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Arko Lucieer

University of Tasmania, arko.lucieer@utas.edu.au

Zbynek Malenovsky

University of Tasmania, zbynek@uow.edu.au

Tony Veness

University of Tasmania

Luke Wallace

University of Tasmania

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HyperUAS - Imaging spectroscopy from a multirotor unmanned aircraft system

Abstract

One of the key advantages of a low-flying unmanned aircraft system (UAS) is its ability to acquire digital images at an ultrahigh spatial resolution of a few centimeters. Remote sensing of quantitative biochemical and biophysical characteristics of small-sized spatially fragmented vegetation canopies requires, however, not only high spatial, but also high spectral (i.e., hyperspectral) resolution. In this paper, we describe the design, development, airborne operations, calibration, processing, and interpretation of image data collected with a new hyperspectral unmanned aircraft system (HyperUAS). HyperUAS is a remotely controlled multirotor prototype carrying onboard a lightweight pushbroom spectroradiometer coupled with a dual frequency GPS and an inertial movement unit. The prototype was built to remotely acquire imaging spectroscopy data of 324 spectral bands (162 bands in a spectrally binned mode) with bandwidths between 4 and 5 nm at an ultrahigh spatial resolution of 2-5 cm. Three field airborne experiments, conducted over agricultural crops and over natural ecosystems of Antarctic mosses, proved operability of the system in standard field conditions, but also in a remote and harsh, low-temperature environment of East Antarctica. Experimental results demonstrate that HyperUAS is capable of delivering georeferenced maps of quantitative biochemical and biophysical variables of vegetation and of actual vegetation health state at an unprecedented spatial resolution of 5 cm.

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HyperUAS – Imaging spectroscopy from a multi-rotor unmanned aircraft system

Arko Lucieer*

University of Tasmania
School of Geography and Environmental Studies
Hobart, Tasmania, Australia
Arko.Lucieer@utas.edu.au

Zbyněk Malenovský

University of Tasmania
School of Geography and Environmental Studies
Hobart, Tasmania, Australia
Zbynek.Malenovsky@utas.edu.au

Tony Veness

University of Tasmania
School of Geography and Environmental Studies
Hobart, Tasmania, Australia
Tony.Veness@utas.edu.au

Luke Wallace

University of Tasmania
School of Geography and Environmental Studies
Hobart, Tasmania, Australia
Luke.Wallace@utas.edu.au

Abstract

One of the key advantages of a low-flying unmanned aircraft system (UAS) is its ability to acquire digital images at ultra-high spatial resolution of a few centimetres. Remote sensing of quantitative biochemical and biophysical characteristics of small-sized spatially fragmented vegetation canopies requires, however, not only high spatial, but also high spectral (i.e. hyperspectral) resolution. In this paper, we describe the design, development, airborne operations, in addition to calibration, processing and interpretation of image data collected with a new hyperspectral unmanned aircraft system (HyperUAS). HyperUAS is a remotely controlled multi-rotor prototype carrying on-board a

*Corresponding author

lightweight pushbroom spectroradiometer coupled with a dual frequency global positioning system (GPS) and an inertial movement unit (IMU). The prototype was built to remotely acquire imaging spectroscopy data of 324 spectral bands (162 bands in a spectrally binned mode) with band-widths between 4 and 5 nm at an ultra-high spatial resolution of 2 to 5 cm. Three field airborne experiments, conducted over agricultural crops and over natural ecosystems of Antarctic mosses, proved operability of the system in standard field conditions, but also in a remote and harsh, low-temperature environment of East Antarctica. Experimental results demonstrate that HyperUAS is capable of delivering georeferenced maps of quantitative biochemical and biophysical variables of vegetation and of actual vegetation health state at unprecedented spatial resolution of 5 cm.

Keywords: Multi-rotor unmanned aerial vehicle (UAV), Unmanned aircraft system (UAS), Hyperspectral remote sensing, Imaging spectroscopy of vegetation, High spatial and spectral resolution

1 Introduction

Recent growth and availability of semi-autonomous multi-rotor helicopters, low-cost Open Source autopilots, and miniaturisation of sensors has resulted in the adoption of unmanned aircraft system (UAS) technology in a wide range of science disciplines, especially in earth observation and aerial surveying. In the field of robotics, Cole et al. (2006), Hrabar (2012), and Kendoul (2012) showed significant advances in guidance, navigation, control, obstacle avoidance, and information gathering. Some of these advances in unmanned aerial vehicle (UAV) technology have resulted in the adoption of UAS in more applied fields. Zhang and Kovacs (2012) provided a review of the application of UAS for precision agriculture and predicted an increased adoption in this area provided relaxation of UAS aviation regulations. While Zarco-Tejada (2008) demonstrated that real-time irrigation scheduling and crop monitoring based on UAS remote sensing will soon become reality, Bryson et al. (2010) proposed a vision-based image classification that can be used to identify weeds in Red-Green-Blue (RGB) imagery acquired by a UAS over farmland. Anderson and Gaston (2013) highlighted the advantages of lightweight UAS in spatial ecology and identified four key advantageous attributes: i) their survey revisit period controlled by the user allows for a high temporal resolution; ii) their low-altitude flights permit data collection at appropriate spatial resolutions; iii) their operating costs are low compared to manned airborne surveys or satellite observations; and iv) they can carry various imaging and non-imaging payloads tuned to the demands of the application and end-user.

Publications of several recent special issues on UAS for remote sensing applications (*IEEE TGRS*: March 2009; *GIScience and Remote sensing*: March 2011; *Geocarto International*: March 2011; *Remote Sensing*: June 2012) and strong interest in dedicated conferences such as *UAV-g* indicate an increasing popularity of UAS for remote sensing and photogrammetry applications. The principal advantage of UAS-based remote sensing is the capacity to bridge

the scale gap between field-based observations and high-altitude airborne and satellite observations. From a scientific perspective, UAS allow optimisation of the sampling technique, e.g. selection of optimal spatial resolution and sensor type, according to the nature of objects of interest and application requirements (D'Oleire-Oltmanns et al., 2012).

Numerous UAS studies have employed structure-from-motion (SfM) computer vision techniques to derive three-dimensional (3D) models of objects on the earth surface from multi-view RGB photography. For example, Niethammer et al. (2012) combined a multi-rotor UAS and SfM image processing techniques to acquire accurate 3D models of a landslide. Similar techniques were applied by D'Oleire-Oltmanns et al. (2012) and Harwin and Lucieer (2012) to quantify the impact of erosion in Moroccan badland landscapes and Tasmanian coastal landscapes, or by Turner et al. (2012) and Lucieer et al. (2013) to generate accurate 3D models of Antarctic moss beds. These studies demonstrated the capability of UAS to produce 3D terrain models with absolute spatial accuracies in the order of centimetres.

Besides digital RGB cameras, more advanced optical sensors, such as multi- or hyperspectral spectrometers, thermal cameras, and laser scanners have been integrated within UAS. Nagai et al. (2009), Lin et al. (2011) and Wallace et al. (2012) built successfully UAS with a mini-LiDAR instrument designed for 3D scanning of the terrain. Laliberte et al. (2011) and Kelcey and Lucieer (2012) collected multispectral images from a UAS for rangeland and saltmarsh vegetation mapping. Berni et al. (2009) combined thermal and multispectral UAS images for stress detection in Mediterranean orchards. Finally, several publications reported UAS experiments with pushbroom imaging spectroradiometers, e.g. Zarco-Tejada et al. (2009, 2012, 2013) and Hruska et al. (2012). In spite of this progress, further development of advanced optical UAS equipped with high resolution imaging spectrometers is needed to facilitate their broad operational use.

