The design and the development of a hyperspectral unmanned aircraft mapping system for the detection of invasive plants

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Summary Cost-effective tools for rapidly identifying the spatial distribution of invasive plants in natural and managed landscapes are needed by land managers across the world to identify and monitor the spread of weeds. This paper describes a low-cost unmanned aircraft system (UAS) designed for the rapid acquisition of hyperspectral image data. The system integrates a Headwall Hyperspectral Visible Near-Infrared (VNIR) sensor covering 400–1000 nm range, a PCO Edge CMOS camera, a Cyber Technology autopilot and Inertial Navigation System (INS) including Real Time Kinematic (RTK) GPS, a data acquisition computer and custom software for operating the sensor. The imaging and autopilot systems are mounted on low-cost fixed wing and helicopter platforms. The Zealous 2 helicopter kit was developed by RC Helicopters and built by Cyber Technology in Western Australia. The Zealous 2 consists of a jet turbine engine powering main rotors spanning 2.1 m and is capable of lifting 15 kg. The fixed wing plane known as a 'Super Hauler' is made from balsa wood, has a wing span of 3.6 m and is 3 m long. The plane was designed and built by BTE Engineering in the USA and is capable of lifting 20 kg. The GPS/INS system provides aircraft position, pitch, roll and yaw information allowing for rapid geo-registration of the imagery. This paper will discuss the challenges associated with development and integration of the components for mapping invasive plants using unmanned aircrafts and the spectral characteristics of a number of target invasive species.

Keywords Invasive plant, UAV, hyperspectral imaging, fixed wing, helicopter, detection.

INTRODUCTION

Spectral imaging technology was developed about 40 years ago for astrophysics, remote sensing and terrestrial military applications. Hyperspectral imaging systems can capture imagery from tens to hundreds of narrow bands in the visible to infrared spectral regions. These systems offer new opportunities for better differentiation and estimation of biophysical attributes and have the potential for identification of optimal bands and/or band combinations for remote sensing applications (Yang *et al.* 2003). In the last 20 years, rapid evolution of imaging systems has occurred. Although research has focused on use of hyperspectral imaging for remote sensing, application of this technology has led to advancements in medicine, pharmacology, environmental sciences, food engineering, agriculture and natural resource management (Fischer and Kakoulli 2006).

Many different types of airborne hyperspectral sensors have been utilised in research projects and commercial applications. Typically, these systems employ fixed wing aircraft as a platform for scanning. The imaging system forms a unique hyperspectral image cube by a collection of scanned lines with the spectral bands of choice (Yang *et al.* 2003). To accomplish this on a landscape or paddock scale, the sensor is mounted on a stable aircraft which serves as a moving front. To evaluate weed/crop complexes, weed invasion fronts and mixtures of vegetation on this scale, an Unmanned Aerial Vehicle (UAV) can be integrated with a hyperspectral remote sensing system for weed detection at high spatial resolution. Instrumentation is designed to allow discrimination of weeds from surrounding natural vegetation or agricultural crops and to provide quantitative high-definition inventories of weed distribution. To achieve this level of discrimination, it is necessary to integrate a suitable unmanned aircraft capable of carrying payloads greater than 5 kg, with an aircraft control and communication systems capable of stable unmanned flight, along with onboard sensors capable of recording high frequency positional and aircraft attitude information during flight.

Recently, we were provided funding from the Rural Industries Research and Development Corporation (RIRDC) National Weed Research Program to further design and develop an effective platform for the study of weed distribution on a landscape level. Our research objectives were: 1) To develop a low-cost unmanned hyperspectral remote sensing platform capable of collecting high spatial and spectral resolution information about weed abundance and distribution at both the farm and catchment scale; 2) To develop a model system for the extraction of spectral information from hyperspectral imagery to produce semi-quantitative abundance maps of key invasive weed species in Australia. Specifically, in order to determine optimal spatial scale to cost-effectively map key weeds using hyperspectral imagery, the most appropriate spectral bands to use and the most efficient image analysis techniques to accurately map selected weed species were evaluated.

MATERIALS AND METHODS

To develop a low-cost UAV hyperspectral remote sensing platform capable of collecting both spatial and spectral resolution information at a farm and catchment scale, we designed a system based on its key components: the payload, the flight control system, and the UAV platform.

