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Band registration of tuneable frame format hyperspectral UAV imagers in complex scenes

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ABSTRACT

A recent revolution in miniaturised sensor technology has provided markets with novel hyperspectral imagers operating in the frame format principle. In the case of unmanned aerial vehicle (UAV) based remote sensing, the frame format technology is highly attractive in comparison to the commonly utilised pushbroom scanning technology, because it offers better stability and the possibility to capture stereoscopic data sets, bringing an opportunity for 3D hyperspectral object reconstruction. Tuneable filters are one of the approaches for capturing multi- or hyperspectral frame images. The individual bands are not aligned when operating a sensor based on tuneable filters from a mobile platform, such as UAV, because the full spectrum recording is carried out in the time-sequential principle. The objective of this investigation was to study the aspects of band registration of an imager based on tuneable filters and to develop a rigorous and efficient approach for band registration in complex 3D scenes, such as forests. The method first determines the orientations of selected reference bands and reconstructs the 3D scene using structure-from-motion and dense image matching technologies. The bands, without orientation, are then matched to the oriented bands accounting the 3D scene to provide exterior orientations, and afterwards, hyperspectral orthomosaics, or hyperspectral point clouds, are calculated. The uncertainty aspects of the novel approach were studied. An empirical assessment was carried out in a forested environment using hyperspectral images captured with a hyperspectral 2D frame format camera, based on a tuneable Fabry-Pérot interferometer (FPI) on board a multicopter and supported by a high spatial resolution consumer colour camera. A theoretical assessment showed that the method was capable of providing band registration accuracy better than 0.5-pixel size. The empirical assessment proved the performance and showed that, with the novel method, most parts of the band misalignments were less than the pixel size. Furthermore, it was shown that the performance of the band alignment was dependent on the spatial distance from the reference band.

1. Introduction

Hyperspectral imaging employs tens to hundreds of contiguous bands in order to accurately reconstruct the spectral signature of the target of interest (Goetz, 2009). Hyperspectral imagers with a variety of imaging principles have been operated from satellites and manned airborne platforms for decades (Schaepman, 2009). Whiskbroom imagers capture object spectra in pixels; examples of these sensors are the AVIRIS (Vane et al., 1993) and HyMap (Cocks et al., 1998). Pushbroom scanners, such as CASI (Babey and Anger, 1989) and the AISA series (Specim, 2017), capture spectra in lines. The use of sensors operating in the frame format principle (for example, those based on filter wheels or tuneable filters) have been rare due to the associated processing challenges (Schaepman, 2009).

Miniaturised hyperspectral sensor technology has developed rapidly in recent years, and the sensors are being implemented in small unmanned airborne vehicles (UAV). These novel technologies offer completely new opportunities for carrying out environmental remote sensing tasks. Several pushbroom hyperspectral sensors have been recently implemented in UAVs (Zarco-Tejada et al., 2012; Hruska et al., 2012; Büttner and Röser, 2014; Lucieer

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et al., 2014; Suomalainen et al, 2014). Researchers have also implemented point-based spectrometers in UAVs (Uto et al., 2013; Burkart et al., 2015). Recently, hyperspectral cameras operating in the frame format principle have entered the market (Mäkynen et al., 2011; Saari et al., 2011, 2013; Honkavaara et al., 2013; Mannila et al., 2014; Aasen et al., 2015).

When considering different sensing principles in UAV, the advantages of the frame imaging approach over the traditional pushbroom or whiskbroom scanning approaches include the possibility to collect image blocks with stereoscopic multiple object views and the geometric and radiometric constraints provided by the rigid rectangular image geometry (Honkavaara et al., 2013). Furthermore, georeferencing processing of 2D frame format sensors is simpler than that of pushbroom sensors that typically require expensive and heavy high-end direct georeferencing systems based on global navigation satellite system and inertial measurement unit (GNSS/IMU). Novel structure-from-motion (SFM) or bundle block adjustment technologies (Wu, 2013) and dense image matching technologies (Hirschmüller, 2005; Gruen, 2012) enable efficient and reliable image orientation and reconstruction of the object 3D structure based on frame-format images. In many applications, the 3D information is a significant feature parallel to the spectral information, for instance precision agriculture, vegetation monitoring, and forest measurements (Honkavaara et al., 2013; Aasen et al., 2015; Näsi et al., 2015). Commercially available frame-format hyperspectral imagers or sensors include the Rikola Hyperspectral Camera (Senop, 2017), the Cubert UHD 185-Firefly (Cubert, 2017) and the IMEC SM5X5 and SM4X4 (Imec, 2017).