Imaging spectroradiometers have a long lasting tradition in optical remote sensing of the earth. For example, the Thematic Mapper (TM) spectrometers on-board of the Land Remote Sensing Satellite (LANDSAT) missions started acquiring images of seven distinct spectral bands in visible and infrared wavelengths already in 1983 (Markham and Helder, 2012). These bands are, however, spectrally broad, integrating from tens to hundreds nanometres. They provide general reflectance of distinct spectral regions, but do not allow reconstruction of a detailed continual reflectance function of observed surfaces. This is feasible only with high spectral resolution imaging spectrometers (also referred to as 'hyperspectral'), recording tens to hundreds narrow spectral bands with their full width at half maximum (FWHM) often below 10 nm. An extensive overview of the current operational satellite and airborne imaging spectroradiometers provided in Malenovský et al. (2009) shows that their high spectral resolution and spectral sampling allows to retrieve not only qualitative, but also quantitative information, as for instance content of green foliar pigments in agricultural crops or forest canopies expressed in μg of chlorophylls per cm^{-2} of plant leaf area (Haboudane et al., 2002; Malenovský et al., 2013). Still, the high-altitude flying air- and space-borne platforms offer only a limited spatial detail, i.e. spatial resolution in the order of metres.

Despite of limited number of suitable lightweight hyperspectral spectroradiometers, several research teams are putting effort into developing hyperspectral-enabled UAS platforms (Hruska et al., 2012). Only few teams, however, are flying hyperspectral UAS operationally and using the acquired data in real scientific applications. Such an example is the Laboratory for Research Methods in Quantitative Remote Sensing (QuantaLab IAS – CSCI, Cordoba, Spain) that accommodated a Micro-Hyperspec sensor (Headwall Inc., USA) in a fixed wing UAS. They employed the collected imaging spectroscopy data in precision agriculture applications (Zarco-Tejada, 2008), particularly in estimation of draught stress in citrus orchards (Zarco-Tejada et al., 2012) and more recently in assessing actual photosynthetic activity of production vineyards using retrieved steady-state chlorophyll fluorescence signal (Zarco-Tejada et al., 2012, 2013). Although being fully operational, this hyperspectral UAS is optimised to acquire images with a spatial resolution of about 40 cm, which might still be insufficient for observing sparse crops of small individual plants (e.g. lattice or cabbage fields) or for fine-scale monitoring of endangered plant species growing in highly fragmented spatial formations due to the extreme harsh environmental conditions (e.g. alpine pioneering grasses or Antarctic mosses). To achieve an ultra-high spatial resolution, slow flights ($< 10 \text{ m s}^{-1}$) at low flying heights ($< 100 \text{ m}$) are required. This combination also enables use of longer sensor integration times thereby increasing signal-to-noise ratios (SNR) resulting in improved spectral image quality. For this purpose, a multi-rotor UAS is more suitable and operationally attractive compared to a fixed-wing platform as it allows for a low and slow flight and flexible take-off and landing.

The main objective of this paper is to introduce a new multi-rotor HyperUAS, designed to acquire 162 or 324 spectral bands between 361 and 961 nm (with FWHM from 4.12 to 5.25 nm) at ultra-high spatial resolution of 2 cm to 5 cm. In this paper, we present our recent progress and lessons learned during development of such a specialised hyperspectral UAV system called HyperUAS.

This paper starts with an overview of the characteristics of the hyperspectral sensor (section 2.1). Section 2.2 contains an in-depth description of the other components of the scientific payload for position and orientation determination, time synchronisation, image acquisition, and power supply followed by the integration of the scientific payload with the multi-rotor UAS. Practical aspects of field operations and data acquisition are discussed in section 2.3. The image processing work flow consisting of spectral, radiometric and atmospheric correction is presented in section 2.4. The derivation of spectral variables quantifying biophysical and biochemical vegetation characteristics is discussed in section 2.5. The application of HyperUAS is demonstrated in three field experiments (section 3). Experiment I demonstrates proof of concept of ultra-high resolution hyperspectral pushbroom scanning over an agricultural crop with a focus on the spectral processing work flow. In Experiment II HyperUAS is tested in the remote and harsh environment of the Antarctic continent for hyperspectral scanning of Antarctic moss beds. Finally, Experiment III is designed to demonstrate the full integration of the hyperspectral sensor with accurate positioning and orientation sensors for direct georeferencing.

2 Material and Methods

2.1 Hyperspectral sensor

The hyperspectral sensor used in this study is the Headwall Photonics Micro-Hyperspec VNIR scanner (Headwall Inc., USA). The dimensions of the sensor unit are 110 by 93 by 50 mm and it weighs 960 g. The incoming light is received through a lens objective with an aperture of f/2.8 and through a slit of 25 μm . The spectral wavelengths are separated by a concentric spectrograph with aberration-corrected convex holographic diffraction grating and projected onto a CCD matrix. Each column of the matrix records the spatial dimension and each row records separated wavelengths. For each capture of the CCD matrix one row of spatial pixels is recorded simultaneously, hence the sensor has to move to ‘sweep up’ a full spatial image, i.e. this design is referred to as a pushbroom scanner. The CCD chip has a 12-bit dynamic range and a Base Camera Link as the data interface.

The size and spatial distribution of the object of interest defines the optimal spatial resolution required to observe this object. The Micro-Hyperspec has a lens objective with a focal length of 8 mm and a field of view (FOV) of 49.8°, a slit entrance of 25 μm , and a CCD matrix with 1004 pixels across the spatial dimension. Flying at 11 m above ground level (AGL), the scanner acquires imagery with a pixel size of 1.0 cm in the across-track direction and an image swath of about 10.2 m. The finest physically feasible spectral sampling of the Micro-Hyperspec spectrometer is 324 spectral bands between 361 and 961 nm with FWHM between 4.12 and 4.67 nm, allowing a maximum frame rate of about 93 frames s^{-1} . The spectral sampling can be reduced to half, i.e. 162 spectral bands with FWHM between 4.75 and 5.25 nm, by binning two neighbouring spectral elements of the sensor matrix as one physical unit. In this configuration the maximum frame rate increases to 115 frames s^{-1} . The general aim is to use a longer frame period and integration time resulting in a higher SNR of recorded spectra, but to prevent simultaneously oversaturation of the sensor dynamic range. In the binned mode the frame period and integration time of about 20 ms combined with the flight speed of 2.5 m s^{-1} at 11 m above the ground produces a pixel size of 5.0 cm in the along-track direction. The across-track dimension has to be consequently reduced by factor 0.2 to obtain regular squared pixels of 5.0 cm. This spatial resolution was found to be adequate for capturing the objects of interest of this study (i.e. grassland, barley crop and also Antarctic moss beds) in a sufficient detail. Therefore, we used these setting for all three airborne experiments presented in this paper. To fulfil the experimental purpose of the orthorectification experiment, we additionally collected a binned hyperspectral image of the highest attainable spatial resolution of 2.0 cm.

2.2 Design and integration of scientific sensor payload

To successfully acquire directly georeferenced hyperspectral imagery using the Micro-Hyperspec spectrometer, a number of electronic and mechanical design criteria have to be met. Although, similar design criteria are applicable for image acquisition undertaken from a low and slow flying UAS as from a manned fixed wing aircraft, the desire to utilise a

small multi-rotor UAS presented a unique challenge in terms of size and weight constraints. Figure 1 provides an overview of the three integrated electronic subsystems of the scientific payload: 1) the Position and Orientation System (POS); 2) the Digital Image Acquisition (DIA); and 3) the power regulation subsystem, described in detail below.

Figure 1: Schematic of the electronic subsystems of the scientific payload.

