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Image plane moving stage for high precision multispectral imaging

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ABSTRACT

This paper presents a solution to overcome longitudinal chromatic distortion typical of spectral imaging. Here, a short description of the experimental setup and smart multispectral imager for industrial applications is presented. The image system is composed of a filter wheel composed of 12 filters spanning from 400 nm until 950 nm with a 50 nm bandwidth (fwhm). Chromatic distortion on the system is explained in details, showing that a high precision moving image plane and an adequate image registration can overcome the aforementioned effects. Development and characterization of a high speed linear-moving-stage is shown subsequently. To conclude this work, a selection of applications exploring the advantages of such solution is presented.

1. Introduction

Spectral imaging is always a compromise between three main parameters: acquisition time (simultaneity); spectral resolution (spectral range); and spatial resolution. That means, it is not feasible to increase one parameter without compromising one or both remaining parameters (Fig. 1). One good compromise for acquisition time and spatial resolution (for few spectral channels) is using systems based on filter wheels for spectral selection and a high resolution imaging sensor. This is the solution chosen at our group for smart multispectral imaging for industrial applications [1]. The system described in this work (shown in Fig. 2) uses a filter wheel composed of twelve exchangeable bandpass. These are application specific. The main parameters of the imager are summarised on Table 1. Along with the system development and extensive evaluation [9–11], effort was put in developing algorithms for image registration, distortion correction and sup-pixel feature detection [3,8,13–16]. State of the art hardware and software development enables high precision for multispectral imaging.

Dioptric optical systems under broadband illumination often suffer from chromatic aberration [1–3]. The next chapter goes into more details on chromatic aberration and describes how it can be overcame.

2. Chromatic distortion

Chromatic distortion comes from the dependence on the index of refraction with the wavelength, i.e. $n = n(\lambda)$. It can be broken down into two components: aberration along the optical path (longitudinal) and perpendicular (transverse) to it. Both are present on our system and strategies for overcoming each of them are different [4].

Longitudinal chromatic aberration can be understood as a focal position dependence along the optical path with the wavelength: $F = F(\lambda)$. For a single material lens (e.g. BK7), light with lower wavelength focus before, or closer to the lens, as seen in Fig. 3(a). This dependence can be analytically expressed, mathematically modelled and corrected (dispersion formulas–p. 590–592 [5]). For real systems, composed of multiple lenses and materials (flint and crown glasses), a mathematical (analytical) description of the focus dependence with wavelength is often not possible, and the calibration of the focal position in dependence with the wavelength is necessary, refer to Fig. 3(b). Calibration is done by moving the image sensor along the optical axis until a sharp image of a calibration object (binary edge transition) is obtained. The best focus routine is an edge-based depth-from-focus described in [6]. It guarantees precise positioning (under 4 µm) and sharp images, regardless of which channel (filter) is being used. After a calibration is done, it is possible to relate position the image sensor to the best focus position, through means of a lookup table connecting filter (λ) and best focus position.

Transverse chromatic aberration comes from the presence of the metallic interference filters, that act as filters (Fabry-Pérrot) [7]. Refraction on both surfaces of the filter introduce an offset to the incoming beam, as seen on Fig. 4(a), this offset is wavelength dependent and its effect can be seen on Fig. 4(b), where two images taken at two different wavelengths are superimposed (λ_1 = 450 nm and λ_2 = 950 nm). With an appropriate image registration, this offset can be compensated with subpixel accuracy, as described in [3]. The improvement effect of an appropriate image registration can be seen on Fig. 4(c) and (d).

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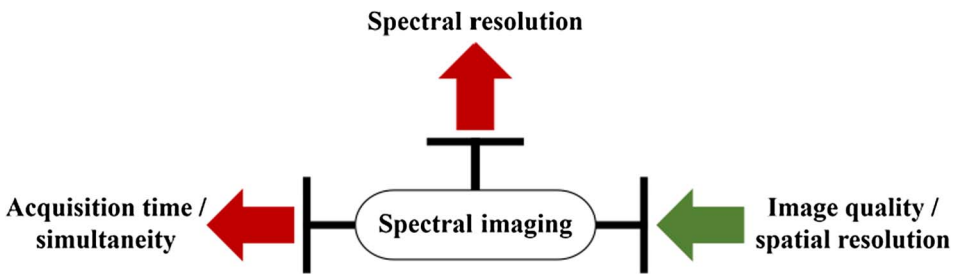

Fig. 1. Spectral imaging constraints. Increasing spatial resolution will deteriorate either the spectral resolution, acquisition time/simultaneity or both. The same goes for increasing spectral resolution or simultaneity.

