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Design and realization of a miniaturized high resolution computed tomography imaging spectrometer

Simon Amann[1,*], *Tobias* Haist[1], *Alexander* Gatto[2], *Markus* Kamm[2], and *Alois* Herkommer[1]

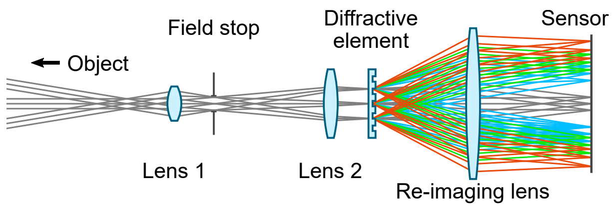
[1]University of Stuttgart, Institut für Technische Optik, 70569 Stuttgart, Germany
[2]Sony Europe B.V, Stuttgart Technology Center, 70327 Stuttgart, Germany

Abstract. The computed tomography imaging spectrometer (CTIS) is a relatively unknown snapshot hyperspectral camera. It utilizes computational imaging approaches to gain the hyperspectral image from a spatio-spectral smeared sensor image. We present a strongly miniaturized system with a dimension of only 36 mm x 40.5 mm x 52.8 mm and a diagonal field of view of 29°. We achieve this using a Galilean beam expander and a combination of off-the-shelf lenses, a highly aspherical imaging system from a commercial smartphone and a 13 MP monochrome smartphone image sensor. The reconstructed hyperspectral image has a spatial resolution of 400 x 300 pixel with 39 spectral channels.

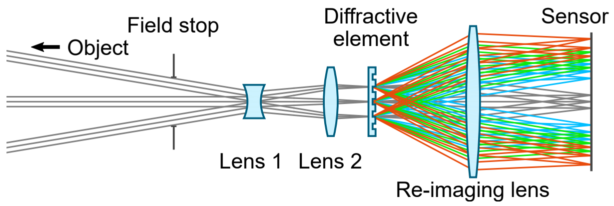
1 Introduction

Hyperspectral imaging is widely used in various fields such as environmental observation, medical diagnosis or food quality control [1]. Most of the used hyperspectral cameras use scanning approaches (spatial, spectral or mixed) to capture the full data cube consisting of a two-dimensional image for each spectral channel. This leads to problems such as motion artifacts or an increased mechanical complexity (moving parts). The computed tomography imaging spectrometer (CTIS) uses a different approach. It computes the hyperspectral information from a single captured sensor image. A typical optical design of such a system is illustrated in Figure 1a.

A diffractive optical element (DOE) is used to create a spatio-spectral smeared two-dimensional sensor image. The zeroth diffraction order is usually placed in the middle of the sensor and is equivalent to a monochrome image of the scene. Several higher diffraction orders, that are similar to an oblique projection of the hyperspectral data cube, are arranged around it. A field stop is used to limit the size of the imaged scene. This is typically done in the intermediate image plane of the first lens. A reconstruction algorithm is required to derive the hyperspectral image from the sensor image. In this paper we use an implementation based on the EM algorithm that utilizes space invariance of the sensor signal [2].



(a) Keplarian (typical) design.



(b) Galilean design.

Figure 1: Different CTIS designs using a Keplarian and a Galilean beam expander.

2 Miniaturization

One major drawback we want to address is the relatively big size of most published CTIS systems, which often hinders their use outside of laboratory environments. The main reason for this is that the focal length of the system has to be very small when a reasonably large field of view (FOV) is used (full scene has the size of the zero order projection in the image plane). The minimal focal length of the re-imaging lens is limited because a distortion effect appears when the angles of the diffracted rays become high. This effect is caused by the non-linear diffraction of light in image space [3]. The first two lenses, therefore, act as a beam expander. They reduce the ray angles and hence the total focal length. The typically used Keplarian type of beam expander does have the big advantage that the intermediate image can be used to crop the imaged scene (field stop). However, we have found that in some cases it

[*]e-mail: amann@ito.uni-stuttgart.de

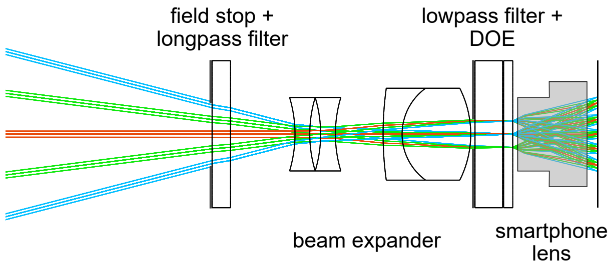


Figure 2: Optic design of the prototype.