2.2.1 Position and Orientation System (POS) subsystem

The position and attitude of the spectrometer must be precisely recorded at the time of every frame capture for post flight georeferencing. The spectrometer has six degrees of freedom (6 DoF) when rigidly attached to the UAS. The three degrees of freedom of the UAS trajectory (x, y and z) and the three degrees of freedom of the UAS attitude along its trajectory (pitch, roll and yaw), all need to be accurately measured and recorded. It should be noted that stable flight of a multi-rotor UAS is facilitated by the closed-loop algorithms implemented in the firmware of all commercial multi-rotor flight controller avionics, which requires accurate continuous measurement of dynamic attitude (and optionally position) in combination with the closed loop control of motor speed. Input from the pilot is also taken into account within the control loops, allowing the UAS to translate away from stable hover. The measurement of multi-rotor UAS airframe attitude and position is typically undertaken using cost-effective two or three axis micro electrical-mechanical (MEMs) based rate gyroscopes and accelerome-

ters, along with barometers, magnetometers, and a navigation-grade single frequency global positioning system (GPS) receiver (Lim et al., 2012).

The consumer-grade components of the POS system of a multi-rotor UAS are typically low in cost (less than \$100). The noise, drift, non-linearity and temperature-dependent characteristics of the low-cost POS components are typically not a limitation for achieving stable flight in a well-designed and properly configured multi-rotor UAS. For direct georeferencing of ultra-high spatial resolution pushbroom imagery captured from a UAS, however, the accuracy requirements of the POS are much greater. Hruska et al. (2012) relied on the GPS/inertial measurement unit (IMU) solution provided by a high quality autopilot for direct georeferencing hyperspectral pushbroom imagery acquired from a fixed-wing UAS, achieving a spatial root mean squared error (RMSE) of 4.63 m. They concluded that the poor results were partially due to the uncertainty in the GPS/INS solution provided by the autopilot. Berni et al. (2009) likewise outlined the reliance on the internal IMU of the autopilot of a small UAS helicopter to provide position and attitude information for direct georeferencing of both thermal and multispectral imagery. Whilst position and attitude measurements were available at 20 Hz post flight from the autopilot, the lack of synchronisation of POS and image exposure prevented the use of the POS data in a direct georeferencing process. Given our desire to acquire ultra-high spatial resolution imagery with pixel sizes less than 5 cm, the use of any single frequency GPS receiver as part of our scientific payload was unrealistic, forcing us to look for a POS solution with a positional accuracy of less than 5 cm.

The components of our POS solution consist of a MEMs IMU (Microstrain 3DM-GX3 35), a dual frequency (L1/L2) GPS receiver (Novatel OEMV-1DF), and a lightweight helical L1/L2 antenna (Maxtena M1227HCT-A). A secondary on-board miniaturised computer (Gumstix Verdex Pro) is used to log data from the on-board POS sensors. The on-board GPS observations are post-processed against a second L1/L2 GPS receiver (Novatel SPAN CPT) logging over a known location using the standard processing algorithms in Novatel GrafNav 8.2 (Novatel, 2012) to produce estimates of position and velocity at a rate of 5 Hz. In order to derive accurate position and orientation estimates for the sensor at the instance of each frame, these estimates were then fused with the IMU observations of rotational rate (deg/s) and acceleration (m s^{-2}) made at 100 Hz, using a loosely coupled sigma point Kalman smoother as outlined in Wallace et al. (2012).

2.2.2 Digital Image Acquisition (DIA) subsystem

The following technical criteria had to be taken into account when designing the digital image acquisition system for use on the UAS:

- Since the small Adimec monochrome machine vision camera (part of the Micro-Hyperspec) uses the CameraLink protocol (Base) for image transfer and control, the image acquisition system had to be CameraLink capable (255 MB s^{-1} at maximum clock rate).

- The image acquisition system must be capable of the sustained recording of megapixel images for tens of minutes at a frame rate between 50 and 100 fps (and optionally recording attitude and position records). Capturing 1004 x 1004 12-bit pixel frames at 50 fps requires a sustained data transfer of 96 MB s⁻¹.
- The image acquisition system must be capable of very accurately time-stamping of each image frame (and optionally also each attitude and position record).
- The image acquisition system must be lightweight and consume minimal electrical power, to maximise UAS flight time.

The requirement for highly accurate time stamping of images, and position and attitude measurements cannot be overstated. Whilst the accuracy of position and attitude measurements are constrained by UAS payload limitations and the desire for a cost-effective POS, the geometric accuracy of the acquired imagery is also greatly constrained by errors in time-stamping. For example, assuming a speed over ground (SOG) of 2 m s⁻¹, a timing error of 10 ms between image acquisition and position measurement will cause an along-track positioning error of 2 cm. Assuming a rate of change of 10'' in camera roll, a timing error of 10 ms between image acquisition and attitude measurement will cause an approximate across-track error of 2.2 cm (at a flying height of 10 m and FOV of 50°). These calculations show the isolated effect of timing error, however, the effect of a 10 ms timing error on a UAS frame exhibiting real-world dynamics will be more than the 2 cm described above. To maximise the accuracy of the direct image georeferencing process, the uncertainty in time-stamping of less than 100 ns between image capture and POS measurements was desired.

2.2.3 Selection process of DIA system

Although a variety of image acquisition systems were considered for use on the UAS, many were suited only for laboratory or industrial use, where size and mass are not a constraint. Third-party applications based on National Instruments LabView hardware and software and also frame grabber printed circuit boards (PCBs) for use with a PC-104 sized single board computer (SBC) were rejected as they do not allow for sufficiently accurate image time-stamping. Dehaan et al. (2012) documents a hyperspectral data logging system using a mini-ITX motherboard and frame grabber for capturing imagery from a CameraLink based hyperspectral sensor on-board a fixed-wing UAS. Whilst the ITX format is small compared to the variety of industry standard desktop PC motherboards, the mini-ITX format is still a sizeable 170 mm x 170 mm for use on the multi-rotor UAS described here. The KINO-QM670 SBC specified in Dehaan et al. (2012) weighs 900 g, while the airborne acquisition unit accompanying an imaging spectrometer on-board a small fixed-wing UAS described in Hruska et al. (2012) was reported to weigh 1.16 kg and measures 102 x 165 x 82 mm.

The IO Industries DVR Express Core was selected as the digital video recorder (DVR) at the core of the image acquisition system. The Field Programmable Gate Array (FPGA) based DVR captured high-speed digital imagery directly from a CameraLink capable camera to a solid-state hard drive (SSD) without relying on a traditional computer operating system.

The system was designed to be portable and thus it utilised a pico-ITX format SBC to command and control the FPGA based DVR. Design features of relevance for use of this unit on the UAS include:

- A variety of interfaces available, including Camera Link (Base).
- The ability to accept a 1 pulse per second (PPS) signal and National Marine Electronics Association (NMEA) telegrams from a GPS receiver allowed microsecond accurate time-stamping of each image frame.
- The ability to sustain a write speed to an serially attached (SATA) SSD allowing image capture at 100 fps.
- The availability of technical documentation and support allowing the trouble-free miniaturisation of the electronics.
- The inclusion of a Microsoft (MS) Windows 7 based application (CoreView) for the basic control of DVR electronics (acquisition start and stop, image preview and export, etc.). Importantly, this application allows the export of imagery in a variety of formats suitable for further processing.

The adaptability of the DVR Express Core, level of manufacturer provided technical support and the overall design philosophy gave confidence that time-stamping and sustained write speed requirements would be robustly fulfilled.

