Evaluation of using coded aperture imaging in the mid- and far-infrared region

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***Abstract*— Hyperspectral imaging in the infrared spectral region makes it possible to identify chemical compounds and, at the same time, locate the compound. We provide simulations of using coded aperture snapshot spectral imaging (CASSI) to reconstruct the hyperspectral information from a single snapshot. We study the effect of using a complex scene, scene illumination by a black-body radiation, and effect of adding a noise to the synthetic datasets. Our results show, that the use of CASSI method with a simple binary mask leads to partially satisfactory results for the realistic scenes in the sense of determining the chemical compound but not for retrieving the quality of reconstructed scene.**

Keywords—hyperspectral imaging; infrared spectrum; coded aperture snapshot spectral imaging; compressed sensing

I. Introduction

Hyperspectral imaging (HSI) denotes all methods where, in addition to an image, we obtain a spectrum of light at each point of the image. HSI in the infrared (IR) spectral region is of great importance, as it can provide us with large amount of information about the scene of interest that cannot be obtained in any other way. An example can be the remote sensing of chemical compounds. For this reason, HSI in the IR has been very lively topic in the recent decades.

A number of studies focuses on HSI in the near-IR spectral range, which is accessible for a commonly used optics and Ge- or InGaAs-based detectors. However, the so-called mid- and far IR ($\lambda > 2.5$ μm) region is not widely utilized due to the need to use uncommon optical materials and array detectors.

A possible solution to this problem can be utilization of compressed sensing (CS) methods. CS refers to a signal processing technique that uses the principle that many natural signals are sparse, i.e. can be described by only few components in a certain basis. Use of CS for sparse signals makes it possible to reconstruct the signals from far fewer measurements than the Shannon-Nyquist theorem requires. In other words, it is possible to reconstruct signals by finding solutions to underdetermined linear systems. For more details we refer reader to [1].

In this article we focus on the use of the so-called CASSI (Coded Aperture Snapshot Spectral Imaging) method in the IR HSI, where sharp spectral absorption peaks superimposed on the black body radiation represent a specific type of scenes. Moreover, the scene has to be recorded by using an IR detector with a high level of a dark noise. The main goal of this article is to evaluate feasibility of using the standard CASSI method for the IR HSI, which would allow a simpler and less expensive construction of HSI devices. An overview of the HSI is supplemented by samples of reconstructions of artificial data (hyperspectral scenes) where we simulate the presence of chemical compounds on parts of the image and subsequently we reconstruct the hyperspectral scene.

II. Experimental Methods

Simulations and reconstructions of data were evaluated by Matlab. Two types of scenes were selected for reconstruction – a simple and a complex scene. The simple one was a scene with constant intensity in every pixel, while the more complex one was an image from infrared camera. Several different variations were simulated for every type of scene by using different sizes of the scene in pixels (32x32, 64x64, 128x128, ...), number of spectral slices (117, 235, 470, ...), and concentration of the chemical substance. Nevertheless, all simulations presented in this article were carried out by using 128x128 mask and scene image, resolved in 470 spectral slices, detected on a 128x597 detector.

As a chemical substance we chose isopropyl alcohol, if not stated otherwise, we employed the path-concentration of 1000 ppm m. The IR spectrum for isopropyl alcohol was obtained from The National Institute of Standards and Technology (NIST), data was compiled by: P.M. Chu, F.R. Guenther, G.C. Rhoderick, and W.J. Lafferty with resolution of 0.4820 cm^{-1} and parameters IFS66V (Bruker); 3-Term B-H Apodization.

For simulation we focused on one of the standard methods of compressed scanning, the so-called CASSI (Coded Aperture Snapshot Spectral Imaging) method. We refer reader for the detailed description of the CASSI method to a number of available articles [1, 2].

For image restoration during the reconstruction we used the TwIST (Two-Step Iterative Shrinkage/Thresholding) algorithm to minimize the following expression:

$$f(x) = \frac{1}{2}\|y - Kx\|^2 + \lambda\Phi(x) \qquad (1)$$

where K is the linear direct operator describing projection of a hyperspectral datacube x onto a single detector snapshot y, Φ is a regularizer, λ is a regularization parameter. We employed as a regularizing term a sum of total variations in each spectral image. [3] Operator K is calculated, for the sake of simplicity, so, that each spectral slice (image for every wavelength) is shifted by one column in the resulting detected image y.

