A New 'Hera' in Hyperspectral Imaging

Low light applications come into range thanks to a novel camera system

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Fig. 1 The Hera Iperspettrale hyperspectral camera

Source all images: Nireos

Hera Iperspettrale is a novel hyperspectral camera based on a patented Fourier-transform approach. The device can be employed in a large variety of applications, ranging from cultural heritage to biology, from material sorting and food inspection to remote sensing and vegetation studies. The exceptional throughput of the optical system ensures high-quality data even at the lowest light dose, making the camera very suitable for fluorescence hyperspectral imaging.

Hyperspectral imaging (HSI) is a novel analytical technique based on spectroscopy, with the aim of measuring the spectrum of the light coming from each point of a scene of interest. While the human eye has only three color receptors, for blue, green and red light, hyperspectral imaging measures the continuous spectrum of the light as a function of the wavelength λ for each pixel of the scene at coordinates (x, y) with fine spectral resolution, not only in the visible but also in the infrared range. The collected data form the so-called hyperspectral image: a three-dimensional data cube as a function of x, y and λ. These data contain an extensive amount of information. Therefore, many numerical methods and algorithms have been developed to enable the extraction of quantitative parameters related to the physicochemical properties of the imaged objects, as well as the clustering into different components, useful for the analysis of congested scenes. For this reason, HSI is an extremely powerful technique, which has been applied to a wide range of fundamental and applied studies in fields as diverse as remote sensing, medical and biological imaging [1], agriculture [2], coastal and geological prospecting, safety and security, military applications, archaeology and conservation science [3].

Approaches to hyperspectral imaging

HSI has been implemented in a wide variety of methods. The simpler approaches are constituted by snapshot HSI systems, which employ a matrix of bandpass filters on the surface of the detector, and spectral HSI systems, which use a tunable spectral filter in front of a monochrome imaging camera. These methods are quite straightforward, the drawback being the acquisition of a limited and discrete number

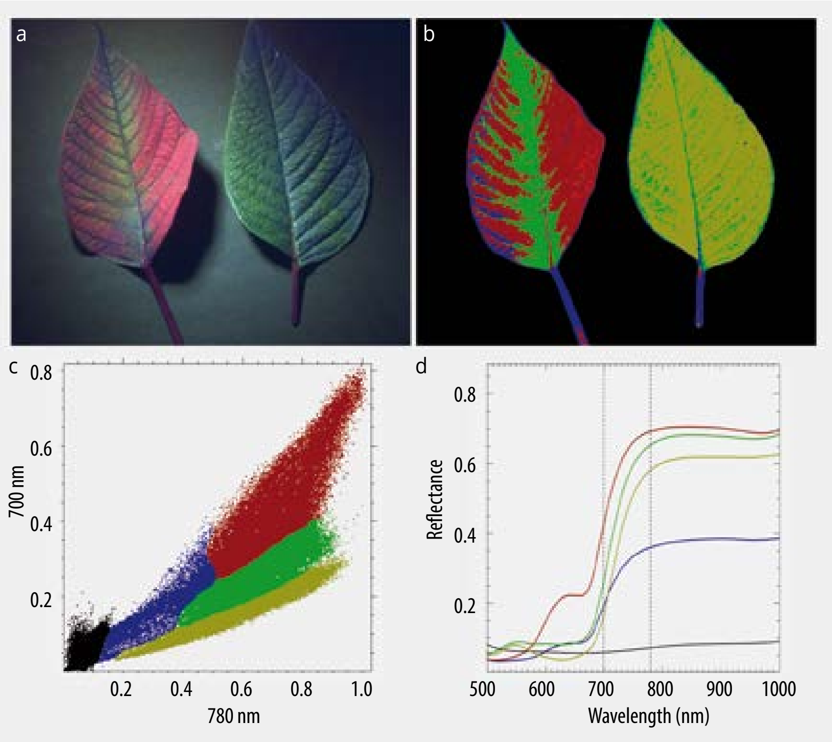

Fig. 2 Hyperspectral image of two leaves from a Poinsettia plant: RGB (a) and classified image (b); scatter plot in the 700 – 780 nm bands space, in which five different classes have been identified (c). Average reflectance spectra of the five classes (d)

of bands. To measure continuous spectra, another common approach is spatial scanning HSI, which combines a dispersive spectrometer with a raster-scanning approach, either in point-scanning (whisk-broom) or line-scanning (push-broom) modes. This technique is widely applied in industrial quality-control monitoring processes. However, the main limitation of these techniques is the high losses imposed by the entrance slit of the spectrometer, which leads to long acquisition times.

