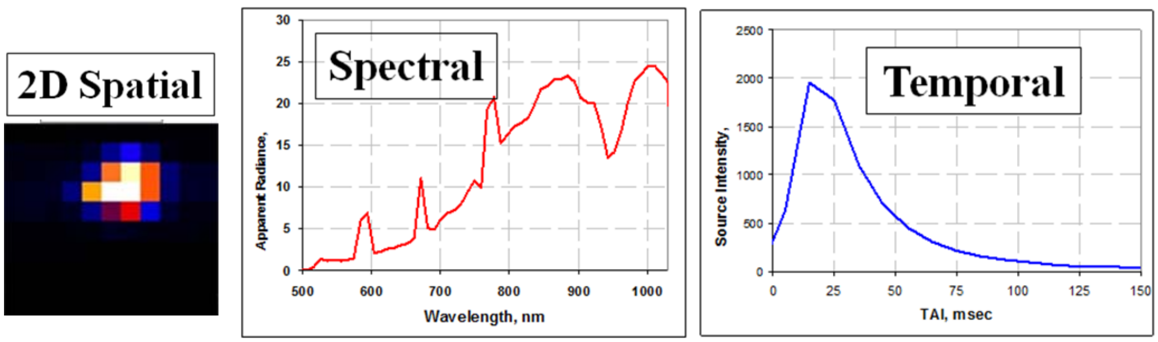


Figure 2. Sample 4 dimensional data from of a high speed energetic explosion at long range, which was collected using a previously developed 4DIS sensor. This prototype sensor has relatively low spatial and spectral resolution as compared to the new system described in this paper.

Even with the use of additional cameras, the computation requirements are relatively low for processing of the 4DIS data, enabling true, real-time display and analysis of the spectral information with standard embedded processors. Real-time display supports efficient focusing and boresighting as well as scene recognition and target tracking. This is a distinct advantage of the 4DIS over other snapshot sensors, such as FTIR[6],CTIS[7] and CTHIS[8], which require intensive computations to deconvolve the raw data.

## 2. 4×4DIS HYPERVIDEO SYSTEM

To improve the spatial resolution of the resulting data cubes, we have developed a new 4DIS system, which combines the output from 4 spectrometers; we call this system the “4×4DIS”, see Figure 3. The 4×4DIS has the following parameters:

- 300 spectral bands in the VNIR range from ~ 0.4 µm to 1.1 µm
- Spectral resolution: 2.4 nm
- Temporal resolution: 30 cubes/s
- Spatial resolution: 44 x 40 pixels.

An optical diagram of the 4×4DIS is shown in Figure 4. A lens focuses light from a scene on to the 2D input end of a custom designed, coherent fiber optic bundle. The output of the fiber bundle consists of four separate linear arrays that provide the input to four separate imaging spectrometers. The resulting spectral/spatial data is remapped into a single data cube in real-time using simple linear equations. Sample data taken with the system is shown in Figure 5, demonstrating two different means of visualizing the 44 x 40 = 1760 separate spectral measurements that are taken during each camera frame period.

Figure 3. Picture of new 4×4DIS HyperVideo sensor.