Determination of the payload The payload weight and flight characteristics required to collect data ultimately determine the flight control system and unmanned aircraft to be utilised. Our payload consisted of a hyperspectral imaging system to measure how electromagnetic energy (sunlight) interacts with materials on the ground and a data acquisition system to record this information. A Headwall Photonics Hyperspec VNIR spectrometer and PCO Edge camera combination was selected because it was robust, had better light capturing characteristics and was suited to low light conditions, which are critical in capturing high spatial resolution data. The data acquisition system consisted of a Mini-ITX QM670 motherboard, Intel I5 processor, Diolin GPIO USB adapter, Camera link frame grabber and solid state hard drives. The final weight of the hyperspectral camera and data acquisition system was between 7–8 kg. The cost of the hyperspectral camera was approximately AUD $60 000.

Construction of the flight control system The objective of the flight control system is to provide stabilised waypoint controlled flight without the need for a skilled pilot. Ideally the system will allow for automated take off and landing and control all aspects of flight based on predefined GPS waypoint navigation, altitude and airspeed parameters. The flight control system was composed of three main elements: a navigation system connected to the UAV controls, a communication system between the ground station and the UAV, and a ground station capable of manual override and flight planning. The Cyber Technology Pty Ltd (Perth WA) autopilot was chosen for this system based on superior technical specifications, the ability for local collaboration and support, cost and our timeline, which was short. The Cyber Technology autopilot (AP) consisted of 3 gyroscopes, 3 accelerometers, and 3 magnetometers measuring and logging the UAV position and attitude. The AP was connected to the ground station *via* a radio modem operating at 1.3 Mbit on the 900 MHz frequency. The autopilot operated at 820 Hz with roll and pitch accuracy approaching 0.1 degrees, three sigma. It could be programmed to operate a number of different UAV's from fixed wing aircraft to helicopter and quadrotor aircraft and was capable of automatic take off and landing. The flight control system was the most expensive component costing between AUD $80–120 000 depending on integration and components.

The platforms To achieve the high spatial resolution (<10 cm) required for detection in cropping canopies, we required a platform capable of both lifting a large payload and moving extremely slowly (<2 m s^{-1}). The downside of such a platform is that only limited areas can be covered quickly. We therefore decided to study two UAV platforms for our project, the first a helicopter for slow flight and the second a fixed-wing aircraft for more broadscale surveys. The helicopter was a modified Zealous II jet turbine helicopter from Cyber Technology. The modifications included a redesigned gearbox and main drive gear suitable for heavy lifting along with changes to the frame and landing gear to accommodate the payload, plus navigation and control systems. The helicopter was powered by a Wren turbine engine and had a main rotor span of 2.1 m and was approximately 2.0 m in length. With a full payload including the sensors and fuel, the helicopter could operate for 30 min at a variety of cruising speeds and weighed approximately 20 kg.

The second UAV platform was a plane developed by Bruce Tharpe Engineering (USA) known as 'The Super Hauler' (Figure 1). It had a simple all-wood design which was ideal as it was easy to maintain and easy to modify to suit a variety of instruments. The plane was powered by a Desert Aircraft DA 120 cc engine, with a wingspan of 3.7 m, a length of 3.0 m and capacity to carry a payload of around 15 kg. Both platforms were purchased for AUD $15 000.

Figure 1. Super Hauler UAV plane manufactured by Bruce Tharpe Engineering, USA.

Each platform was equipped to carry fuel equivalent to a 1 hour flight. The plane's stable cruising speed for the acquisition of hyperspectral remote sensing data was around 15 m s^{-1} while for the helicopter the speed was approximately 2 m s^{-1}. Both platforms were capable of substantially higher speeds, however to prevent gaps in the imagery, there was consideration of parameters such as flight speed of the platform, frame rate of the hyperspectral camera, and desired pixel size on the ground. Several tests for both platforms were performed in a variety of wind conditions. In winds greater than 15 km h^{-1} significant stability issues effected the acquisition of useful imagery although both aircraft were still able to be safely flown. It is recommended that hyperspectral data only be collected when wind speeds are below 15 km h^{-1} for both safety and data quality.

System integration The various components that make up a UAV imaging system require significant integration before an operational system is realised. This is particularly true when purchasing system components from a variety of manufacturers. The first level of integration was to develop a data acquisition system capable of recording the spectral information collected by the hyperspectral imaging system. To operate the camera and data acquisition system, software was written by the project team to control a number of aspects of camera operation, including triggering the camera along with routines to record the data to hard drives in a Windows 7® operating system environment. The next level of integration involved synchronising the hyperspectral camera data to the attitude information (pitch, roll, yaw) recorded by the Cyber Technology autopilot. In our case the Headwall hyperspectral system collected data at approximately sixty scan lines every second. To geo-locate these lines on the ground surface it is necessary to know the orientation of the camera relative to the ground at each scan. This can be done by either measuring the attitude of the aircraft if the camera is fixed to the aircraft or in the case of many traditional commercial airborne systems knowing the orientation of the stabilised mount that houses the hyperspectral scanner. In this project we chose an autopilot that measures the attitude of the plane as part of its autopilot operations rather than purchasing a separate attitude sensor. Integration was achieved by sending a simultaneous pulse using a General Purpose Input/Output (GPIO) chip to the autopilot log when each camera frame was captured.