2.2.4 Implementation of DIA

The IO Industries DVR Express Core unit comprises of a PC-104 sized DVR PCB, pITX sized SBC and one to four 2.5 SSDs in an aluminium case with associated power supplies and cabling. Total weight with a single SSD was over 1.5 kg. After initial bench testing, the manufacturer supplied DVR system was dismantled to allow a mass and volume saving redesign. The suitability of existing SSDs were bench tested to ensure that their capacity and write speed were sufficient for the intended flight times and frame rates respectively. The relatively small camera pixel count, moderate frame rate and relatively short flight times allowed the use of a single SATA 2.5 SSD connected via one of the DVRs four storage device SATA ports. Custom fibreglass PCBs were designed to physically mount the DVR and SBC along with associated SSD, flash memory modules, isolation and power regulation circuitry. The 1.8 mm thick fibreglass PCBs sandwiched the fragile multilayer DVR PCB to achieve lightweight mechanical protection. PCB connectors were suitable placed on the PCB to make wiring as easy as possible in the limited available space. Lightweight cable looms were fabricated to connect system components together. Isolated high frequency switching direct current (DC-DC) convertors were used to power the major components from a single 18.5 VDC (5S) 5000 mAh Lithium-Polymer (LiPo) battery.

The use of the 1 PPS signal and NMEA date and time (\$ZDA) telegram from the Novatel OEMV-1DF dual frequency GPS receiver board allowed very accurate timekeeping as previously outlined. Novatel state the timing accuracy of the 1 PPS signal to be 20 ns (RMS) between subsequent pulses. The transistor-transistor logic (TTL) level 1PPS signal was connected directly between the GPS and the DVR PCB via optical isolation. NMEA \$ZDA telegrams were transmitted at 9600 bps at 1 Hz via a RS232-USB converter, connected to the SBC running the IO Industries control application (CoreView) under the multitasking MS Windows 7 operating system. The combination of the 1 PPS and \$ZDA telegram allowed real-time time-stamping of each frame at 50-100 fps with nanosecond accuracy. The direct connection of the 1 PPS signal to the FPGA based DVR removed image time stamping problems caused by latency of the operating system. The custom PCBs, mounting the DVR and SBC (and associated electronics) along with a custom power supply PCB, were mounted on a lightweight aluminium equipment tray via moulded rubber vibration dampeners.

2.2.5 Power supply subsystem

All electrical power for the scientific payload is supplied from two off-the-shelf LiPo battery packs. These batteries are used in addition to the battery packs supplying unregulated DC power to the UAS avionics and motors. Electrical isolation between the UAS avionics and scientific payload electronics is an important design feature to permit testing of either system without reliance on the other. The power supply subsystem consists of a number of isolated DC-DC switching regulators and associated components mounted on custom designed PCB. All regulators are wide range input devices capable of supplying a regulated 5 or 12 VDC under full load with an unregulated input range between 9 and 36 VDC. This allows LiPo batteries with a cell count between 3 (11.1 V) and 9 (33.3 V) to be used. Isolated regulators are used throughout the design to enable the future electrical isolation of attached subsystems if required. The POS and DIA subsystems are supplied from separate LiPo batteries and power regulation electronics. This allows the POS and power regulation electronics to be removed or replaced as a standalone assembly.

2.2.6 UAS airframe and sensor integration

For the UAS airframe we chose the Droidworx Skyjib 8 multi-rotor heavy-lift UAS (Droidworx Limited, New Zealand). The use of carbon fibre sheet and thick wall rod held together with alloy machine screws enabled the fabrication of a very light but rigid assembly. The undercarriage supported the combined mass of the UAS and scientific payload (4.5 kg) when standing on the ground. To mount the hyperspectral payload on the UAS, a number of issues had to be considered:

- The scientific payload was expected to be easily installed and removed without tools, i.e. avoiding use of small fasteners. This is especially relevant for work in cold and physically demanding field conditions as for instance in Antarctica.
- UAS flight characteristics must not be compromised by the addition of the scientific

payload. Whilst a reduction in flight time and manoeuvrability is to be expected, the UAS with the scientific payload must be able to fly outdoors in real-world conditions.

- The mass of mechanical components of the scientific payload had to be as low as feasible. The unavoidable mass of the scientific payload greatly limits the flight time of the UAS compared to the modest payload of a simple two-axis gimbal with a standard digital camera. Desirable minimal reduction of flight time is, therefore, achievable only by designing lightweight mechanics of the scientific payload.
- The scientific payload had to be sufficiently mechanically isolated from the UAS airframe to prevent vibration from causing image motion blur and damage to electronics. The major source of in-flight vibration was the eight electric motors and propellers operating at 4000-6000 RPM.
- The scientific payload had to be a standalone instrument, capable of operation when not mounted on the UAS. This enabled on-ground testing and calibration without the requirement for UAS or pilot.
- The arrangement of the imaging spectrometer and the IMU within the scientific payload had to permit the rigid mounting of both units. Accurate measurement of spectrometer attitude would not be possible without hard co-mounting of both instruments.
- The L1/L2 antenna for the dual frequency Novatel GPS receiver and the L1 antenna for the GPS receiver built into the IMU both needed clear views of the sky for optimum performance. The L1/L2 antenna needed to be rigidly mounted to allow measurement of accurate and repeatable lever arm distances from the antenna phase centre to the spectrometer focal plane.
- Locating the IMU close to the Center of Gravity (CoG)/Center of Rotation of the UAS is advantageous. Attitude measurement using a lightweight MEMs based IMU is limited in part by the accuracy of the IMUs rate gyroscopes. By locating the IMU at the CoG of the UAS, the IMU is able to measure changes in UAS pitch and roll (using accelerometers) without having to account for large simultaneous changes in the acceleration of the IMU (measured by a rate gyroscope). Changes in IMU acceleration result from natural UAS pitching and rolling, when the IMU centre is not precisely located at the CoG of the UAS. The smaller the distance between IMU centre and UAS CoG, the smaller the changes in acceleration, and hence the smaller the adverse effect on the accuracy of dynamic attitude measurements.

Design of the scientific payload was undertaken with these mechanical specifications in mind. Computer Aided Design (CAD) environment was used, enabling the on-screen trialling of a variety of equipment layouts and construction techniques prior to fabrication. Certain components were fabricated using Computer Aided Manufacturer (CAM) techniques. Lightweight off-the-shelf components and composite materials were used where possible. SolidWorks (Dassault Systems) was employed to create models of components,

sub-assemblies and assemblies representing the majority of the mechanical components of the UAS and scientific payload. Measured masses were assigned to all components in Solid-Works to enable accurate total mass comparisons of a variety of physical designs. Accurate mass assignments also allowed the calculation of the CoG of the combined UAS and scientific payload. The comparison of the CoG of the UAS alone with the CoG of the UAS with scientific payload attached was useful for assuring that UAS hover performance will not be drastically affected.

The Droidworx supplied undercarriage was replaced with a custom designed undercarriage. The new undercarriage was fabricated from four sections of 10 mm nylon rods and turned acetal plastic rod mounts. The custom designed eight-rod mounts replaced the eight Droidworx supplied bottom motor mounts and held the four Nylon hoops in semicircular loops between adjacent motor mounts. The new undercarriage provided a larger on-ground footprint, which assisted better stability during take-off and landings in windy conditions. The use of flexible nylon rods provided shock absorption to both the UAS and scientific package during the inevitable occasional hard landing.

The scientific payload was designed to hang on four silicon mounts that were in turn attached to four of the motor booms. The mechanical design of the silicon mounts prevented excessive movement of the scientific package, which would tear the supply silicon mounts. Deviations from a neutral position were limited to approximately 10 mm in all directions, which was found sufficient to allow for unhindered movement of the scientific package in general use. The final design of the HyperUAS is illustrated in Figure 2.

(a)

(b)

Figure 2: HyperUAS: (a) CAD model of multi-rotor UAS with custom designed payload package; (b) photo of the HyperUAS during test flight.