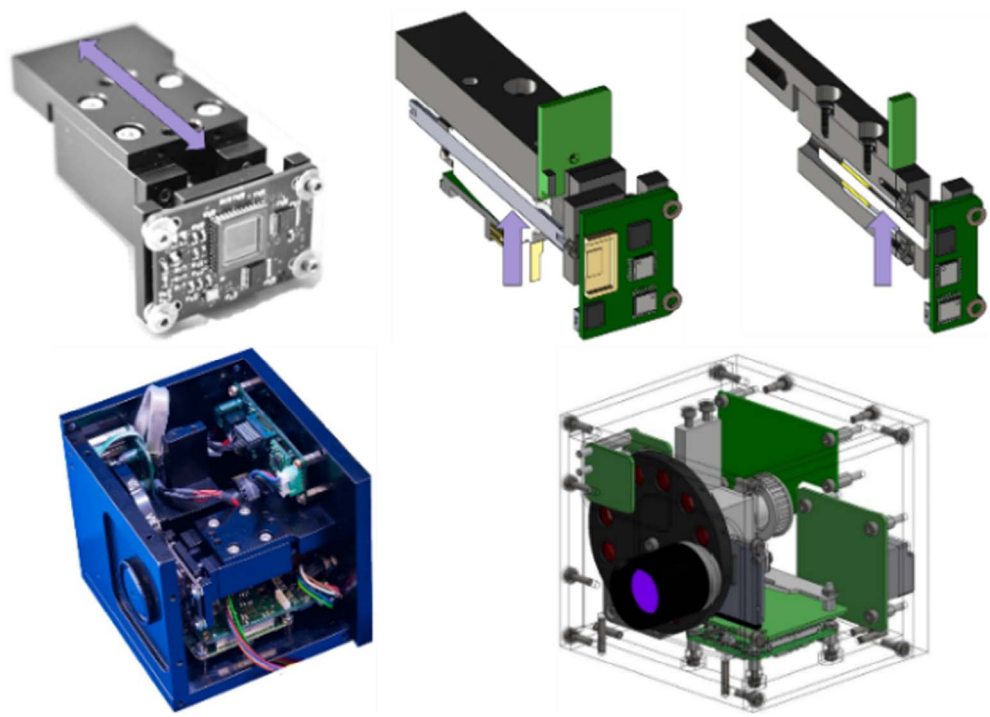

Fig. 2. Top row: shows an image of the imaging sensor and the axis (arrow) where the sensor can move along (left). A sketch shows a cut of the moving stage and its main components with the linear motor (centre) and the linear bearings in evidence (right). Lower row: image of the smart imaging sensor without its casing, for better visualisation (left). A sketch of the imager ($10 \times 10 \times 11\ cm^3$) with the main components is also presented. Special attention to the imaging optics, filter wheel and sensor (right).

Table 1
Main electro-opto-mechanical parameters of the smart imager.

Electro-opto-mechanical parameters	
Lateral resolution[a]	100–630 µm
Pixel size	5.3 µm
Sensor	EV76C661 CMOS
Focalisation speed	< 20 ms
Filter bandwidth[b]	10–50 nm
Spectral range[c]	350–950 nm
Imager volume	$10 \times 10 \times 11\ cm^3$
Number of filter slots	12
Frame rate	60 fps
Filter wheel rotation speed	120 rpm
Full wavelength scan time[d]	410 ms–2.1 s
Interface	GigE-Vision

[a] Values depends on the objective lens used. Values here are for 8 mm and 50 mm objectives.
[b] The bandwidth and spectral range can be tuned by choosing an appropriate filter set.
[c] Values for full resolution (1024 per 1280 pixels).
[d] Values depends on light source spectrum, integration time and image size.

3. Image plane moving stage

The smart camera is controlled by an FPGA and two microcontrollers: the first one controls the filter wheel and the second one, the image sensor positioning, which is done by an optical feedback system and counting steps on the motor. The moving stage, which consists out of two high precision linear bearings, a high precision linear motor and a special mechanical mounting (Fig. 5), are integrated in a self-constructed 12-channel-multispectral imager [1]. For the correction of the longitudinal chromatic aberration [3], the image sensor is mounted on two high precision linear bearings, which will guarantee a deviation of less than one micrometre along the specified working range of four millimetres. This enables a wide working range for the chromatic error compensation as well as for the usage of a wide variety of different lenses and filters inside the system, while holding the sensor in a stable lateral position to minimise image shifts. The linear motor is directly connected in the middle of these two bearing.

During the assembly of the system, the linear motor is actuated along the working range while the mounting was not fixed, so the stresses resulting from the mechanical over-determined construction can be reduced, which translates to a decrease in friction along the