III. Hyperspectral Imaging

A. Overview

There are three basic configurations of how one can obtain hyperspectral information (3D datacube). (1) *Whisker-broom* – the sample is scanned point by point, and for each such point one spectrum is recorded (1D detector, 2D scanning). (2) *Push-broom* – the detector acquires the spectral information for the entire line of pixels of the image simultaneously (2D detector, 1D scanning). The light passes through a slit and it is spectrally sheared on the detector, thus making is possible to record the spectral information along the entire line depending on the location from which the light comes. In this way a two-dimensional array is obtained which has one spectral dimension and one spatial dimension. For another spatial dimension of the datacube, we need to scan the sample in a direction perpendicular to the imaging line. (3) *Staring configuration* – (2D detector, 1D scanning) this type of configuration does not require any movement (or spatial scanning) of the sample or a slit, so it is also referred as "staring configuration". The incoming light is recorded on the detector as a two-dimensional spatial array for each wavelength. This is done by means of filters (band-pass filters [4] or adjustable acousto-optic filters [5]) which can be placed on a revolving disc or change the passing wavelength respectively. [1]

Whisker-broom and push-broom scans have excellent spatial and spectral resolution, however, the necessity to mechanically scan an image implies that the acquisition times are long. Typically, the times are in the order of tens of minutes to hours, depending on the size of the scanned area, the wavelength range and the number of scans per pixel [6]. For processes that are not stable in time is favorable to use the staring configuration since it is possible to record a complete datacube in a matter of seconds or minutes, depending on the number of scanned wavelength intervals.

Selection of the suitable method depends highly on the concrete field of application, since HSI is being used in a wide variety of fields, e.g. medical imaging [7], quality control and food analysis [8, 9], forensic sciences [10, 11], art conservation [12], etc.

B. Compressed sensing

In conventional signal processing, we are limited by the so-called Shannon-Nyquist theorem, which imposes that for the correct reconstruction of the signal, the sampling frequency must be at least twice as high as the highest frequency present in the signal. This is very inconvenient for capturing rapid processes or for the IR region, where we are significantly limited by the structural elements of IR cameras and their high purchase prices.

However, Shannon-Nyquist theorem can be bypassed by compressed sensing (CS), which is based on two assumptions – (i) sparsity of a signal and (ii) signal measurement by using a set of incoherent (often random) projections of the signal.

CS is often employed in imaging since common images count to the sparse datasets in the Fourier or wavelet space. For example, a conventional camera captures the scene pixel by pixel, creating a huge amount of RAW data. However, the image can be compressed to few percent of the original size without apparent loss of the image quality by using the strongest Fourier transform coefficients (JPEG compression). The problem is that we are not able to compress the scene until we capture it because we do not know *a-priori* which Fourier components will carry the important information about the image.

The so-called CASSI (Coded Aperture Snapshot Spectral Imaging) method employing the CS theory makes it possible to encode the whole hyperspectral scene (3D dataset) in a single instant (2D snapshot) using a random mask. The random mask (random pattern) serves as an incoherent measurement projection. By employing a spectral shearing (prism or grating) the random mask is shifted to different positions for different wavelength, thus enabling subsequent HSI reconstruction.

Variations of the CASSI technique are used also for shearing the temporal information (e.g. CACTI), thus making it possible to capture events taking place in the order of tens of ps (CUP technique) [13].

C. Using compressed sensing in IR hyperspectral imaging

Absorption of mid-IR light changes the fundamental vibrational and rotational states of the chemical bonds. When the molecule interacts with IR light, chemical bonds begin to vibrate more energetically, and thus affect absorption at certain wavelengths in the spectrum that are characteristic for each chemical bond.

The ability to absorb near-IR is relatively small and depends on the harmonic and anharmonic movement of molecules, which is due to electronic transitions. [14] Therefore, this paper is focusing on mid- and far-IR region.

There are not many articles on application of CS in mid- and far-IR HSI [15-17]. This could be attributed to the problematic connected with the need of special optic elements and detectors in IR region.