2.2.7 Limitations of design

The central hub and radial boom configuration of the Droidworx SkyJib airframe is preventing the co-location of the CoG of the UAS and the CoG of the scientific payload. This limitation is common to all commercially available heavy lift multi-rotor UAS. The thrust vectoring design of current multi-rotor UAS means the UAS is always constantly pitching, rolling and yawing to some degree when flying to a set waypoint. Multi-rotor UAS do not have control surfaces and rely on deviation from vertical direction by varying propeller thrust to translate from one position to another. As the IMU and L1/L2 antenna cannot be physically mounted at the CoG of the UAS, the natural rotations will cause its small translations. Also, as the mass of the scientific payload is hanging below the CoG of the UAS, small unwanted pendulous motions are introduced into the POS measurements. Rotation of the UAS around three axes will cause the rotation of any hard mounted equipment, such as the scientific payload. These rotations are unavoidable in a hard mounted sensor system, but the availability of an accurate on-board POS, measuring UAS attitude in conjunction with image capture, enables post-processing of the image geometrical distortions caused by natural rotations and direct georeferencing of the acquired pushbroom imagery.

2.3 Description of field operation procedure

Hyperspectral images should be collected under the prevailing direct solar irradiation and during solar noon to ensure a high signal quality. This was the case for the first proof of concept experiment. For the second experiment, the images of Antarctic mosses were acquired during the local solar noon, but due to the time and logistical constraints only under a full overcast. This offered us with an unintentional opportunity to assess feasibility of HyperUAS deployment under prevailing diffuse irradiation conditions. Finally, the third experiment was conducted under a partially cloudy sky, as it was not focusing on spectral interpretation, but only on geometrical corrections and rectification of acquired images.

Five artificial directionally isotropic (near-Lambertian) spectral calibration panels (each 25 x 25 cm in size), providing a flat reflectance response ranging from 5 % to 70 % in visible and near-infrared (NIR) wavelengths, were placed on flat ground within the sensor FOV to remove the spectral influence of atmospheric scattering and absorption processes from the acquired images. Their reflectance functions are used during the processing phase as the reference for eliminating confounding atmospheric effects. Finally, bright metallic discs of two sizes (10 cm and 30 cm in diameter) were systematically deployed within the area of image acquisition during last two experiments. Precise geographic positions of their centre points were measured with the geodetic Differential Global Positioning System (DGPS) Leica 1200 (Leica Geosystems, USA). The ground control points (GCPs) were used in the second experiment for geometric image correction and co-registration, and in the third experiment as the reference points for the GPS/IMU direct georeferencing accuracy assessment.

As the operational flight time of the HyperUAS is currently limited to 2-3 min and all autopiloted test flights in Antarctica failed due to the unstable magnetic field and the extreme

magnetic declination of 98° , the UAS operator had to execute all experimental flights manually. The lens objective of the sensor was focused before each flight at the distance of the flight altitude. A hyperspectral dark current image (i.e. measure of sensor noise) was then recorded under the actual environmental conditions. After uncovering the sensor lens a new image acquisition was started and the system was flown along a predefined approximately 30 m long transect. The actual UAS location, flight speed, and altitude were monitored in real-time via a telemetry link. After landing the image acquisition was stopped and supportive ancillary ground measurements (e.g. spectral signatures of verification targets and position of GCPs) were conducted.

2.4 Spectral, radiometric calibration and atmospheric correction of hyperspectral image

Raw images of the Micro-Hyperspec spectroradiometer are recorded in digital counts of the 12-bits sensor range (i.e. the maximal signal strength is equal to 4096 digital numbers – DN). Spectral and radiometric calibration of the Micro-Hyperspec sensor had to be carried out prior to its operation to reveal sensor specific spectral characteristics (i.e. spectral sampling and resolution) and to facilitate transfer of the DN counts into the physically meaningful radiance units ($\text{mW cm}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$). Both calibrations were performed at the optical calibration facility of the Australian national science agency, The Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Canberra. The spectral calibration was conducted in accordance with standard methodology using a pen-ray line source producing sharp gas absorption features of well-known wavelengths (Chen, 1997). The Micro-Hyperspec sensor was exposed by a Mercury-Argon (Hg-Ar) calibration source HG-1 (Ocean Optics, USA) and set-up to collect 100 frames in unbinned and also binned spectral mode, with the frame period and integration time set to 40 ms. The spectral bands of well-defined features with a single peak were identified and attributed to the 13 known Hg-Ar emission lines at 404.656, 435.833, 546.074, 696.543, 706.722, 727.294, 738.393, 763.511, 772.4, 811.531, 826.452, 842.465 and 912.297 nm (see Fig. 3). A linear function established between the recognised wavelengths of Hg-Ar emissions and the corresponding spectral bands (i.e. spectral elements of the sensor matrix) was used to derive missing wavelengths of the remaining bands ($R^2 = 99.99$, $p = 0.001$). The spectral response specific Gaussian functions were afterwards fitted to each of the 13 Hg-Ar emission features (see Fig. 3) and the width at the half of the function maximum identified the sensor spectral resolution (i.e. FWHM). The FWHM values of the in-between spectral bands were linearly interpolated. The resulting mean spectral sampling (i.e. spacing between two consecutive spectral bands) of 1.857 nm and 3.714 nm with the mean FWHM of 4.12 nm and 5.05 nm was found for unbinned and binned spectral mode of the Micro-Hyperspec sensor respectively.

Figure 3: Spectral signature of the Mercury-Argon (Hg-Ar) calibration source HG-1 (Ocean Optics, USA) as recorded by the Micro-Hyperspec spectroradiometer during its spectral calibration (324 spectral bands, frame period and integration time set 40 ms). Numbers above spectral peaks are indicating 13 wavelengths [nm] of the gas emissions used in Micro-Hyperspec spectral calibration.

An integrating sphere is an optical component designed as a hollow ball with relatively small openings as light entrance and exit ports and interior coated for high diffuse reflectivity producing a uniform light reflectance at each position. Sensor radiometric calibration was performed with Micro-Hyperspec facing a opening of the certified optical integrating sphere USR-SR 2000S (Labsphere Inc., USA) equipped with four electric current stabilised light sources (labelled as SI and INGAAS lamps), which are producing calibrated irradiance levels of traceable uncertainties (Fig. 4). A tungsten ribbon filament lamp is the most widely used standard for spectral radiance for visible and NIR wavelengths (Kostkowsky, 1997). The Quartz Tungsten Halogen (QTH) lamps were used to illuminate the Micro-Hyperspec CCD sensor, which recorded images of 100 frames with the integration time varying from 10 ms to 40 ms to prevent sensor saturation. Images were acquired in unbinned and binned spectral mode with the objective focused on infinity (case of airborne acquisitions) and near distance (case of ground-based acquisitions). Corresponding dark current images (DCIs) were also acquired with the sensor facing a dark integrating sphere port. To compute the radiometric calibration coefficients for each spectral band, hyperspectral DCI was subtracted from spectral image containing DN values of predefined irradiance levels, thereby eliminating the sensor white noise. Subsequently, it was divided by the integration time to make calibra-

tion independent of the frame exposure time. The image frames were averaged per band and divided by appropriated calibration values corresponding to the irradiation intensity used (Fig. 4). The radiometric calibration of an airborne and/or ground-measured Micro-Hyperspec image starts analogously with diminishing the sensor noise by subtracting the DCI recorded before flight from the acquired image and with normalising it by the applied frame integration time. Each spectral band is afterwards multiplied by the corresponding radiometric coefficient to translate the DN counts into the physical units of radiance. An example of this conversion in case of a grass canopy recorded by Micro-Hyperspec during the first study experiment is provided in (Fig. 5).