An alternative HSI method to measure continuous spectra combines a monochrome imaging sensor with an interferometer [4]. In this approach, known as Fourier transform (FT) spectroscopy, the light of interest is split into two collinear delayed replicas, whose interference pattern is measured by a detector as a function of their relative delay. The Fourier transform of the resulting interferogram yields the continuous-intensity spectrum of the light. The FT approach has prominent and well-known advantages over dispersive techniques:

- all the wavelengths are measured simultaneously, thus increasing the number of photons reaching the sensor and leading to a higher signal-to-noise ratio in a read-out-noise-dominated regime (multiplex or Fellgett's advantage),
- higher throughput, due to the absence of slits (the Jacquinot's or étendue advantage),
- high wavelength accuracy, thanks to the calibration of the device with a laser beam (the Connes' advantage),
- variable spectral resolution, which can be adjusted at will by varying the maximum scan delay of the interferometer via software, without affecting the throughput of the device,
- the spatial resolution can be adjusted independently of the spectral resolution.

Two essential conditions must be met by an FT-imager to provide high quality spectra:

- the relative delay of the two generated replicas of light must be controlled to within a fraction (1/100 or better) of the optical cycle and
- the bundle of rays that form the interferogram at a given pixel must preserve a high degree of coherence.

FT-based imaging is achieved using either a static or a temporal approach. In the static scheme, the interferometer has no moving parts, and a spatial interferogram is formed along one of the dimensions of the image. The acquisition is performed by moving the object with respect to the camera, making this method particularly suited to production lines where the object to be measured is moving on a conveyor belt, or for airborne remote sensing. In the temporal approach, the interferometer has a moving element, which is scanned to vary the delay of the replicas, with no need for relative movement between the object and the camera. This method is better suited to the imaging of stationary objects and is thus widely applied in applications such as biology or cultural heritage studies. FT-HSI systems have been built based on Michelson or Mach-Zehnder interferometers; however, since they are sensitive to vibrations, it is difficult to achieve the required interferometric stability without active stabilization or tracking. Alternatively, liquid crystal cells have been used to introduce a voltage-controlled delay between orthogonal polarizations. In the last few years, birefringent interferometers have attracted particular attention because of their compactness and insensitivity to vibrations, due to their common-path

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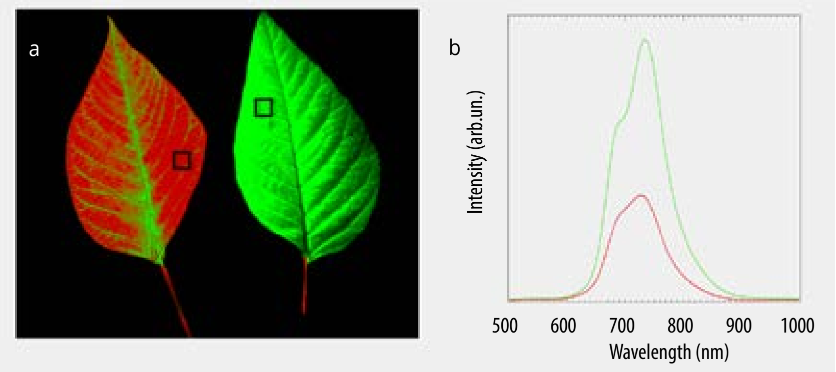

Fig. 3 Fluorescence hyperspectral image of two leaves from a Poinsettia plant: (a) Classified image in false color, showing the spatial distribution of the two main components in red and green. (b) Fluorescence spectra of the two components, corresponding to the selected squared areas in (a).

nature. They are mostly based on Wollaston or Savart prisms, or their variants. Because of the arrangement of their optical axes, they are characterized by a strong chromatic lateral displacement, which reduces the visibility of the interference fringes.