Field test sites were restricted to Charles Sturt University, Wagga Wagga for initial ease of access and safety. The three test sites were chosen because they contained over a dozen weed species of interest including: Paterson's curse (*Echium plantagineum*), wild oats (*Avena* spp.), barley grass (*Hordeum* spp.), phalaris (*Phalaris aquatica*), annual ryegrass (*Lolium rigidum*), great brome (*Bromus hordeaceus*), spear thistle (*Cirsium vulgare*), and St Barnaby thistle (*Centaurea solstitialis*). Across these test sites we measured over twenty weeds and compiled the results as a digital reflectance spectral library of the weed spectra that cover wavelengths from the near-infrared to the shortwave infrared from 400 to 2500 nm. Each spectrum was collected using an identical process to maintain consistency and to standardise the results, particularly for those samples collected under natural illumination. The test sites were also used to determine the stability of the platform, ensure the flight control system functioned correctly, and to test the integration between the autopilot, data acquisition system and hyperspectral camera system. Over a dozen test flights were completed.

In order to effectively calibrate the hyperspectral data and to provide training data for classification along with ground truth information for accuracy assessment, a range of field measurements of weeds were made. Uniform canvas calibration targets of known spectral reflectance were laid out within the test site prior to image acquisition. PVC signboard was used to construct quadrats measuring 1 m × 1 m on the inside of the square and placed randomly across the test site. The edge of the quadrants had a width of 15 cm to ensure that the edges could easily be identified.

RESULTS AND DISCUSSION

Hyperspectral image analysis and preprocessing The interpretative techniques used to produce quantitative abundance maps differ greatly from those traditionally applied to multispectral remote sensing data. To separate weeds from other vegetation or soil, the analysis of hyperspectral data can be divided into three distinct phases of analysis.

(1) Pre-analysis — raw data are converted from raw brightness values to radiance and then atmospherically corrected to apparent reflectance. Radiance values can be converted using a radiative transfer model based on MODTRAN for calibration to absolute reflectance as implemented in software such as ATREM, or in the case of this study using empirical based methods where brightness values are relatively calibrated by forcing the corresponding image spectra of calibration targets to fit the field spectra of the same calibration targets. The second phase of preprocessing is to geometrically correct the lines of hyperspectral data known as orthorectification. In this study we used commercial software known as PARGE to complete the orthorectification process.

(2) Analysis — representative spectra are selected either from field sites or image training areas or selected using endmember selection techniques such as the n-dimensional visualiser. Spectra are then mapped using traditional classification techniques, unmixing or spectral matching techniques. Data are also sometimes transformed to reduce data dimensionality, emphasise unique reflectance features and aid endmember identification using techniques such as Principal Component Analysis (PCA) or the Minimum Noise Fraction (MNF) transformation (Green *et al.* 1998). Several specialised mapping methods have been developed to take advantage of the high spectral resolution of hyperspectral imagery. These methods estimate the sub-pixel composition of a pixel using unmixing techniques that identify multiple materials and their fractional abundance within the pixel. In this study we examined the matching methods SAM, SFF and the unmixing MTMF approach. The hyperspectral imagery was processed using the established techniques of the MNF transform (to both remove noise and to compress the hyperspectral data into a small number of derived bands) and the Pixel Purity Index to identify potential image endmembers. The full spectral range was investigated covering 400–1000 nm wavelength range. The MNF bands were visually inspected for noise with the first 14 MNF bands analysed; noise was characterised by MNF bands containing a high degree of speckle or banding. The most extreme pixels were identified by repeatedly projecting n-dimensional scatter plots onto a random unit vector. The extreme pixels in each projection, and the total number of times each pixel was marked as extreme were recorded.

