Adaptive Coherence-Sensing Imaging Spectrometer

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The ability to measure spectral information at each pixel simultaneously makes imaging Fourier transform spectrometers particularly useful instruments. However, their tremendous processing and storage requirements impede their widespread use (>7Gb/s data at 100 bins spectral resolution, VGA resolution, 30frames/s). If one could reduce the particular spectral features of interest to a small number of scalar values per pixel, the data burden would be decreased significantly [2]. For example, spectral bandwidth is a salient feature of interest and a unique property of many types of light-sources and surface reflections. Given the ability to classify optical emissions by spectral bandwidth, one can discriminate among light source types beyond the capabilities of, e.g., 3-band color cameras.
We describe the theory and experimental results of a new imaging system, based on a Fourier transform spectrometer, that generates two scalar output values per pixel: intensity and coherence length. Coherence length, which is inversely proportional to spectral bandwidth, is derived directly from the interferograms measured at each pixel. The system described here allows us to discriminate coherence lengths in the range from 1 μm to 50 μm (corresponding to bandwidths from 6 nm to 300 nm in the visible range). We also propose and demonstrate a new application, the detection of "invisible" passive tags that are uniquely identified solely based on their coherence.

System: The system consists of a 352 x 288 pixel silicon CMOS monochrome camera [2]. The active optical system that precedes the monochrome detector is a Michelson interferometer with two identical aluminum mirrors and one non-polarizing cube beam splitter. It includes two imaging lenses to relay the image from the source to the mirrors and the sensor surface. One of the two mirrors is movable by a piezo element, where the motion is controlled to be sinusoidal, typically driven at 7μm scan range. This range is sufficiently small that minimal defocusing of the image formed by the moving mirror arm occurs during the scan; at the same time it is sufficiently large to yield about 20 wavelengths of optical path difference. The CMOS sensor's capture process is synchronized with the mirror motion. Each time the mirror is at one extreme, the capture and processing sequence is initialized. A full interferogram is measured at each pixel in a 2D array and processed as below.

Processing: Figure 1 illustrates the key concepts: the top row shows the spectra of three light sources, the second row shows the corresponding measured interferograms at one pixel, the third row shows the AC coupled and rectified interferograms, and the fourth row shows the low pass filtered version of row three. The coherence length is approximated by the widths of the interferograms. We introduce two methods to obtain the coherence length. Method I integrates the area under the rectified curves and normalizes it by the DC value. Only the normalized area is independent of the brightness of the respective pixel. Method II measures the ratio of the envelope amplitudes at two time points. This way the coherence measure is also brightness independent. Method II can better discriminate cases where the areas of two interferograms are similar, but the roll off behavior differs. The images that are obtained by these two methods are shown at the bottom. On the left, as reference, is a conventional monochrome image of the scene, with the following three sources (left to right): halogen lamp (L1), green LED (L2), and 550nm laser (L3). The center graph shows the result for coherence-measure with Method I, the right graph the result with Method II. With either method, the three light sources can be discriminated well according to their coherence lengths. The filter properties of the system are electronically adaptable with no mechanical changes to the system: the mirror scan range sets the maximum resolution; the distance between X and Y (see Figure 1, bottom row) determines whether the system is more sensitive in a regime of either wide or narrow bandwidths.

Applications: We propose a new application: detection and tracking of spectrally narrow reflecting tags, invisible to the eye and conventional color cameras, but specifically detectable with our adaptive coherence-sensing system. One example for this application is shown in Figure 2. The scene is a Lambertian surface that emits white light (color coordinates CIE x=0.31, y=0.32) in two different ways: a white background emitting broadband white light (S1); a small embedded structure emitting a different spectrum (S2). Having the same color and intensity, the embedded structure is invisible to the eye and to conventional 3-band cameras (Figure 2a). However, our system can clearly detect the hidden structure (Figure 2 b1,b2). Other examples of this application that we have successfully demonstrated with the system include the detection of green emitters (bandwidth $\Delta\lambda$=40nm) hidden in green foliage, as well as green narrowband reflectors ($\Delta\lambda$=4nm) in green foliage. Passive tags with medium-bandwidth ($\Delta\lambda\leq$40nm) reflection are advantageous because they can be manufactured as multilayer polymer or coating at very low cost. With the system presented here, these tags can be distinguished from almost all other surfaces that occur in natural environments [3].

Conclusion: We have designed and built a new coherence-sensing imaging system for the visible range and demonstrated a new "invisible" tag application that provides a unique method of marking or identifying objects by spectral bandwidth.