The empirical line correction (Smith and Milton, 1999) is a standard remote sensing calibration technique using spectrally uniform ground targets to remove optical influences of atmospheric gases and aerosols between the sensor and observed surfaces and converting at-sensor radiances to surface hemispherical-directional reflectance functions (HDRF) (Schaepmanstrub et al., 2006). The atmospheric correction of Mirco-Hyperspec images was carried out in ENVI/IDL image processing software (Exelis Visual Information Solutions, USA). Five directionally nearly isotropic (i.e. near-Lambertian) grey scale calibration panels (cream, pearl, light grey, stone grey and anthracite, Fig. 4(a)) that were manufactured to produce a flat reflectance function ranging from 5 up to 70 % were located on the hyperspectral image. Their actual per-band radiances were extracted from the image and empirically related to their HDRF measured beforehand with a numerical spectroradiometer in the laboratory (Fig. 4(b)). The atmospheric correction coefficients (including the maximum solar irradiance and the atmospheric path radiance) computed from this coupling were applied across the whole image to convert the at-sensor radiance to the surface HDRF. An example of the atmospherically corrected grass canopy HDRF, extracted from Micro-Hyperspec image displayed in Fig. 7, is together with the original at-sensor radiance shown in Fig. 5.

(a)

(b)

Figure 4: Radiometric calibration of the Micro-Hyperspec sensor using the Labsphere optical integration sphere USR-SR 2000S (a) equipped with four calibrated light sources (lamps) producing predefined irradiances in visible and near infrared wavelengths (b).

Figure 5: Spectral profile of a grass canopy in (a) digital numbers (DN) as acquired by the Micro-Hyperspec sensor from the altitude of 11 m, (b) in radiance units after the radiometric calibration, and (c) in unit-less reflectance after the atmospheric correction.

Figure 6: Spectral calibration panels: (a) five directionally nearly isotropic (i.e. near-Lambertian) spectral panels of a grey scale (cream, pearl, light grey, stone grey and antracite); (b) manufactured using a special paint to provide a flat reflectance function from 5 % to 70 % in visible and near-infrared wavelengths.

2.5 Quantitative estimations of vegetation biophysical and biochemical variables

As demonstrated by several studies published in a special issue of Remote Sensing of Environment on Imaging Spectroscopy (Ustin and Schaepman, 2009), modern hyperspectral remote sensing offers, besides traditional qualitative products (e.g. land cover or land use maps), also the possibility to map quantitative characteristics of natural and rural ecosystems (e.g. plant functional traits as leaf area index or leaf chlorophyll content). The quantitative vegetation traits can, for instance, help predicting potential crop yield (Clevers, 1997) or indicate a level of environmental stress impact in vulnerable natural areas (Kokaly et al., 2009). In this study we demonstrate capability of our HyperUAS data to generate these products at unprecedented high spatial resolution of 5 cm.

An efficient way of quantifying vegetation traits from hyperspectral images is transformation of acquired reflectance spectra in so-called optical vegetation indices (VIs). VIs are mathematical combinations of purposely selected spectral bands that can maximise sensitivity towards biophysical or biochemical variables and simultaneously minimise effects of confounding environmental factors (e.g. a negative spectral influence of bare soil underneath vegetation canopy) (Myneni et al., 1995). In our first and second experiment we applied the following three specific VIs: i) the most frequently used Normalized Difference Vegetation Index (NDVI), proposed to separate green vegetation from abiotic surfaces based on their red/NIR spectral contrast, ii) the ratio of the Transformed Chlorophyll Absorption in Reflectance Index (TCARI) and the Optimized Soil-Adjusted Vegetation Index (OSAVI), designed to assess total leaf chlorophyll a + b content (C_{ab}) as a measure of photosyn-

thetically active foliar pigments (Haboudane et al., 2002), and iii) the Modified Triangular Vegetation Index 2 (MTVI2), invented by (Haboudane, 2004) to estimate green biomass density via leaf area index (LAI) defined as one sided green leaf area per unit ground area. NDVI was developed based on LANDSAT observations in the 1970s as a simple difference ratio of red and NIR TM bands (Tucker, 1979). In our experiments, we computed NDVI from the Micro-Hyperspec spectral bands located at 680 (ρ_{680}) and 800 (ρ_{800}) nm as:

$$\text{NDVI} = \frac{(\rho_{800} - \rho_{680})}{(\rho_{800} + \rho_{680})} \quad (1)$$

TCARI/OSAVI was calculated as:

$$\text{TCARI} = 3 \left[\rho_{700} - \rho_{670} - 0.2(\rho_{700} - \rho_{550}) \left(\frac{\rho_{700}}{\rho_{670}} \right) \right] \quad (2)$$

normalised by:

$$\text{OSAVI} = \frac{(1 + 0.16)(\rho_{800} - \rho_{670})}{\rho_{800} + \rho_{670} + 0.16} \quad (3)$$

where ρ_{550} , ρ_{670} , ρ_{700} , and ρ_{800} are the reflectance values at 550, 670, 700 and 800 nm. Haboudane et al. (2002) proved that TCARI/OSAVI is highly sensitive to C_{ab} variations, while staying resistant to the variations in canopy LAI and solar zenith angle. Using computer models instructed to simulate radiative transfer through virtual vegetation, they deduced that C_{ab} of remotely sensed wheat or grass canopies can be empirically estimated via a non-linear logarithmic function:

$$C_{ab} = -30.94 \ln \left(\frac{\text{TCARI}}{\text{OSAVI}} \right) - 18.363 \quad (4)$$

where TCARI/OSAVI is obtained from airborne imaging spectroscopy data. Finally, MTVI2 was computed as:

$$\text{MTVI2} = \frac{1.5 [1.2(\rho_{800} - \rho_{550}) - 2.5(\rho_{670} - \rho_{550})]}{\sqrt{(2\rho_{800} + 1)^2 - (6\rho_{800} - 5\sqrt{\rho_{670}}) - 0.5}} \quad (5)$$

MTVI2 is a successor of TVI (Triangular Vegetation Index) (Broge and Leblanc, 2001) that can successfully suppress a negative confounding influence of varying C_{ab} and bare soil beneath the plant canopy. According to Haboudane (2004), it can be used to estimate green LAI from an exponential equation:

$$\text{LAI} = 0.2227 \exp(3.6566 \text{MTVI2}) \quad (6)$$

where MTVI2 is expected to originate from a hyperspectral image of structurally homogeneous plant canopies.

3 Experimental results

3.1 Experiment I: Assessing chlorophyll content and green biomass of pasture and barley crop

The first proof-of-concept experiment was designed to test the general field operation of the HyperUAS. This first test was carried out without GPS/IMU georeferencing capability to investigate steadiness of radiometric and spectral calibration of the Micro-Hyperspec mounted on the multi-rotor SkyJib airframe. The main intention was to prove that HyperUAS images can provide spatially meaningful patterns of biochemical and biophysical vegetation variables, particularly C_{ab} and LAI, at a spatial resolution of 5 cm. The experimental flight was conducted over a canopy of grass pasture and green barley crop at the research farm of the University of Tasmania (UTAS, Hobart, Australia) on a sunny day on 8 November 2012. The image data was acquired in binned spectral mode (i.e. 162 spectral bands), which resulted after radiometric calibration and atmospheric correction in expected standard HDRF signatures of sensed agricultural canopies (Fig. 5). TCARI/OSAVI and MTVI2 were subsequently computed (eq. 2, 3, and 5) for a geometrically consistent image subset of approximately 35 m in length and converted into the C_{ab} and LAI products (eq. 4 and 6).

Figure 7: The radiometrically and atmospherically corrected Micro-Hyperspec image in near infrared colour representation (bands 120 (800 nm), 84 (670 nm), and 57 (570 nm) mapped to RGB) acquired over grass and barley canopy on 8 November 2012 (a), and the subsequently generated biochemical and biophysical products of actual leaf chlorophyll content (b), and true leaf area index (c).