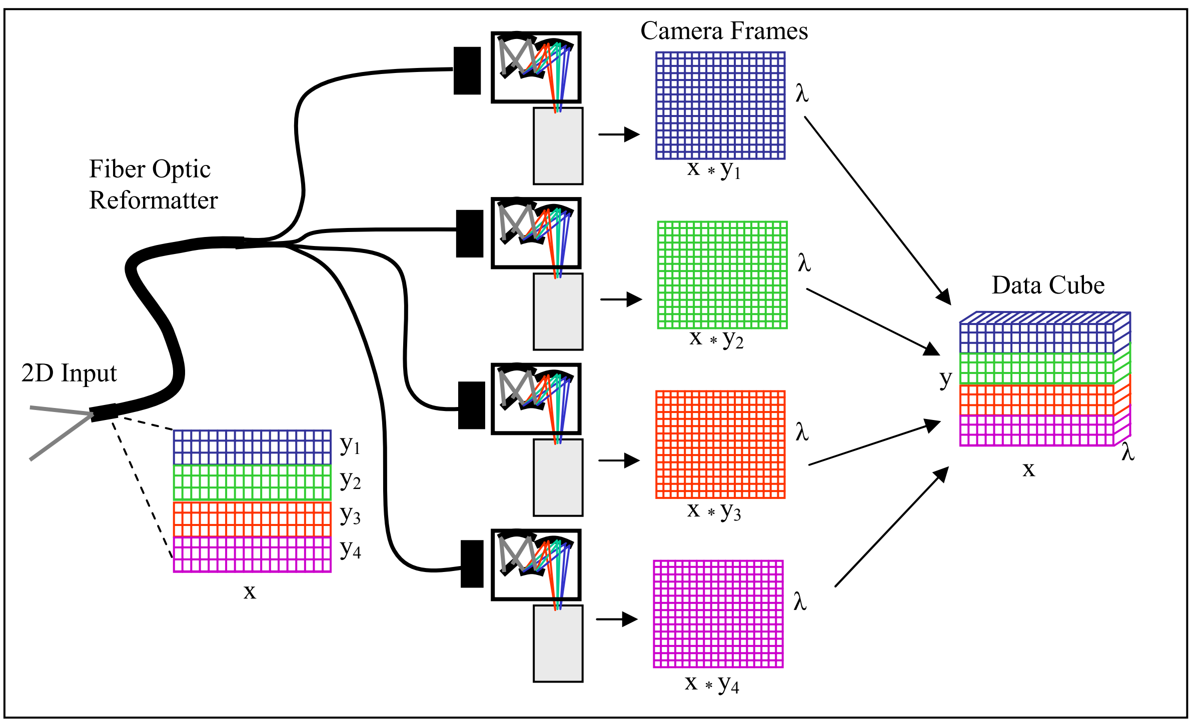


Figure 4. Diagram of 4×4DIS HyperVideo sensor, illustrating the use of a fiber optic reformatter and four separate spectrometers. Color is used in this diagram to denote the input and output corresponding to the four separate spectrometers. The combination of the separate camera frames and reformatting of the data into a single hyperspectral image cube is relatively simple and is easily conducted within the 30 cubes/second data rate of the sensor.