When concerning mobile applications, the frame sensors can be further classified based on the imaging principle as those capturing registered spectral bands (snapshot imaging) or as those capturing non-registered bands (Aasen et al., 2015). The technologies collecting registered bands are based on mosaic filters, which reduce the spatial resolution, and the full resolution is provided by applying interpolation. Technologies that produce non-registered bands include techniques such as multiple cameras, filter wheels and tuneable filters. Different techniques could also be combined, for example, mosaic filters and tuneable filters. This study concerns band registration of the novel hyperspectral camera based on a tuneable Fabry-Pérot interferometer (FPI) (Mäkynen et al., 2011; Saari et al., 2011, 2013; Honkavaara et al., 2013). The FPI technology makes it possible to manufacture a lightweight, frame-format hyperspectral imager operating on the time-sequential principle, and it is also commercially available (Senop, 2017). The camera captures each individual hypercube by scanning the spectral range with different spectral settings within a short time interval, for example 1–2 s, by modifying the air gap between the FPI. As a result, the individual bands are 2D frame-format images, captured successively at each FPI gap size along the camera spectral range (Honkavaara et al., 2013; Oliveira et al., 2016). Thus, this technology will produce hypercubes with non-registered bands, when operated on a moving platform. More details of the technology and sensor used in this study are given in Sections 2.1 and 3.1. The above division is useful for mobile data capture; when operated in static mode, these techniques can also generate registered bands.

The image registration process is required in order to compensate for the band misalignment. Image registration is a technique to transform a target image into a reference image frame or a certain map projection (Dawn et al., 2010). Generally, image registration contains four main steps: (1) feature extraction, (2) feature matching, (3) image transformation, and (4) image interpolation or resampling (Dawn et al., 2010; Zitová and Flusser, 2003). Transformations can be two dimensional (such as rigid body, helmert, affine, polynomial or projective) or three dimensional, based on the collinearity model and accounting for the object 3D structure, i.e. the orthorectification process (Mikhail et al., 2001).

A previous study by Tommaselli et al. (2015) assessed empirically the potential of various 2D transformations in band registration of the time-sequential FPI camera images. The results showed that accuracy of registration decreased when the relative distance of the bands to the reference band increased or when the height variations in the object increased. Besides, the polynomial transformation outperformed the affine transformation. Results by Honkavaara et al. (2013) and Vakalopoulou and Karantzalos (2014) showed that the band registration of FPI images using feature-based matching and 2D image transformations provided good registration in flat agricultural scenes. Jhan et al. (2016) developed an approach utilising the relative calibration information and projective transformations for sensor systems with several rigidly integrated cameras, such as the MiniMCA lightweight camera, which is composed of six individual, integrated cameras. The approach was based on determining the relative orientations of individual cameras in the laboratory with respect to the master camera in the multi-camera system. The relative orientations of the master camera (red band) and an additional RGB camera were determined. The RGB camera was oriented with bundle-block adjustment, and the object-to-image transformations of the rest of the images were calculated based on relative orientations. An accuracy of 0.33 pixels was reported. Several researchers reported accuracies on the level of approximately 2 pixels when using 2D band registration approaches with the MiniMCA camera (Laliberte et al., 2011; Torres-Sanchez et al., 2013; Turner et al., 2014).

The objective of this investigation was to develop a method for accurate registration of non-registered hyperspectral data cubes captured using cameras based on tuneable filters. An important property of tuneable filter-based hyperspectral imaging is that the exterior orientation of each band in the image block is unique. Thus, each band presents its own central perspective projection of the object. If an object has 3D height variations, these will produce scale differences, which cannot be modelled accurately using 2D image transformations. This investigation presents and assesses an approach for determining accurate band registration accounting for the 3D object geometry that is determined by the structure-from-motion (Wu, 2013) and the dense digital image-matching technologies (Hirschmüller et al., 2005; Leberl et al., 2010; Rosnell and Honkavaara, 2012; Lisein et al., 2013; Eltner and Schneider, 2015).

Section 2 presents the FPI based hyperspectral imaging technology and the 3D approach for band registration. The method was tested using three forest image blocks. Section 3 presents the materials and methods, and Section 4 presents the results. Discussion is given in Section 5.

2. Theory of geometric processing of hyperspectral images based on a tunable filter

2.1. FPI camera technology

The hyperspectral camera technology developed by the VTT Technical Research Centre of Finland (VTT) (Mäkynen et al., 2011; Saari et al., 2011, 2013; Mannila et al., 2014) is based on a variable air gap FPI. When the FPI is placed in front of the sensor, the wavelength of the light passing the FPI is a function of the interferometer air gap. By changing the air gap, it is possible to acquire a new set of wavelengths. The final spectral response is dependent on the light passing the FPI and the spectral characteristics of the detector. The spectral bands can be selected according