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The effect of spatial resolution on radiometric and geometric performances of a UAV-mounted hyperspectral 2D imager

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ABSTRACT

The effect of spatial resolution on the radiometric and geometric performances of hyperspectral sensors is an essential issue in remote sensing that urgently needs to be investigated, especially for low-altitude remote sensing principles and applications. Using an unmanned aerial vehicle (UAV)-mounted miniature hyperspectral 2D imager (Cubert UHD 185) system, a series of hyperspectral images of several reflectance targets (5%, 20%, 30%, 40%, 60% and 65%) were imaged in hovering flight at various spatial resolutions (ground sampling distances (GSDs)) from 1.2 cm to 4.8 cm, with intervals of 0.4 cm, which correspond to flight altitudes from 30 m to 120 m in increments of 10 m. Subsequently, the effect of spatial resolution on radiometric and geometric performances was evaluated in terms of the change in reflectance and geometric recognition ability of the shape of targets at visible to near-infrared wavelengths. This paper provides a set of methods for assessing the effect of spatial resolution on radiometric and geometric performance, including a radiative transfer model simulation for imaging quality performance, the geometric recognition loss degree (GRLD) for measuring image geometry recognition ability, and a trend projection analysis for developing continuous distribution images of radiometric and geometric performances. The results show that when the size of the target is not less than 50 (row) × 50 (column) pixels in a Cubert hyperspectral image, the absolute error (AE) and the root mean square error (RMSE) of the reflectances of its central pixel are both less than 0.05. Additionally, as the spatial resolution decreased, the AEs of the target reflectances in visible bands increased and then stabilized, and those in the red-edge band and near-infrared bands first increased slowly and then decreased rapidly because an increasing number of pixels were influenced by the surrounding area; thus, the shapes of the spectral curves of the sample area became increasingly similar to those of the surrounding area. This study provides a guide for selecting an appropriate spatial resolution for UAV remote sensing to improve operational efficiency. The reflectance and geometric quantitative losses at different spatial resolutions are conducive to parameter inversion in quantitative remote sensing and spatial resolution transformation and enrich the knowledge of low-altitude UAV hyperspectral remote sensing.

1. Introduction

Hyperspectral remote sensing makes use of as many as hundreds of contiguous spectral bands, with which many subtle objects and materials can be extracted for classification, detection, and quantification (Ustin et al., 2002; Melgani and Bruzzone, 2004; Goetz et al., 2009; Govender et al., 2009; Lunga et al., 2014). Recently, low-altitude unmanned aerial vehicles (UAVs) have allowed the use of hyperspectral imaging spectrometers with low production and maintenance costs to obtain spectral images in numerous and continuous wavebands with high spatial, spectral, and temporal resolutions (Mitchell et al., 2012; Zhang and Kovacs, 2012; Liu et al., 2017). This technology is becoming an area of focus in surface monitoring and will play an important role in the fields of geology, agriculture, disaster prevention, and defense in the future (Zhang and Kovacs, 2012; Lucieer et al., 2014; Zheng et al., 2016).

In recent years, the successful development of lightweight hyperspectral sensors has contributed to the development of low-altitude remote sensing using small UAVs (Hugenholtz et al., 2012; Anderson and Gaston, 2013). Recently developed frame hyperspectral imaging spectrometers, such as the Cubert UHD 185 (www.cubert-gmbh.de), the Senop RIKOLA (www.rikola.fi), and the BaySpec OCI-1000 (www.bayspec.com), are more attractive to use than line-scan sensors because they do not require a high precision pipe inertial navigation

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system (Bareth et al., 2015). The radiometric and geometric characteristics, which are critical factors for the evaluation of a sensor's imaging capability, have attracted wide attention in remote sensing applications (Hashim et al., 2013), including radiometric and geometric correction (Yang et al., 2017). The former mainly refers to the reflectance performance of ground objects, which is closely related to the selection of proper spatial resolutions (Aplin, 2004), scale conversion problems (Wu et al., 2015) and the fusion of multi-source remote sensing data (Mäkynen et al., 2012). Edges are important shape features for the assessment of the geometric performance because they represent significant local intensity changes (Huang et al., 2017). Most remote sensing applications, including image registration, image segmentation, region separation, object description, and recognition, rely on edge detection (Huang et al., 2017).

Significantly, these characteristics are closely related to spatial resolution (Woodcock and Strahler, 1987; Hsieh et al., 2001; Wu and Li, 2009), which is essential for surface feature identification and parameter extraction (Wu and Li, 2009). Therefore, it is particularly important to systematically evaluate the quality of a sensor's imaging capability through radiometric and geometric analysis at different spatial resolutions (Hassan-Esfahani et al., 2017).