In this first evaluation of the system, we were not able to accurately identify image endmember pixels in field quadrants used in this study. Endmember pixels derived from the pixel purity index corresponded to a mixture of green and dry vegetation endmembers. Refinement of the identification process through targeted reduction of vegetation image components may have yielded potential weed endmembers but has not yet been assessed. Instead we identified known occurrences of the fleabane (*Conyza* spp.), horehound (*Marrubium vulgare*), *Echium plantagineu,* dock (*Rumex crispus*) and extracted representative reflectance (Figure 2) and MNF image spectra for use in mapping routines. The reflectance endmember spectra were used as input in the SAM mapping algorithms. Endmember spectra were further transformed using the continuum removal technique for use with the SFF algorithm. The continuum removal technique isolates spectral features and standardises reflectance. The spectral plots showed that while each plant has a similar characteristic green vegetation shape, there are differences in the depth of the chlorophyll absorption trough (around 680 nm), the slope of the red edge (around 680–720 nm), the height of the green peak (around 540 nm), and the overall reflectance in the visible (400–680 nm). These differences allow the spectra to be separated and weeds to be mapped. The MNF transformed endmember spectra were used as input in the MTMF mapping algorithm. A rule classifier was used to classify each pixel according to the endmember class that predominated (highest score) in each pixel to help with the interpretation and classification of mapping scores for the SFF and MTMF mapping methods.

(3) Accuracy assessment — classifications or abundance maps are compared to groundtruth data and an assessment made of their agreement (Congalton 1991). In this study preliminary accuracy assessments were made using high quality digital photos of quadrants,

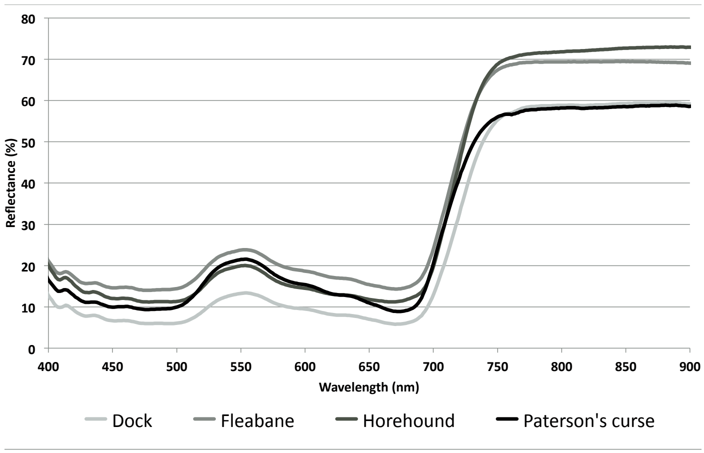

Figure 2. Reflectance spectra (400–1000 nm) of fleabane, dock, horehound and Paterson’s curse.

and several photographed areas where known weeds were evident in the photographs. An error matrix was constructed for these subsets. The MTMF mapping method showed the highest overall accuracies for all weeds examined, however more work is required to assess if these results are consistent in different weed environments and for differing weed densities. Preliminary results for fleabane showed accuracies of 72%, for horehound showed accuracies of 65%, for Paterson's curse showed accuracies of 84%, and for dock showed accuracies of 70%. These overall accuracy results were encouraging for broader weed studies but less than the researchers' experiences in previous hyperspectral studies. Closer examination of the image and groundtruth data showed that manual classification errors between groundtruth and image mapping results had occurred due to shifts in pixel locations between image data and groundtruth data. This was partly a result of the orthorectification process and the known errors associated with the GPS and attitude data along with the way quadrants were divided for groundtruth comparisons. A hard classification of the most dominant weed in each pixel was used to form the groundtruth quadrant maps. However, in reality even at the high spatial resolution of 15 cm, each pixel is a mixture of several weeds. Given that hyperspectral imagery allows several surface (endmember) components to be mapped and semi-quantitative abundances to be reported, adjustments to the methodology for the collection of groundtruth data are required.

Further examination of this issue showed that where weeds covered the entire pixel, the results of the mapping algorithm correctly highlighted the weed. However, where pixels were a mixture of weeds, confusion between the weed, the soil background and other weeds in the pixel was evident. The MTMF mapping method (Boardman 1998) is a technique designed for the partial unmixing of hyperspectral data. In our case the input weed endmembers were not true endmembers (pure pixels as identified using the pixel purity index and n-dimensional visualiser) but rather target spectra that we selected. It is likely that the partial unmixing of target spectra will always result in lower accuracies than true endmembers but more research is required to determine if this is indeed the case.

This study pointed to the need to investigate at what level a patch of weeds is too small to be identified as a true endmember in a hyperspectral data set. While accuracy is important for informing system performance, it may not be as critical in terms of weed management particularly at a landscape scale. It is therefore important that ongoing research looks at both the detectability using hyperspectral data collected at various scales but also at how that spatial resolution can practically be managed by the endusers of the data. Having highly accurate abundance maps might be useful for weed inventories but are likely to be less useful if the weeds cannot be cost effectively managed at these scales. The development of a learning community through the establishment of our management committee will bring together representatives from the research community, catchment management agency and local council to provide ongoing guidance for future research and real world practical applications of this technology.

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