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Illumination compensation in ground based hyperspectral imaging

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A B S T R A C T

Hyperspectral imaging has emerged as an important tool for analysing vegetation data in agricultural applications. Recently, low altitude and ground based hyperspectral imaging solutions have come to the fore, providing very high resolution data for mapping and studying large areas of crops in detail. However, these platforms introduce a unique set of challenges that need to be overcome to ensure consistent, accurate and timely acquisition of data. One particular problem is dealing with changes in environmental illumination while operating with natural light under cloud cover, which can have considerable effects on spectral shape. In the past this has been commonly achieved by imaging known reference targets at the time of data acquisition, direct measurement of irradiance, or atmospheric modelling. While capturing a reference panel continuously or very frequently allows accurate compensation for illumination changes, this is often not practical with ground based platforms, and impossible in aerial applications. This paper examines the use of an autonomous unmanned ground vehicle (UGV) to gather high resolution hyperspectral imaging data of crops under natural illumination. A process of illumination compensation is performed to extract the inherent reflectance properties of the crops, despite variable illumination. This work adapts a previously developed subspace model approach to reflectance and illumination recovery. Though tested on a ground vehicle in this paper, it is applicable to low altitude unmanned aerial hyperspectral imagery also. The method uses occasional observations of reference panel training data from within the same or other datasets, which enables a practical field protocol that minimises in-field manual labour. This paper tests the new approach, comparing it against traditional methods. Several illumination compensation protocols for high volume ground based data collection are presented based on the results. The findings in this paper are applicable not only to robotics or agricultural applications, but most very low altitude or ground based hyperspectral sensors operating with natural light.

1. Introduction

An elevated awareness of environmental issues, food security and sustainability, coupled with an ever-present desire to reduce costs and waste, maximise quality and increase productivity has highlighted precision agriculture (PA) as an important tool for optimising farming practices (Tey and Brindal, 2012). Mapping and analysing the reflected light spectrum of vegetation has emerged as an important method for various PA objectives (Lee et al., 2010). Multispectral imaging, which can capture image data in several wavelength bands, has been used in various mapping applications (Zhang and Kovacs, 2012; Mulla, 2013), such as the estimation of soil properties (Gomez et al., 2008), weed management (López-Granados et al., 2016), pest management (Du et al., 2008), and crop classification (Panigrahy and Sharma, 1997).

Hyperspectral imaging, which is able to sense spectra of objects in hundreds of narrow bands, provides even more detailed information. This allows for precise measurement of plant health indicators (Thenkabail et al., 2002; Behmann et al., 2014), as well as classification of individual plant species based on spectra alone (Okamoto et al., 2014). There is a substantial body of research covering hyperspectral imaging in the remote sensing community, where both satellite and aerial imaging have been used to map vegetation for various research and farming applications, for example for mapping cotton field variability (Yang et al., 2004), vegetation cover estimation (Zhang et al., 2013), biomass estimation (Marshall and Thenkabail, 2015), vegetation/crop classification (Oldeland et al., 2010; Xue et al., 2017), disease mapping (MacDonald et al., 2016) and nutrient/chlorophyll concentrations

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(Sims et al., 2013; Rao et al., 2008; Moharana and Dutta, 2016; Pullanagari et al., 2016).

More recently, hyperspectral imaging solutions operating at lower altitudes have begun to appear on both unmanned aerial vehicles (UAVs) (Uto et al., 2013; Honkavaara et al., 2013, 2016; Aasen et al., 2015) and mobile ground vehicles (Deery et al., 2014; Klose et al., 2010), which are increasingly being used to provide high spatial resolution data. Mobile ground platforms for agricultural applications have ranged from simple hand pushed frames to manually driven motorised tractors or buggies to autonomous systems (Zhang et al., 2012; Deery et al., 2014). Recent examples of autonomous platforms include Bonirob (Ruckelshausen et al., 2009), and the tracked Armadillo (Nielsen et al., 2012). Larger manually driven “buggies”, such as BreedVision (Busemeyer et al., 2013) and PhenoMobile (Deery et al., 2014), can carry more weight and supply more power, and therefore tend to include a greater array of sensors, including 3D time-of-flight, light curtains, and thermal imaging.