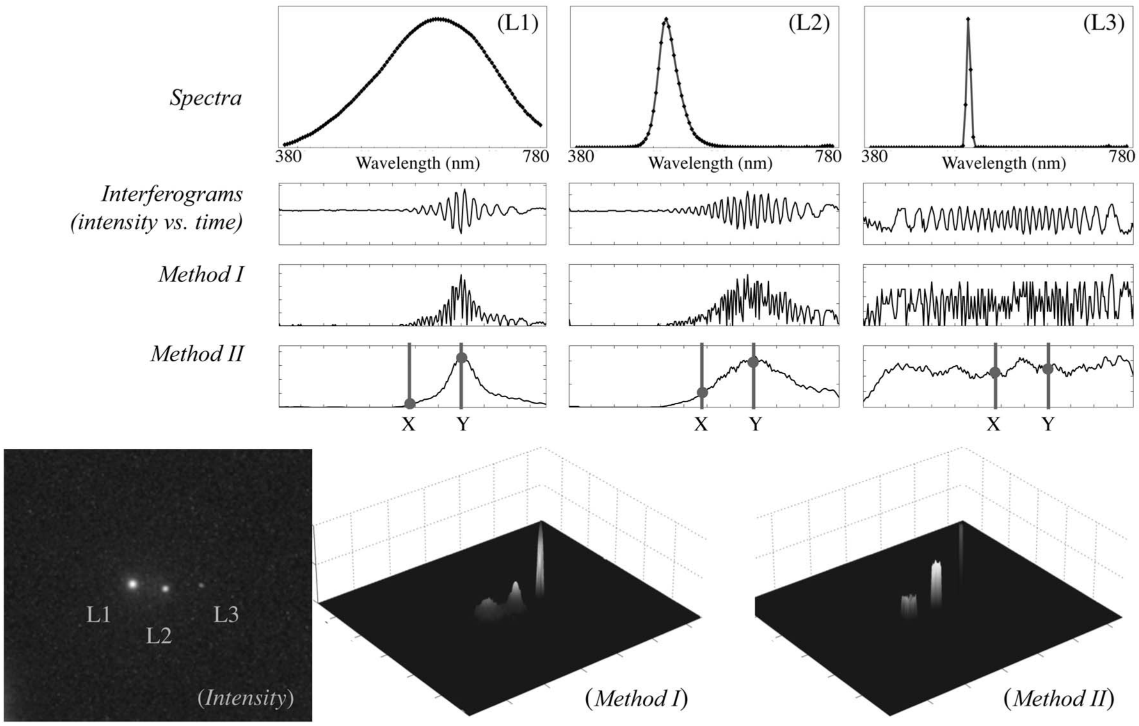

Figure 1: Sensing intensity and coherence length using Method I and II for three different light sources (L1, L2, L3); black floor represents image plane and height indicates coherence length.

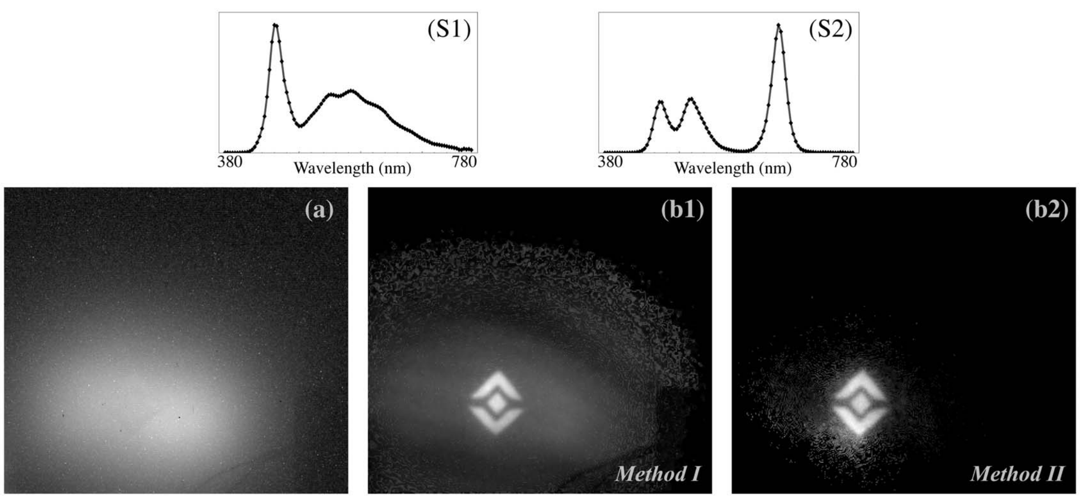

Figure 2: Detection of a narrowband tag: (a) the hidden tag S2 has the same color and intensity as the surrounding surface S1. (b1, b2) light emitted from the tag is detected because it exhibits a higher coherence length.

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