As illustrated in Fig. 7, the spatial patterns of both products are highly detailed, but systematic, meaningful and consistent. Although, we had no possibility to collect ground truth measurements for direct validation of retrieved characteristics, the quantitative ranges of both variables were found to be plausible, estimating most of the C_{ab} values between 10 and $60 \mu\text{g cm}^{-1}$ and LAI between 1 and $10 \text{ m}^2 \text{ m}^{-2}$. They also correspond to the previously

published results of similar canopies (Haboudane et al., 2002; Haboudane, 2004). Grassland is gaining, in general, lower C_{ab} and LAI than barley, which might be caused by stress from animal trampling and grazing. More interestingly, 5 cm pixel-size allows identification of very small canopy openings (only a few centimetre) in the barley field with gradually increasing LAI from the centre point toward the edge. These openings are, however, not identifiable in the C_{ab} pattern, suggesting that they do not limit the actual photosynthetic capability of surrounding plants. Such a detailed observation would not be achievable without combining narrow spectral bands of the Micro-Hyperspec with the ultra-high spatial resolution obtainable by HyperUAS.

3.2 Experiment II: Mapping actual vigour of Antarctic moss beds

The second experiment tested performance of HyperUAS in a remote and harsh, low-temperature environment of Antarctica during our scientific activities mapping the current health vigour of Antarctic moss beds. Mosses *Schistidium antarctici*, *Ceratodon purpureus*, and *Bryum pseudotriquetrum* are dominant photosynthetically active plant species growing along the rocky coast of Antarctica. Recent changes in temperature, wind speed and stratospheric ozone are, however, negatively influencing their growth rate, health state and spatial abundance. A need for mapping the actual state of Antarctic moss beds arose within the scientific community in the last decade. Because the vegetation season in Antarctica is very short, lasting only about three months, and weather conditions are changing fast, the moss monitoring approach must be time efficient, easily deployable and still able to capture highly fragmented distribution of only few cm large moss patches in rocky terrain. This practical mapping problem was one of the motivations for developing HyperUAS, which fulfils all these requirements. HyperUAS was after rigorous preparations successfully flown over several moss beds surrounding the Australian Antarctic station Casey (Windmill Islands, east Antarctica) in January and February 2013. For more information about the study site, see Lucieer et al. (2013). The spectrally binned nadir looking hyperspectral images acquired from 11 m AGL were first radiometrically calibrated and corrected for atmospheric influence. Geometric correction required an orthophoto to be acquired as a reference image.

Directly after the HyperUAS flight we flew a smaller OktoKopter with a digital single-lens reflex (DSLR) camera to collect ultra-high resolution RGB imagery. These photos were collected to derive a 5 mm resolution orthophoto mosaic and a 1 cm resolution digital surface model (DSM) based on SfM techniques (for more detail on this workflow see Turner et al. (2012) and Lucieer et al. (2013)). Twenty large GCP discs were laid out along the HyperUAS flight transect with a 30 m measuring tape in the middle of the strip for scale and georectification purposes. Thirty smaller discs were spread out to identify areas for spectral field sampling. An ASD HandHeld2 field spectrometer was used to collect reference spectra for the calibration panels described in section 2.4, and to collect validation spectra for ten rocky areas and ten moss covered areas. All discs were geolocated with a dual frequency geodetic GPS receiver (DGPS) with an absolute geometric accuracy 2–4 cm. Accurate coordinates for the large GCPs were used in the bundle adjustment of the SfM workflow, resulting in a 3D model of the moss bed topography at cm accuracy. The orthophoto mosaic

was exported to a GeoTIFF in the Universal Transverse Mercator map projection (UTM Zone 49 south, datum: WGS 1984).

For this experiment we had not been able to fully integrate and test the POS sub-system on the HyperUAS. Therefore, we had to rely on slow and steady flights for reasonable image geometry. The HyperUAS image was co-registered to the orthophoto mosaic by matching all 50 GCPs. The GCP discs were clearly visible in both images and GCPs were manually identified in each image. A triangulation (i.e. rubber sheeting) transformation was applied to the hyperspectral image to: 1) geometrically transform the image into the WGS84 UTM49S coordinate system, 2) correct for geometric distortions resulting from flight dynamics, and 3) co-register the hyperspectral image to the orthophoto and DSM (Toutin, 2004). The co-registration was carried out with the widely used image-to-image registration tools in the IDL/ENVI software. We then compared the spectral signatures of the geometrically corrected HyperUAS image with spectral signatures observed in the field. An example of this comparison for a healthy moss patch is shown in Fig. 8. The signatures match very closely with an RMSE of 0.6% reflectance. After all correction steps, the biophysical and biochemical properties of the moss beds were derived.

The separation of patchy moss from abiotic rocky surroundings was achieved by selecting pixels with NDVI >0.6 (Tucker, 1979). Since mosses are photosynthetically active plants growing in water-filled turf, their reflectance signature is similar to the evolutionary more advanced high plants, i.e. to some extent reflecting green, strongly absorbing red and highly reflecting NIR radiance. Being stressed by insufficient water supply and elevated ultraviolet irradiation, a moss turf can change its compactness and colour. It can turn from a healthy airy green turf to a stress resisting denser yellow-brown pack and finally, during the dormant stage, into a compact black biomass (called here for the sake of simplicity dead moss). Since these physiological stress reactions are changing their reflectance function, we could apply MTVI2 to distinguish the following four classes of moss vigour: i) high (MTVI2 >0.75), ii) medium (MTVI2 <0.75 and >0.50), iii) low (MTVI2 <0.50 and >0.25), and iv) dead, i.e. suffocated dormant moss (MTVI2 <0.25). Fig. 9 shows the final map assessing moss vigour at the research site Robinson Ridge, located south of the Casey Antarctic station, as observed on 5 February 2013. A simple statistical analysis revealed that 47 % of mosses captured on the Micro-Hyperspec image are recently dormant (dead). From the remaining 53 % of photosynthetically active moss patches about 32 % show low vigour, 13 % medium vigour, and only 8 % are healthy green moss packs (Fig. 9). Performing the same HyperUAS investigation in future years would allow us to monitor spatio-temporal changes of Antarctic moss ecosystems in relation to their surrounding environmental conditions and consequently to predict future trends in the regional impacts of Antarctic climate change.

Figure 8: Comparison of spectral signatures for a patch of healthy moss derived from the HyperUAS image (3 by 3 kernel average) and the matching location measured in the field with an ASD field spectrometer.

Figure 9: Radiometrically and atmospherically corrected hyperspectral image of Antarctic moss bed at Robinson Ridge (East Antarctica, 5 February 2013) displayed in false near-infrared colours (a) and derived map of actual moss vigour (superimposed over the 3D terrain model with orthophoto mosaic in natural colours) with graph presenting relative abundance of moss vigour classes in the image (b).

3.3 Experiment III: Incorporating GPS and IMU – orthorectification

The last experiment was carried out to test the integration of the POS sub-system and to use position and orientation data synchronised with the hyperspectral image lines for direct georeferencing and orthorectification. The orthorectification workflow is based on the airborne Parametric Geocoding (PARGE) approach (PARGE Manual Version 3.1, 2011). Although being originally designed for airborne data acquired from high altitudes with a pushbroom scanner mounted on highly stable gyroscopic platforms, PARGE was found to perform effectively also for our small-size UAS platform flying at lower altitudes around 10 m. PARGE considers the parameters of aerial platform and terrain geometry and creates orthorectified imaging spectrometry cubes using a forward transformation algorithm (Schlöpfer and Richter, 2002). Based on the sensor geometry, the GPS flightpath, and the sensor orientation an image geometry map is first calculated by PARGE storing the coordinates for every pixel. An appropriate resampling method is then selected to obtain a final georectified image cube. Optionally, a DSM can be provided for rigorous orthorectification.