Figure 3: Assembled prototype.

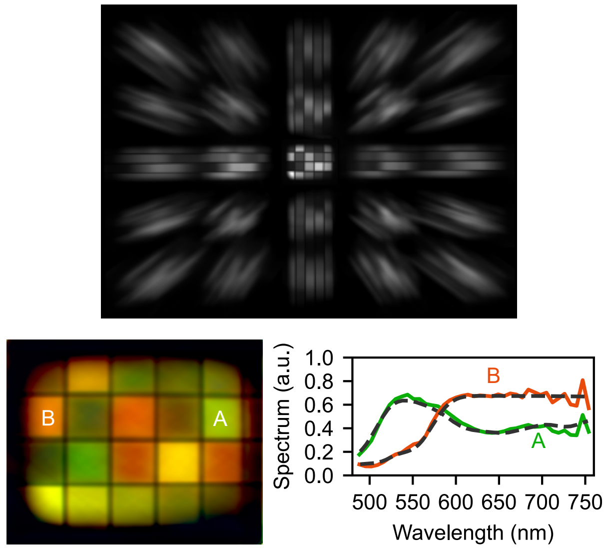


Figure 4: Pre-processed sensor image and reconstruction results. The shown spectra are averaged over a 5 x 5 pixel area. The ground truth is shown in dashed black lines.

is beneficial to use a Galilean type of beam expander instead (Figure 1b). It often achieves a better optical performance in a smaller form factor when the same complexity of lenses is used. The field stop is placed with some distance in front of the first lens. One major drawback of this approach is that the intermediate image, and consequently the reconstructed hyperspectral image, is considerably vignetted when the field stop is placed close to the system or a small f-number is used. The optimal design depends on the requirements of the system.

3 Setup and results

The optical design of our prototype is shown in Figure 2. The first element is the field stop that is made of laser cut cardboard. It is followed by an absorptive longpass filter (Hoya Y48) that is used to block light below 480 nm. Lens 1 is realized using two stacked lenses with a focal length of −4 mm each (SLM-04B-04N from OptoSigma). Lens 2 is an achromatic lens with a focal length of 7.5 mm (#49-275-INK from Edmund Optics). Subsequent to this is a dichroic shortpass filter (#47-817 from Edmund Optics) with a cut-off wavelength of 750 nm. The following DOE is a custom, in-house produced binary computer generated hologram. The lens from a Sony Xperia 10 Plus smartphone (illustrated as black box) is used as the re-imaging lens. We chose this because its entrance pupil is close to the front of the lens housing and its big image size (compared to the focal length of approximately 4 mm). The See3CAM CU135M from e-con Systems, with a monochrome 13MP image sensor, is used as the camera body. The vital parts of the mechanics are made of anodized aluminium.

An image of the assembled prototype can be seen in Figure 3. The total optical track length is only 21 mm; the total size including the housing is 36 mm x 40.5 mm x 52.8 mm. The effective focal length of 0.9 mm results in a diagonal FOV of 29°.

Figure 4 shows one exemplary, pre-processed sensor image taken of a ColorChecker. The zero order image is taken with a lower exposure time than the higher diffraction orders and afterwards superimposed. Furthermore we subtracted stray light and corrected the distortion effect caused by the non-linear diffraction. The reconstruction result is illustrated in its RGB representation together with some selected spectra. It has a spatial resolution of 400 x 300 pixel with 39 spectral channels (7 nm steps from 488 nm to 754 nm). The result is in a good agreement with the ground truth values. We assume that remaining inaccuracies originate from noise, stray light and artifacts of the reconstruction algorithm. A custom lens design together with a better reconstruction (for example by using neural networks [4]) can help to improve the result.

4 Conclusion

A strongly miniaturized and portable CTIS has been presented. Despite its size, it has a large resolution and field of view. We achieved this using a Galilean instead of a Keplarian beam expander. It can be used in applications where a small physical size is required.

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