Hera Iperspettrale's working principle

Hera Iperspettrale (Fig. 1) is based on a Fourier transform (FT) approach and it employs a patented common-path birefringent interferometer (CPI) in combination with a bidimensional CMOS sensor. The CPI overcomes the limitations of the Wollaston and Savart prism-based imagers, providing negligible chromatic dispersion and small geometrical separation between the interfering replicas, leading to high degree of coherence at each pixel and a strong interference modulation. The three-dimensional datacube is acquired in the time-domain by serially stacking multiple images acquired at different positions of the CPI. The software then automatically computes an FT at each pixel of the image, thus providing the final hyperspectral data cube. As a result of an FT, the spectrum at each pixel is a continuous curve, so the number of bands is virtually unlimited, and it is not defined by the hardware. Hera Iperspettrale works in a broadband spectral region, from the UV to the near infrared (0.4 – 1 µm), and it features an exceptional throughput, a high spectral accuracy, and a wide versatility of use [5]. The spectral resolution, proportional to the wavelength as in any other FT techniques, corresponds to 3 nm at 600 nm. The objective has focal length $f = 25$ mm and maximum aperture $f/1.85$. The detector is a 1280 × 1024 monochrome silicon CMOS sensor and the total angular field of view of the imaging system is 16°.

Reflectance and fluorescence hyperspectral imaging

Thanks to the absence of aperture slits and gratings, and to its 10-mm clear aperture, Hera Iperspettrale is specifically designed to provide an extremely high light throughput, making it the ideal device for low light conditions or delicate samples.

As an example, Fig. 2 reports the results of a reflectance measurement performed on two different leaves of a poinsettia plant. The leaves were illuminated with a 50-W halogen lamp placed at 200 cm distance from the scene, to avoid heating or damaging of the sam-