IV. Results and Discussion

The CASSI technique is exploiting a coded aperture and dispersive element(s) to modulate the optical field from the scene, which is captured in one instance on the detector into the two-dimensional snapshot. We used a random binary mask (see Fig. 1, right panel) as a coded aperture to encode a scene. The random mask is blocking approximately ½ of the incoming light and the columns in the mask, owing to their randomness, are incoherent. We created a HS datacube $H(i,j,\lambda)$ by using the same scene $S(i,j)$ in all spectral images multiplied by a radiation spectrum of the light illuminating the scene $R(\lambda)$:

$$H(i,j,\lambda) = S(i,j).R(\lambda) \qquad (2)$$

To simulate the presence of a chemical substance the central part of the scene was "contaminated" with isopropyl alcohol which caused distinguishable difference in intensity at specific slices of the datacube (see Fig. 1, middle panel). In other words, we multiplied the datacube $H(i,j,\lambda)$ by an absorption spectrum of the studied compound $A(i,j,\lambda)$ for each scene pixel i,j:

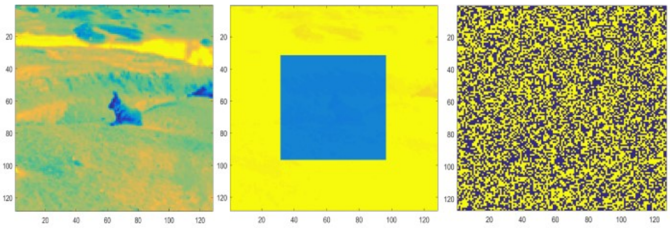

Fig. 1. Complex scene (left), slice of the datacube (complex scene 128x128 pixels) with applied chemical substance (middle), random mask 128x128 pixels (right)

$$H'(i,j,\lambda) = H(i,j,\lambda).A(i,j,\lambda) \quad (3)$$

$H'(i,j,\lambda)$ is a datacube that is coming to a HS camera where it is encoded by the random mask pattern $M(i,j)$ for every wavelength. The encoded image E can be expressed as:

$$E(i,j,\lambda) = H'(i,j,\lambda).M(i,j) \quad (4)$$

We used two types of test scenes S. One was a plain scene (S is constant), which equals for capturing an IR image obtaining a constant temperature through the whole scene, i.e. same intensity in each pixel. The second one was an arbitrarily chosen image from an IR camera (Fig. 1, left pannel).

Spectrum of the light illuminating the scene R was either left constant for initial experiments or set according to a black body radiation attribute (Planck's law) which is wavelength dependent. We set temperature to be 300 K for a plain scene or differ from 283 to 323 K for an IR image.

A. Detector signal

The detected IR light in a CASSI-type camera is transmitted through the IR optics and then is refracted by a dispersive element to different positions on the detector depending on the wavelength. Every spectral slice of the datacube (scene for each wavelength) was shifted on the detector by one pixel-column to the right compared to the previous slice, i.e. slices were overlaying each other, which led to the total signal on detector (Fig. 2, lower panel) $D(k,l)$:

$$D(k,l) = \sum_{\lambda} E(k,l+\lambda,\lambda) + n(k,l) \quad (5)$$

where the term $n(k,l)$ enabled us to add a certain noise level to the detected image.

In Fig. 2 (upper left panel) we can see the example of one spectral slice of the datacube *H'*. For the sake of clarity, we selected among many slices the wavelength, at which the absorption was the most significant. The resulting detector image for this scene is provided in Fig. 2 (lower panel).

B. Data reconstruction

Data reconstruction was evaluated by TwIST algorithm, which is an improved version of a standard IST algorithm [17]. For each slice of original datacube we obtain one slice of reconstructed datacube – see Fig. 2 (upper right panel) for an example of a reconstructed spectral slice. We can subsequently also recover the absorption spectrum of the chemical compound from the reconstructed datacube as a sum of the central area, where the chemical compound was in the original image. We obtain a good agreement between the original and reconstructed spectrum (see Fig. 3). The relative intensity and position of the

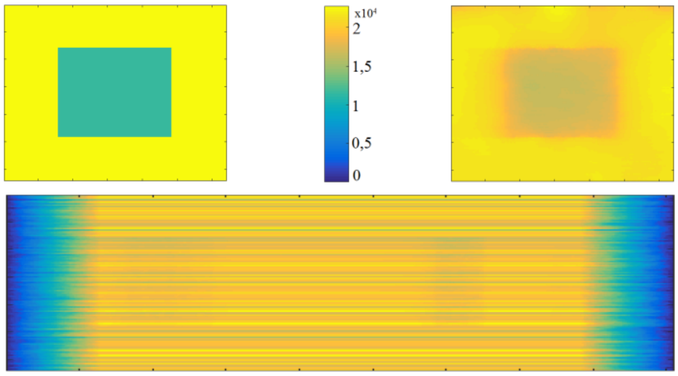

Fig. 2. Reconstruction of the simple scene. Slice of original datacube (upper left), detected image at the detector (lower), reconstructed slice of the datacube (upper right).

peaks to each other is particularly important to successfully determine the chemical compound and its volume.

