Concept, manufacturing and challenges of ultra-compact snapshot multi-spectral multi-aperture imaging systems

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Abstract. Snapshot multispectral imaging is a rising non-invasive and contact-free analysis method and technology to discriminate or identify objects based on their spectral characteristics. We demonstrate a versatile system approach for compact and real-time capable snapshot cameras for the visible (VIS) and the near-infrared (NIR) or the short-wave infrared (SWIR) wavelength range based on a micro-optical multi-aperture system and various spectral filter approaches. In addition, the manufacturing, the calibration, and the limitations of the demonstration systems are described.

1 Introduction

Well-known solutions for multi- and hyperspectral imaging systems are based on one- or two-dimensional scanning approaches suffer from artefacts due to motion blur by non-uniform movements or a reduced signal-to-noise ratio in dynamic scenes. However, several snapshot imaging techniques are reported in Hagen et. al [1], which try to overcome these drawbacks including the TOMBO approach for multispectral imaging [2]. In the last years, a major trend is seen towards miniaturized and real-time capable systems especially adapted for UAV-supported applications for precision farming and environmental monitoring or for handheld devices. There, size, weight and power as well as the costs are crucial parameters.

So, we developed a couple of multispectral snapshot cameras based on a multi-aperture imaging approach using a customized micro-lens array (MLA) and various spectral filters. Each system features different spectral and spatial resolutions in the multispectral data cube depending on the used filter technology as well as the size of the image sensor. The peculiarities and similarities of these are described in this article in excerpts.

2 System design

The object is imaged via multiple regularly (i.e. rectangular) organized miniaturized objective lenses on a common glass substrate (denoted as MLA) onto a commercial image sensor, where the object distance is several times larger than the focal length of each micro objective (aka. channel) shown in Figure 1. The spectral filters are either placed close to the aperture of the system or to the image sensor plane (special image sensor with tiled filter arrays or a customized cover glass is required). Additionally, there are different spectral filter technologies like band-pass filters (BP), linear variable filters (LVF) and Fabry-Pérot filters (FP), which we have applied to our systems (see Sec. 2.1). Furthermore, a baffle array is indispensable for the overall setup serving as a field aperture to suppress cross-talk between neighboring channels and out-of-FoV false light.

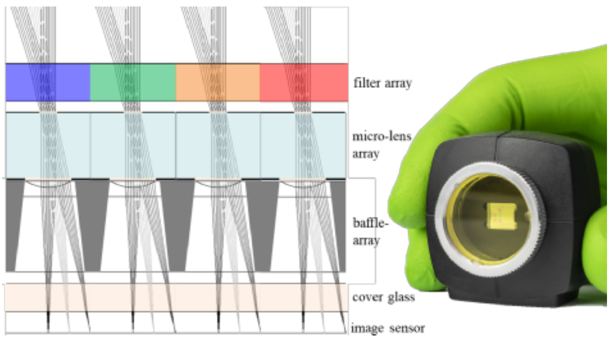

Figure 1. Generalized optical system concept including the main parts of the snapshot multispectral camera (left). Compact size of the ETCHED-VIS demonstration system compared to a hand (right).

Using this approach, a single shot acquisition of the spectral data cube is obtained without an additional bulky objective lens.

2.1 Filter approaches

LVFs are spectral band-pass filters on one glass substrate with a variation of the pass-band along one physical direction. So, it is worthwhile to rotate this filter around the optical axis of the MLA by a certain angle in order to achieve a linear spectral sampling over all channels using a monolithic element (see [3]). However, the limited gradient of such a continuous varying filter requires a relatively

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Table 1. Overview of several parameters of our accomplished systems.

parameter/demo system	LINE-VIS [3]	ETCHED-VIS	BP-VIS	LINE-SWIR	ETCHED-SWIR [4]
filter approach	LVF	FP	BP	LVF	FP
spectral range	VIS-NIR	VIS-NIR	VIS-NIR	SWIR	SWIR
spectral resolution	10 – 16 nm	30 – 40 nm	20 - 40 nm	40 – 50 nm	20 – 30 nm
spectral sampling	continuously (~6 nm)	discrete	discrete (~50 nm)	continuously (~25 nm)	discrete
data cube [X x Y x λ_n]	400x400x66	640x640x12	750x620x9	128x128x20	256x213x6
FoV (diag.)	68°	32°	45°	36°	70°
F#	F/7	F/5.4	F/5.1	F/3.5	F/3.0
pixel size	7.4 µm	2.2 µm (4.4 µm w/ binning)	3.45 µm	15 µm	15 µm
physical size [L x W x H]	60 x 60 x 28 mm³	46 x 47 x 33 mm³	90 x 40 x 30 mm³	80 x 55 x 55 mm³	80 x 55 x 55 mm³
weight	200 g	55 g	110 g	350 g	350 g

large image sensor size and the suppression of the blocking range is lower than for single BP filters. So, BP filters are more feasible for a few spectral channels. Besides BP filters, FP filters are another possibility to apply a spectral filter, which can be narrow-band depending on the complexity of the mirror system at the boundary of the cavity height. The cavity height defines the transmission wavelength which can be tuned via a structuring process and a filter tile array can be fabricated as monolithic element reducing assembly technology costs compared to single BP filters.

2.2 Demonstration systems

An overview of our accomplished systems including several important parameters, i.e. optical and spectral properties, are found in Table 1.

3 Manufacturing and Challenges

All MLAs are fabricated as polymer-on-glass optic via reflow of photoresist or ultra precision tool mastering technologies and a subsequent replication step on wafer-scale inhouse, which offers cost-efficient elements for large quantities. The one- or double-sided MLAs feature also buried black apertures. However, the sag height and shapes of the micro-lenses achieved by those technologies limit the spatial resolution and the f-number of each channel, but there are emerging technologies to overcome these restrictions for multi-aperture imaging systems.

The manufacturing of the filter tile array is performed by a grayscale photolithography process [5] in resist and a subsequent proportional dry-etching process (RIE) into fused silica of the filter's cavity layer. However, the realization of the differences in cavity height between the filter tiles as well as the final absolute height are ambitious due to a varying etch rate factor over time and the selectivity during the dry-etching process. The coating of the filter tile arrays in the ETCHED-VIS and ETCHED-SWIR demonstration system has been realized by magnetron sputtering on Borofloat glass (Schott B33) wafers.

The manufacturability and the performance of the baffle array for the optical system is challenging due to the reflection and scattering coefficients of the materials and coatings under large angle of incidence and the aspect ratio of the separator walls. A thick cover glass and a large gap between cover glass and image sensor reduces the relative illumination behavior of each optical channel due to additional vignetting of outer fields. Removed cover glass image sensors are preferred for very high fill factors. The baffle arrays for the demonstrators were milled out of metal alloys and coated subsequently through plasma chemical oxidation.

The spectral calibration of the individual cameras is performed via measurements using a monochromator setup as presented in [3]. The similarity of all is the wavelength shift of the central transmission wavelength due to the increase of the angle of incidence for outer fields.

4 Conclusion

The versatile approach shows a high potential for capturing spectrally resolved, extended object fields in a snapshot for a wide range of applications in different wavelength ranges, that benefits from a compact architecture. Challenges for further miniaturization, monolithic filter tile array elements, or higher spatial resolution have to be solved in the near future.

References

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