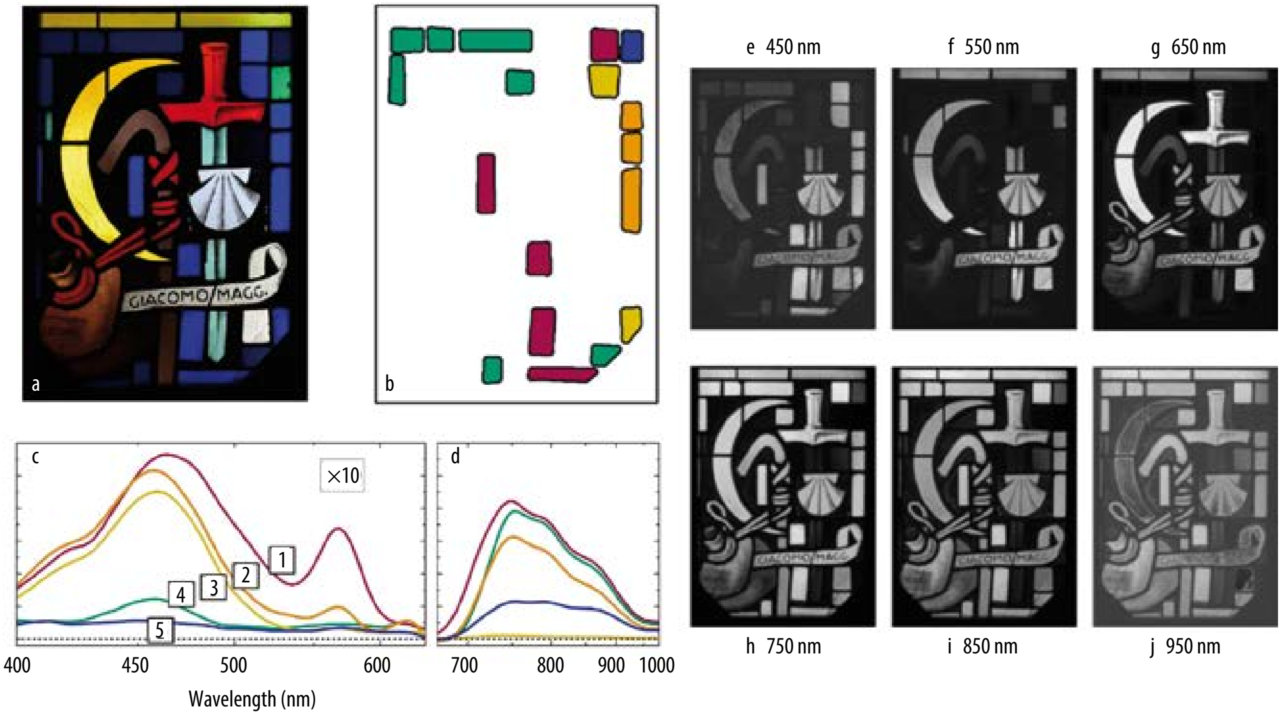

Fig. 4 Hyperspectral image of an artistic glass window (A. M. Nardi, 1969): RGB image synthesized from the spectral data (a); map (b) and corresponding transmitted spectra of the blue tiles, after automatic image segmentation (c, d); hyperspectral data at selected wavelengths (e-f).

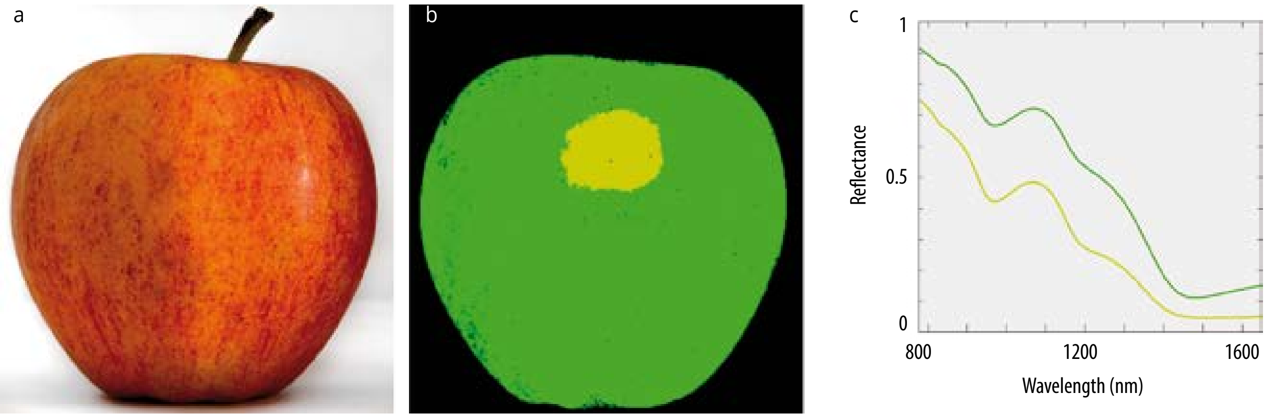

Fig. 5 Infrared hyperspectral image of a bruised apple: standard RGB picture of the sample (a) and classified image obtained from the infrared hyperspectral data. The yellow area shows the bruised portion of the apple (b). Infrared reflectance spectra of the bruised and healthy areas of the sample, in yellow and green lines, respectively (c).

ple. The absolute reflectance was calculated after spectral calibration with a white reflectance reference (not shown in the image) and correction for spatial and spectral non-uniformities of the illumination by imaging a white Lambertian surface at the object plane. The synthesized RGB color image obtained from the hyperspectral data is shown in Fig. 2a. We then applied a classification algorithm based on the scatter plot of Fig. 2c, which reports the distribution of the pixels in the 700 – 780 nm bands space. By analyzing the scatter plot, we identified five different classes, whose average reflectance spectra are shown in Fig. 2d. Fig. 2b reports the spatial distribution of the identified classes, clearly exhibiting the different structures of the two leaves with an excellent spatial resolution.