During field trials, electrical interference was observed between the dual frequency GPS receiver and other electronic components of the scientific payload. By using the Novatel Connect software on an attached laptop, the SNR of the L1 and L2 GPS signals and various quality flags were observed in real-time. The operation of the DVR and the SBC had

large detrimental effects on the L1/L2 GPS reception. When either was switched on, a large reduction in both the L1 and L2 SNR was repeatedly observed. The GPS receiver would often lose lock completely when the DVR or SBC were switched on. Investigations confirmed interference was direct electromagnetic radiation from the DVR and SBC into the GPS receiver and GPS antenna. Grounded lightweight brass and aluminium shields were installed around the DVR and GPS and an aluminium ground plane was fitted to the GPS helical antenna to reduce the effects of interference. The shielded GPS receiver was located as far from the DVR and SBC as practical. Whilst the electromagnetic interference was not completely eliminated, the shielding reduced the interference to an acceptable level.

The field trial was carried out on the (flat) university sports oval. The HyperUAS was manually flown at approximately 10 m AGL along a 20 m transect at 2–3 m s⁻¹. GPS and IMU data was processed against a nearby base station and a position and orientation solution generated for each image line using a sigma point Kalman filter. A flat surface was assumed for orthorectification in PARGE. The pitch, roll and yaw angles of the flight are presented in Fig. 10. Summary statistics of these sensor attitude data are provided in Table 1. Nine large GCP discs and 36 smaller discs were spread out on either side of a straight measuring tape to check the geometry of the hyperspectral image strip and to assess the geometric accuracy of the direct georeferencing technique. The resulting image has a spatial resolution of 1.0 cm across-track and approximately 4.0 cm along-track. Fig. 11 shows the resulting image from this trial flight, including the observed (white) and true (yellow) location of the measuring tape, and the observed (white) and true (yellow) location of the GCPs. The geometric accuracy was calculated for the 45 GCPs and is presented in Table 2. The overall root mean square error (RMSE) is 25 cm. The maximum error for a pitch and roll angle of 5° is in the order of 87 cm at this flying height, which indicates that a higher absolute spatial accuracy is obtained with the PARGE orthorectification workflow. For such a low flight and high spatial resolution a higher accuracy is expected, however, these results only present the outcome of the first direct georeferencing trials. More research needs to be done on the accuracy of the POS and the accuracy of time synchronisation. In addition, lever arm distances and bore sight angles need to be measured in detail and taken into account in the filtering process. Future research will focus on a detailed analysis of the orthorectification workflow. This field trial shows that the concept of direct georeferencing of HyperUAS data is both possible and feasible.

Figure 10: Pitch, roll, and yaw plotted against each image line for the sport oval flight in Experiment III. Maximum pitch and roll angles were close to 5° . In this plot, the yaw was normalised by subtracting the average heading (38°) for presentation purposes.

Table 1: Summary statistics for the pitch, roll, and yaw of the HyperUAS. All values are in degrees.

	Min	Max	Mean	Abs Mean	St.Dev.
Pitch	-4.93	4.13	-0.31	2.12	2.48
Roll	-1.09	4.81	1.48	1.69	1.56
Yaw	33.78	41.34	38.16	38.16	2.58

Table 2: Geometric accuracy of direct georeferenced image calculated from 45 ground control points.

	Mean [m]	St.Dev. [m]	RMSE [m]
Easting	-0.19	0.09	0.22
Northing	-0.07	0.08	0.13
Total	-0.20	0.09	0.25

Figure 11: Orthorectification of HyperUAS image strip: a) raw uncorrected data with non-uniform pixels, b) resampled image with uniform 4 cm resolution pixels, c) orthorectified hyperspectral image based on synchronised GPS and IMU observations. True coordinates of ground control discs can be seen in the image. The observed (white) and true (yellow) location of the measuring tape, and the observed (white) and true (yellow) location of the GCPs are visible.

4 Conclusions

This study has demonstrated the design, implementation and field trials of a hyperspectral unmanned aircraft system (UAS), which was developed for ultra-high resolution image

acquisition with an imaging pushbroom spectroradiometer. A scientific payload sensor package consisting of the hyperspectral scanner, a high-accuracy position and orientation system (POS), and a time synchronised digital image acquisition (DIA) system was integrated with a multi-rotor UAS. An image processing workflow was implemented for spectral, radiometric, atmospheric, and geometric correction of the hyperspectral imagery. Quantitative estimations of biophysical and biochemical vegetation variables, such as leaf area index (LAI) and chlorophyll a + b (C_{ab}) content, were derived from the corrected hyperspectral imagery (with 162 or 324 spectral bands depending on binning). Three real-world field experiments were carried out to demonstrate the effectiveness of the HyperUAS prototype. The first experiment showed that LAI and C_{ab} can be retrieved from 5 cm resolution imagery of grass and a barley crop in southern Tasmania. The second experiment demonstrated that the HyperUAS can be operated in harsh environmental conditions. In this study, the HyperUAS was flown over moss beds in East Antarctica. The hyperspectral image was geometrically corrected via co-registration to an orthophoto mosaic, which was generated from a UAS survey and structure-from-motion (SfM) processing of the RGB photographs. Moss vigour was assessed from the hyperspectral image at unprecedented spatial detail using the modified triangular vegetation index 2 (MTVI2). The third field experiment demonstrated the integration of the POS and DIA sub-systems and their use in direct georeferencing of the raw hyperspectral image strip. An absolute accuracy of 25 cm was achieved on the 2 cm resolution imagery.

The flight time with the described scientific payload in ideal conditions at sea level was limited to 3 min. Whilst the current flight time allowed the work described to be successfully undertaken, there was very little possibility of extending the flight duration using the current hardware. Whilst there is the potential to reduce the weight of the scientific payload at the cost of mechanical rigidity, reductions will be modest at best given the unavoidable weight of the key components. Likewise, adding extra LiPo batteries to extend flight time is partially negated by the weight of the extra batteries and the associated cabling and mounts. The stability and flight performance of the UAS, both loaded and unloaded was acceptable for the work undertaken. The use of a large well-designed UAV airframe and commercial flight controller electronics meant minimal time was spent building and tuning the UAS. The stability achieved was typical of the stability achievable during outdoor flight using a commercial MEMs based flight controller. Whilst the addition of the scientific payload below the unloaded CoG of the UAS may have increased flight stability to some extent, the natural pitch, roll and yaw movement of the UAS during transects were directly transmitted to the spectrometer affixed in the scientific payload. The results of the direct georeferencing process presented here clearly show the challenge of acquiring ultra-high spatial resolution imagery from a low and slow multi-rotor UAS based around a cost effective MEMs-based IMU.

The major limitations to be overcome in future work are limited flight time and limited scientific payload stability. Future work will explore the combination of the design features of both multi-rotor and conventional helicopter UAS in an attempt to meld the advantages of both into a platform specifically suited to scientific applications that require longer flight times. In addition, techniques allowing the scientific package to be isolated from changes in UAS attitude will also be explored. Tiimus and Tamre (2012) describe a mechanical

gyroscopically stabilised approach to isolating a camera from changes in UAS attitude. Such an approach in combination with the considered location of a downwards looking camera and IMU may greatly improve results of the direct georeferenced workflow outlined here.

We have demonstrated that hyperspectral pushbroom scanning from a low and slow flying multi-rotor UAS is both possible and feasible, resulting in high quality hyperspectral imagery and image products at unprecedented levels of detail. The HyperUAS system presented here, opens up new opportunities for real-world remote sensing studies requiring on-demand ultra-high resolution hyperspectral imagery. Future work will investigate the value of the HyperUAS system for precision agriculture applications.

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