For the radiometric and geometric performances of a sensor at high spatial resolutions, the reflectances of a pure pixel that corresponds to a homogenous area nevertheless can be affected by neighboring pixels due to spectral interactions (Wu and Li, 2009). As sensor altitude increases in low-altitude UAV remote sensing, theoretically the radiance at a sensor is independent of the flight altitude because the atmospheric effect is usually negligible for a large homogeneous area (Zeng et al., 2017). While the spatial resolution decreases, image pixels representing ground objects may change from pure pixels to mixed pixels (Hsieh et al., 2001). In this case, the spectrum received by the sensor contains the combined reflectance from features in neighboring pixels and heterogeneous surface features (Teillet et al., 1997; Wu and Li, 2009). This demonstrates that the change in reflectance is closely related to spatial resolution and ground surface complexity (Kraft et al., 2016). However, few studies have investigated the change in reflectance from a pure pixel to a mixed pixel at high spatial resolutions.

Although UAV low altitude remote sensing platforms have significant advantages in the acquisition of remote sensing images at different resolutions, previous research has mostly focused on a specific object or a certain flight altitude and concentrated on the performance of sensors in obtaining the reflectance of surface features or accuracies of extracted parameters (Hruska et al., 2012; Mitchell et al., 2012; Duan et al., 2013; Lucieer et al., 2014; Kraft et al., 2016). For example, Hruska et al. (2012) studied the calibration and characterization of the Resonon PIKA II imaging spectrometer. Kraft et al. (2016) studied a modular airborne camera system for small UAVs, the DLR MACS-Micro, and developed standardized calibration procedures for photogrammetric workflows. Moreover, the few studies that have developed the effect of spatial resolution on the quality of remote-sensing images have considered only two or three spatial resolutions (Lee and Sung, 2016; Hassan-Esfahani et al., 2017). Lee and Sung (2016) measured and analyzed the spatial resolutions of images obtained with fixed-wing UAVs operating with a spatial resolution of 4.08 cm at the flying height of 130 m and 7.94 cm at 260 m and rotary-wing UAVs operating with a spatial resolution of 4.10 cm at a flying height of 130 m. They indicated that it was necessary to accumulate images photographed under different conditions and to conduct further studies on a test of continuous spatial resolutions of UAV images. Overall, few systematic studies of low-altitude, multi-resolution remote sensing have been performed.

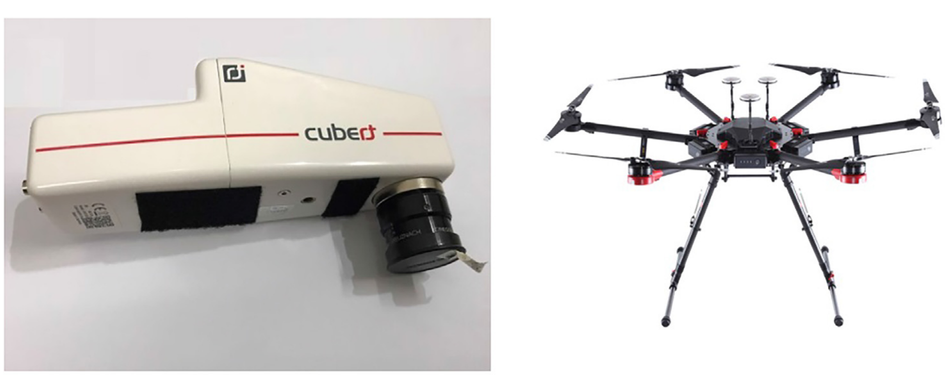
Fortunately, a UAV-mounted miniature hyperspectral sensor system can facilitate the performance of a sensor's imaging capability at centimeter- to sub-meter-level resolutions (various flight altitudes) and spectral dimensions (Mäkynen et al., 2012; Aasen et al., 2015; Bareth et al., 2015; Zheng et al., 2016). In this study, a UAV equipped with the Cubert UHD 185 frame hyperspectral spectrometer (Bareth et al., 2015; Takács et al., 2017) was used to obtain images at multiple observational resolutions. The effect of the spatial resolution on radiometric and geometric performances of the hyperspectral sensor was systematically analyzed. The objectives of this study were threefold: (i) to provide a set of methods for assessing the effect of spatial resolution on the performance of a hyperspectral sensor; (ii) to determine variation regularity in reflectance and geometric characteristics as a pixel changes from homogeneous to heterogeneous due to a change in spatial resolution; and (iii) to provide reflectance and geometric quantitative losses at different spatial resolutions for guidance in practical applications, especially when developing flight plans. The results expand the knowledge base of the effect of resolution in low-altitude remote sensing with UAVs and provide guidance for the practical application of sensors in remote surface feature monitoring, quantitative parameter extraction, and scale conversion problems encountered in multi-sensor data fusion.

Sections 2 and 3 introduce the remote sensing system (sensor and platform), and the study site and datasets, respectively. The methodology for studying the effect of spatial resolution on radiometric and geometric performances is developed in Section 4. The results and discussion are presented in Sections 5 and 6, and the conclusions are given in the final section.

2. System overview

2.1. Sensor system

A Cubert UHD 185 frame hyperspectral 2D imager (http://cubert-gmbh.com/) (Bareth et al., 2015), which was developed by the Institute



(a) (b)

Fig. 1. Sensor system and UAV platform. (a) Cubert hyperspectral camera and (b) DJI Jingwei M600 PRO.