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Terrestrial lidar and hyperspectral data fusion products for geological outcrop analysis

Simon J. Buckley [a],*, Tobias H. Kurz [a], John A. Howell [a], Danilo Schneider [b]

[a] Uni CIPR, P.O. Box 7810, N-5020 Bergen, Norway
[b] Institute of Photogrammetry and Remote Sensing, Technische Universität Dresden, D-01062 Dresden, Germany

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ABSTRACT

Close-range hyperspectral imaging is an emerging technique for remotely mapping mineral content and distributions in inaccessible geological outcrop surfaces, allowing subtle chemical variations to be identified with high resolution and accuracy. Terrestrial laser scanning (lidar) is an established method for rapidly obtaining three-dimensional geometry, with unparalleled point density and precision. The combination of these highly complementary data types – 3D topography and surface properties – enables the production of value-added photorealistic outcrop models, adding new information that can be used for solving geological problems. This paper assesses the benefits of merging lidar and hyperspectral imaging, and presents qualitative and quantitative means of analysing the fused datasets. The integration requires an accurate co-registration, so that the 2D hyperspectral classification products can be given real measurement units. This stage is reliant on using a model that correctly describes the imaging geometry of the hyperspectral instrument, allowing image pixels and 3D points in the lidar model to be related. Increased quantitative analysis is then possible, as areas and spatial relationships can be examined by projecting classified material boundaries into 3D space. The combined data can be interpreted in a very visual manner, by colouring and texturing the lidar geometry with hyperspectral mineral maps. Because hyperspectral processing often results in several image products and classifications, these can be difficult to analyse simultaneously. A novel visualisation method is presented, where photorealistic lidar models are superimposed with multiple texture-mapped layers, allowing blending between conventional and hyperspectral imaging products to assist with interpretation and validation. The advantages and potential of the data fusion are illustrated with example outcrop data.

1. Introduction

The combination of data and products derived from multiple spatial and geophysical acquisition sensors is common in the study of geological outcrops. Data sources are often complementary, allowing more information to be extracted than from a single component technique (e.g. Jones et al., 2009). The past decade has seen the rapid adoption of digital spatial measurement techniques in field geology. Global Navigation Satellite Systems, photogrammetry, airborne and terrestrial laser scanning (lidar), digital elevation models (DEMs), and remote sensing imagery have all been used to provide a precise framework for digital mapping and interpretation, at multiple scales (McCaffrey et al., 2005). The integration of these geometric data with traditional geological field measurements (e.g. sedimentary logs, photographs and structural measurements) and geophysical data (e.g. ground-penetrating radar and petrophysical measurements), in advanced modelling and visualisation software, has changed the way that many geological problems are addressed (Jones et al., 2009).

The integration of terrestrial laser scanning with digital imaging has become common in outcrop geology, as well as the wider geoscience discipline. Laser scanning is now a widespread means of obtaining precise and high resolution three-dimensional (3D) topographic information, with high efficiency and ease of use (Bellian et al., 2005; Buckley et al., 2008; Hodgetts, 2009). Most laser scanners suitable for outcrop-scale applications (c. 10 m–1 km) obtain 3D point positions by measuring the range between the instrument and a target surface, based on the time of flight of a laser pulse, together with its direction. The strength of the returned laser pulse, commonly referred to as intensity, is also recorded (Höfle and Pfeifer, 2007). Measurements are made many thousands of times per second, resulting in the formation of a dense point cloud that accurately describes the outcrop surface in great detail, and may be displayed using the recorded intensities. However, the inherently discrete nature of a point cloud makes it difficult to interpret without ancillary imagery (Buckley et al., 2008). In addition, geological features may have a minimal 3D signature, but may be easily

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* Corresponding author. Tel.: +47 5558 3458; fax: +47 5558 8265.
E-mail addresses: simon.buckley@uni.no (S.J. Buckley), tobias.kurz@uni.no (T.H. Kurz), john.howell@uni.no (J.A. Howell), danilo.schneider@tu-dresden.de (D. Schneider).

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apparent in the 2D images as colour or edge information. Therefore, integration of the laser point cloud with digital imagery gives an additional continuous data source that can enhance geological interpretation. This is performed using an integrated camera, or by registering separately captured imagery to the lidar scans. In both cases, point clouds can be assigned red, green and blue (RGB) values by projecting each point into an appropriate image (e.g. White and Jones, 2008), though the discontinuous nature of the lidar point cloud often remains a limitation during visualisation.

Conversion of the lidar point cloud to a triangular mesh makes the outcrop representation continuous. Adjacent points are connected by triangle edges, and the digital photos can then be textured onto the mesh (e.g. El-Hakim et al., 1998; Bellian et al., 2005). The result is a photorealistic model (Xu et al., 2000) that has facilitated interpretation, quantification and education in many reported projects (e.g. Bellian et al., 2005; Fabuel-Perez et al., 2009; Buckley et al., 2010; Enge et al., 2010). However, such models provide little quantitative information on the mineral and chemical composition of the outcrop. Knowledge of the distribution of the minerals and materials in an outcrop is valuable for assessing connectivity of rock bodies, but may be difficult to determine remotely, requiring laborious spot sampling in accessible areas. A number of studies have attempted to use spectral approaches to remotely classify materials at close-range. These have included the analysis of lidar intensity to separate different lithologies (Bellian et al., 2005; Franceschi et al., 2009; Burton et al., 2011) and surface properties (Pesci and Teza, 2008; Nield et al., 2011), the use of multispectral photographs (e.g. Lerma, 2001), the combination of lidar intensity and RGB imagery (Lichti, 2005), and the use of multispectral lidar sensors (Hemmleb et al., 2006). Despite the reported successes, current laser scanners are limited by their spectral sensitivity, typically a single narrow wavelength in the visible or near-infrared part of the electromagnetic spectrum (Höfle and Pfeifer, 2007). This precludes the possibility for surface classification where complex material compositions exist.