Retrieving reflectance, which is a property of the imaged surface only (Chandra and Healey, 2008; Ahlberg, 2010), by compensating for environmental illumination is a particular consideration for hyperspectral sensors. Because higher altitude and satellite imagery generally require relatively clear skies, lighting is more consistent, being only dependent on the time of the day and atmospheric composition. Low altitude and ground based platforms can operate under cloud cover, allowing data acquisition whenever there is sufficient light, but this increases the amount of dynamic lighting variation, due to fluctuating cloud cover density. Additionally, because these configurations image smaller regions of the scene at a time, total scan durations are longer, increasing likelihood that not only the intensity but also the spectrum of light on the ground changes. This makes it difficult to obtain reflectance accurately, but it is often impractical to wait for opportune lighting conditions.

These difficulties highlight the need for autonomous platforms, which ensure that data acquisition is both consistent and fast, while minimising disruption to crops. Factors such as the trajectory of the platform, including its orientation and velocity can be tightly controlled, allowing data to be obtained in a regular manner, which is suitable to feed into automated processing frameworks. Autonomous systems allow very high resolution data to be obtained practically over large areas of a farm, breaking the trade-off between resolution and coverage.

In this paper, we examine the use of an unmanned ground vehicle (UGV) to gather high resolution hyperspectral data of crops, which are post processed to compensate for illumination changes in order to retrieve reflectance.

The contributions of this paper are:

- The development of several different field protocols for gathering the necessary training data for the illumination compensation method by Drew and Finlayson (2007). These present different trade-offs between the accuracy of illumination compensation and the logistical complexity of the field work.
- Testing the applicability of using historical reference data to correct for illumination in future datasets.
- An analysis of the sensitivity to illumination compensation of several metrics/indices that are commonly used in agricultural applications.
- Evaluating the suitability of a previously developed logarithm subspace method for illumination and reflectance extraction (Drew and Finlayson, 2007) for use on a large, high spatial and spectral resolution agriculture based field dataset.

By using the approach detailed in Drew and Finlayson (2007), the following important advantages can be realised:

- No reference target readings need to be tied to imaged pixels.
- Significantly reduced number of reference target readings.
- Feasibility to recover reflectance and illumination from previously acquired training data, where no reference panel readings are available.
- No need to obtain or estimate atmospheric parameters.

In Section 2, we briefly review the literature on illumination compensation. Particular focus is given to the subspace model method by Drew and Finlayson (2007), which approximates both illumination and reflectance spectra based on sets of training data. We posit this method as a basis for more convenient and practical novel field protocols that facilitate compensation for lighting. In Sections 3 and 4, experiments are documented that use high spatial (3 mm by 9 mm) and spectral (2 nm) resolution hyperspectral data cubes, covering 2.75 hectares of a plant phenomics trial. The experiments highlight the magnitudes of reflectance error that can occur when illumination compensation is ignored, and demonstrate the effectiveness of several illumination compensation approaches. Based on these results we provide some clear guidelines for obtaining reflectance in hyperspectral data from ground based field robotics systems (Section 5).

2. Surface reflectance retrieval methods

In this section, we summarise the most common methods used for atmospheric correction and illumination compensation in order to retrieve surface reflectance. For brevity, we use “reflectance” and “surface reflectance” synonymously, as opposed to “at-sensor reflectance” or “top of atmosphere (TOA) reflectance” (Teillet, 2015).

2.1. Empirical methods

There are several early scene-based approaches to reflectance retrieval from the 1980s (Gao et al., 2009), including the Internal Average Reflectance (IAR) (Kruse, 1988) and flat field (Roberts et al., 1986) correction approaches. The former divides a hyperspectral image by the average spectrum for the whole scene, while the latter assumes that there is an area with spectrally neutral reflectances (little variation with wavelength) in the scene, which can be averaged and used to retrieve reflectance. While these methods are convenient, because no in field reference measurements are required, they often do not provide accurate results (Gao et al., 2009).

Using a reference panel that is measured in the same lighting conditions (i.e. in the same scene or the same image as the surface of interest) is a common way to determine reflectance of a surface (Yao and Lewis, 2010; Uto et al., 2013). Ideally this target should be a Lambertian scatterer with uniform reflectance in the spectral range of the sensor, such as Spectralon by Labsphere, which exhibits a very flat reflectance curve at a wide wavelength interval from about 300 to 2400 nm (Geladi, 2007). Once the radiance of the reference target has been measured, the reflectance of a surface in the same lighting conditions can be obtained by dividing its radiance spectrum by the reference’s and multiplying by the target’s known reflectance (see Section 3.4). This method is effective in situations where the sensor is close to the object being measured, such as laboratory, factory, low altitude aerial and ground based applications, as long as lighting does not change from the conditions measured at the reference panel. Interpolation has been used in the past to take into account gradual lighting changes (Suomalainen et al., 2014). This is useful over shorter durations, where lighting conditions change approximately linearly. However, this method is less