For a further analysis and demonstration of its excellent sensitivity, Hera Iperspettrale was also employed to measure the fluorescence hyperspectral image of the optical emission of the same leaves, upon excitation with a UV LED (760 mW @ 405 nm) placed at 20 cm distance from the scene. The weak fluorescence signal was collected using a long-pass filter at 500 nm wavelength to filter out the more intense excitation light. Despite the extremely weak signal, the quality of the data is excellent and in good agreement with the literature. A classification algorithm identified two main spectral components in the image, spatially distributed as represented in Fig. 3a. The average fluorescence spectra relative to the areas delimited by the black rectangles in Fig. 3a are shown in Fig. 3b. By analyzing the spectra, it is possible to clearly distinguish the two components, with the feature around 700 nm, probably due to re-absorption, that uniquely characterizes the spectrum represented in green.

Works of art

The great advantage of this FT-based hyperspectral device in terms of extremely high light throughput can also be exploited in the study of works of art and cultural heritage, where low-illuminance conditions are recommended in order not to damage the samples. In this field, Hera Iperspettrale has already been used to investigate the attribution and the dating of paintings [6], to monitor their state of conservation and to assess their authenticity [5].

As an example, we report here the analysis of a portion of an artistic stained-glass window located at the Santo Spirito Church in Milan, Italy, realized in 1969 by A. M. Nardi (1897 – 1973). Stained glasses typically exhibit unique spectral features due to strong absorption bands located at well-defined wavelengths. Since the manufacturing process of window glass has changed throughout time, its spectral characterization is a valuable method to determine its composition and coloring agents, therefore enabling the assessment of the authenticity of ancient windows. In this measurement, the window was back illuminated by natural sunlight, and the camera recorded the transmitted light. The synthesized RGB color image is shown in Fig. 4a. Due to the back-illumination configuration it was not possible to measure a reference image of a Lambertian source. Therefore, the RGB image shown in Fig. 4a is a colored representation rather than a projection in the RGB space. A selection of images corresponding to specific wavelengths are reported in Fig. 4e – j; as expected, each tile absorbs at specific spectral bands. An automatic image segmentation algorithm was performed to extract the different characteristics of the blue tiles. This algorithm is based on ‘k-means’ statistical analysis of the measurement. The blue colored tiles were assigned to five classes with different spectral transmission as shown in Fig. 4c – d. The spatial distribution of these classes is shown in Fig. 4b. Interestingly, despite very similar RGB colors, these classes show peculiar spectral differences. This is especially evident by looking at class number 3. Indeed, the tiles belonging to this class are strongly absorbing in the NIR spectral region. This is a very different behavior with respect to all the other classes. This might suggest that these tiles were added later to the artwork, maybe as a replacement for broken ones.

Towards the infrared

As the CPI employed in the Hera Iperspettrale works in a broad spectral range, from the ultraviolet to the short wavelength infrared (SWIR) region, the presented hyperspectral system can be straightforwardly extended to the infrared range using a suitable detector and objective. The Nireos team is already working on this development, and the first measured infrared hyperspectral image is presented in Fig. 5. The measurement was performed on a specially bruised apple, employing a monochrome SWIR camera as sensor. Fig. 5a shows a standard RGB picture of the sample, in which it is not possible to detect any sign of damage. The damage was also not detectable by analyzing the hyperspectral image obtained using the Hera Iperspettrale in the standard 400 – 1000 nm spectral region. However, the classified image obtained from the hyperspectral data in the 800 – 1700 nm range, reported in Fig. 5b, clearly distinguishes the damaged area (colored in yellow) from the healthy portion (colored in green). The average reflectance spectra of the two identified classes are shown in Fig. 5c.

The implementation of the infrared hyperspectral system will enable the exploitation of all the advantages of Hera Iperspettrale's Fourier transform approach, such as high light throughput, high signal-to-noise ratio, and the user-adjustable spectral resolution, also in the infrared spectral region. Consequently, this development will unlock a broad range of novel imaging and sensing applications in both the scientific and the industrial sectors.

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Fabrizio Preda studied physics engineering in Politecnico di Milano, where he worked as a research fellow for five years after receiving his master's degree. He is the author of several peer-reviewed articles and the co-inventor of three international patents. Since 2018, he is co-founder and chief executive officer at Nireos, where he coordinates a team of passionate and highly skilled scientists and engineers.

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