An enhanced spectral range and resolution is offered by close-range hyperspectral imaging. Hyperspectral sensors measure many narrow spectral bands across an extended part of the electromagnetic spectrum, allowing a near-continuous reflectance curve to be derived per image pixel (see e.g. van der Meer and de Jong, 2001). High spectral resolution permits subtle variations in surface composition to be quantitatively analysed, even at sub-pixel levels (Keshava and Mustard, 2002). In geology, hyperspectral imaging has been successfully employed using airborne and spaceborne sensors for decades, for regional mapping and mineral prospecting, detection of hydrocarbon seeps, and interplanetary exploration (e.g. van der Meer and de Jong, 2001; Bellian et al., 2007; Bowen et al., 2007; Griffes et al., 2007). Lightweight hyperspectral sensors are now available, making the method applicable from the ground in field geology (Kurz et al., 2008, 2012; Murphy et al., 2012). These sensors negate the past problems associated with imaging outcrop surfaces – typically having near-vertical orientation – from nadir platforms where field of view and spatial resolution are not optimal.

The aim of the current paper is to highlight the potential of combining terrestrial laser scanning and close-range hyperspectral imaging in outcrop geology. The focus is on the products that can be obtained from the fused data, along with means of assessing the quality of both the geometric fit and the hyperspectral classifications. This is achieved using an empirical workflow developed using a specific hyperspectral device, where the imaging geometry dictates the method chosen for integration with the lidar data. The instrumentation and processing steps are briefly outlined for both component techniques, as well as the procedure for co-registering the hyperspectral image with the lidar data. The paper presents a visualisation method that allows multiple hyperspectral processing products to be displayed with the photorealistic lidar model, and outlines quantitative analysis that can be performed following integration. Benefits of the synergy are presented throughout the paper using example outcrop datasets.

2. Data collection and processing

2.1. Instruments

The proposed integration method is developed using data from a Riegl LMS-Z420i terrestrial laser scanner (Riegl, 2011) and a HySpex SWIR-320 m hyperspectral imager (NEO, 2011). The former is one of several time-of-flight-based laser scanners currently available that share similar specifications, and that are suitable for geological outcrop studies. In this project the scanner is equipped with a calibrated Nikon D200 digital camera, mounted rigidly on top of the instrument body. Captured digital images are therefore registered to the scanner coordinate system by means of known orientation angles and positional offsets (Ullrich et al., 2003), allowing the 3D lidar geometry to be later assigned RGB colour.

The HySpex SWIR-320 m is sensitive to short-wave infrared (SWIR) light, from 1.3 to 2.5 μm. Within this range, 240 individual bands are sampled with 5 nm spacing, permitting detailed spectral analysis at wavelengths where many terrestrial materials have distinguishing absorption features (Clark et al., 1990). The sensor itself is a charge-coupled device (CCD), where incoming light is focussed and passed through a grating that separates the wavelengths and projects them onto one line of the sensor chip. As one dimension of the CCD is reserved for the spectral bands, the instrument operates as a pushbroom scanner, and a rotation stage is required to build-up an image in the spatial direction. This results in images with 320 pixels in the across track direction (covering a 14° field of view; FOV) and a variable number of pixels in the along track direction, defined by the width of the scanned segment. This configuration results in cylindrical rather than planar imaging geometry. With a focal length of 40 mm, one pixel represents approximately 3.5 cm on the outcrop at a range of 50 m. Though spatial resolution is low compared to a contemporary digital camera, the high spectral resolution allows significantly smaller geological features to be identified and mapped than previously possible. The field deployment of the two instruments is shown in Fig. 1, and typical data characteristics are presented in Table 1.

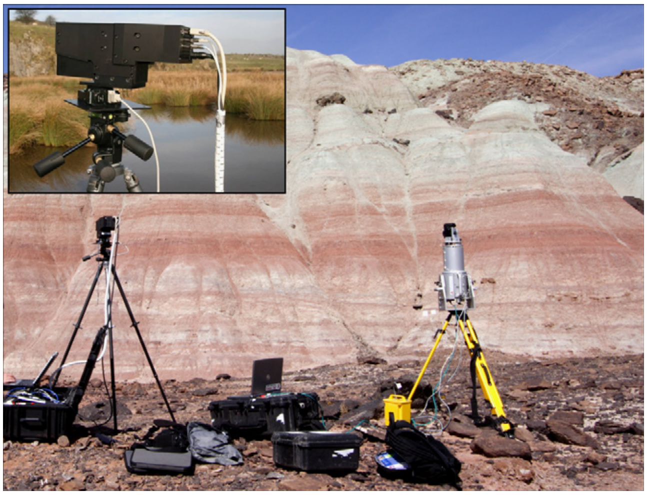

Fig. 1. HySpex SWIR-320 m hyperspectral camera (left) and Riegl LMS-Z420i laser scanner (right). Inset: close-up of HySpex instrument.