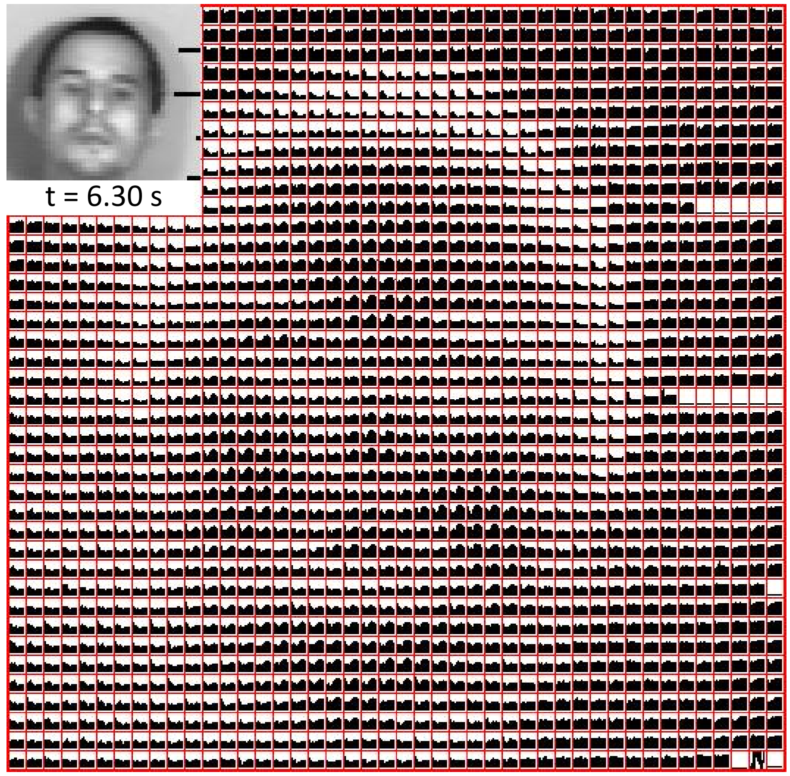


Figure 5. Sample 4×4DIS HyperVideo data at one instance in time (i.e., t = 6.30 seconds into a video sequence). The grid shows the spectra at each pixel of the image cube, and the image in the top left corner is generated by summing over a range of spectral bands. Both images illustrate the 44 x 40 spatial resolution of the 4×4DIS sensor.

In addition to utilizing multiple spectrometers, we further compensate for the relatively low spatial resolution of the 4×4DIS system by fully integrating imagery from a relatively high resolution context camera. Specifically, we are using a 1.4 Megapixel digital camera with a 1380 x 1040 pixel format. The context camera frame rate is synchronized with the cameras used in the 4×4DIS system, and the resulting data fused in a manner commensurate with a specific application. A wide range of off-the-shelf lenses can be used, and the system can be operated so that the fields of view match, or in a "spectral fovea" mode, in which the 4×4DIS system uses narrow field of view optics and is cued by the wider field of view context camera.

## 3. SAMPLE HYPERVIDEO APPLICATIONS

One particular application that is particularly suited for the HyperVideo system is real-time target detection of dynamic scenes; an illustration is shown in Figure 6. In this scene there are two similar looking targets with different spectral features. A matched filter algorithm is applied to the 4×4DIS data using a library spectrum corresponding to one of the objects. The resulting score map is displayed on a color scale and fused with the context camera using the hue, saturation, value (HSV) color space, where the brightness (value) is from the context camera and the hue and saturation from the matched filter score map. The power of this system is that the processing can be conducted within a frame period and the results shown in real-time at video rates enabling target detection of dynamic scenes and/or from moving platforms. We reiterate: neither scanning nor complicated deconvolutions are needed to produce an image cube.

Another example of fused HyperVideo data is shown in Figure 7. In this demonstration, the blood flow to two fingers of a human hand was constricted by a rubber band, and then the constriction was removed. The 4×4DIS data was processed using a modified band-ratio technique with the resulting value designed to correspond to the saturated oxygenation value in hemoglobin ($SO_2$). The $SO_2$ value is displayed on the color scale shown in the image and fused with the context camera imagery using the HSV color space in a similar manner to the target detection example. With the rubber band on, the blood oxygenation level decreases in the affected fingers, and after the rubber band is taken off the oxygenation values quickly return to a normal level. While this is a contrived example, it demonstrates the general ability of the system to provide spatially resolved spectra of dynamic events. This capability can be particularly important in biomedical applications where one needs to monitor the temporal evolution of a specific spectral signature.