The reconstructed data are satisfying in terms of recognition of the chemical compound and, most importantly, its localization. However, it is not possible to retrieve details of the original scene back. As you can see in Fig. 3 (small panels), there is not a significant difference between simple and complex scene in the reconstructed slices. This indicates that subtle changes in a scene due to absorption from a minor concentration of a chemical compound are likely to be suppressed by the reconstruction algorithm.

When we included the black body radiation (Planck's law) into the simulation, the quality of reconstructed spectrum is only slightly degraded (see Fig. 4), nevertheless the quality of the reconstructed datacube slices is notably worse in case of the complex scene – Fig. 4 (small panel). In this case, it would be very difficult to correctly localize the chemical compound. This is likely caused by a significant complexity of the IR spectra, which are sparse in terms of the image information, however, contain complex spectral information.

Finally, it is also worth noting, that with an addition of up to 5% noise the data reconstruction is still reasonable for simple

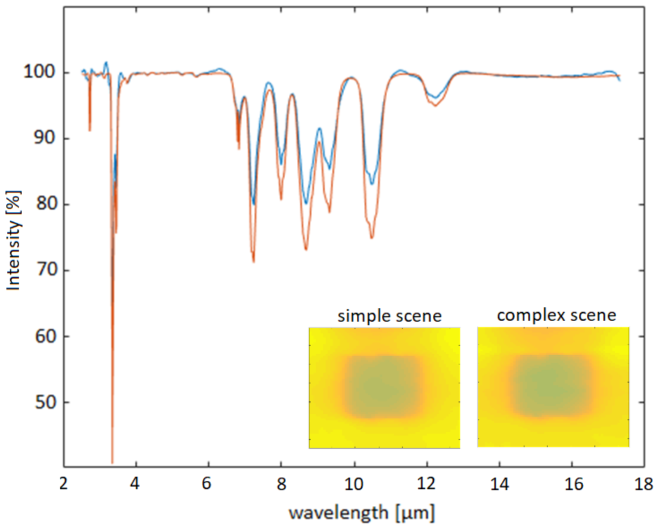

Fig. 3. Original (red) and reconstructed (blue) spectrum of constantly irradiated complex scene, reconstructed slices of datacube (small panel).

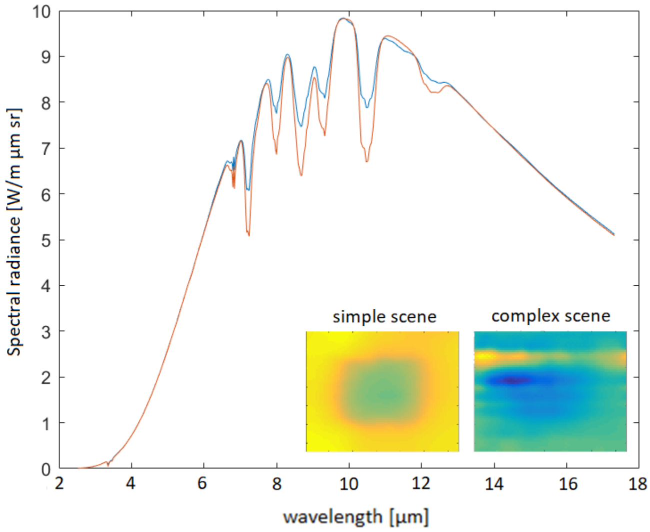

Fig. 4. Original (red) and reconstructed (blue) spectrum of the complex scene with black body radiation, reconstructed slices of datacube (small panel)

scene, however in the case of the complex scene, even 1% of noise level has a significant effect on the reconstruction.

V. Conclusion

In this article we provided an overview of IR hyperspectral imaging, with particular attention to compressed sensing. We also summarize results of our testing calculations, which evaluate the feasibility of using CASSI technique for hyperspectral imaging of IR absorption spectra of chemical compounds.

The central goal is to provide the possibility to rapidly capture spill of chemical substances, enabling both their localization and identification.

We came to conclusion that for complex scenes we are able to determine the type of chemical compound, nevertheless we do not achieve sufficient reconstruction quality. The CASSI method using binary masks cannot be therefore directly applied in this case. Further research will be focused on using, for example, several measurements of different random masks, rotation of spectral sweeping, improved mask design, improving of the reconstruction algorithm, etc.

Acknowledgment

We gratefully acknowledge the financial support of the Grant Agency of the Czech Republic (project 17-26284Y) and the Ministry of Education, Youth and Sports of the Czech Republic (Project NPU LO1206).

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