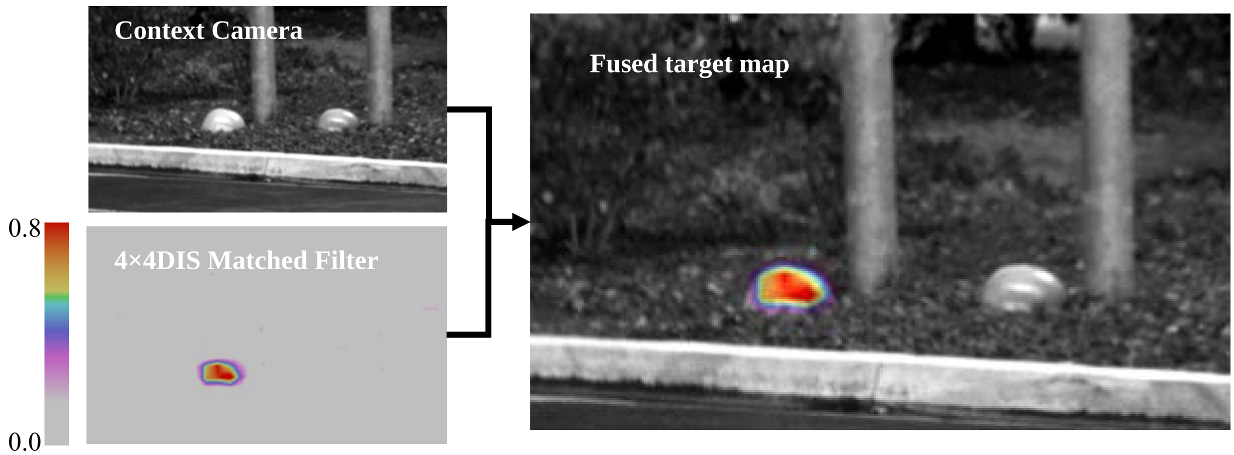


Figure 6. Example use of HyperVideo sensor for target detection. In this case, 4×4DIS data is analyzed with a matched filter algorithm using library spectra corresponding to one of the objects in the scene. The resulting matching score is displayed based on the color scale shown in the figure and fused with the context camera image.

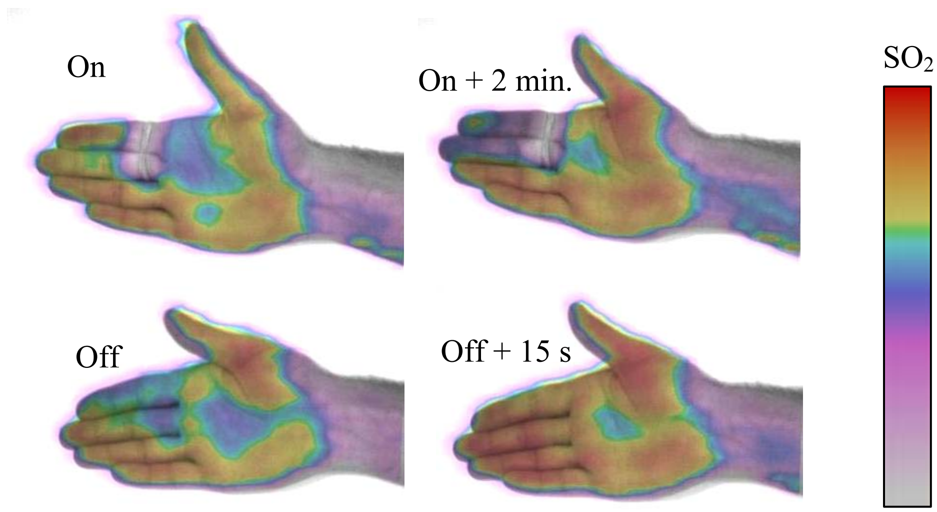


Figure 7. Fusion of spectral analysis from HyperVideo data with context camera imagery. In this example, a rubber band was placed “On” the index and middle fingers of a human hand and then taken “Off” about 2 minutes later. The spectral analysis was designed to display the saturated oxygenation hemoglobin value ($SO_2$).

## 4. SUMMARY AND FUTURE WORK

In summary, we have a developed a new HyperVideo spectral imaging system with relatively high spectral and temporal resolution. The spatial resolution is relatively low; however, the new system is a factor of four better than previous systems. Furthermore, by fusing the information derived from the hyperspectral sensor with relatively high spatial resolution output from a context camera, the combined data product can be useful for a range of applications. Systems based on the concept have been developed for research into the spectral analysis of dynamic scenes, and lower SWaP versions can be developed for field applications. In addition to the VNIR 4×4DIS system described in this paper, OptoKnowledge is also currently in the process of developing higher spatial resolution SWIR and MWIR HyperVideo sensors.

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