Potential of Unmanned Aerial Vehicles (UAVs) in the grains industry

A report for

by Ben Boughton

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Executive Summary

- Australian dryland crop yield increase has plateaued in the last decade. Those involved in the industry are searching for new productivity gains.
- Unmanned aerial vehicles (UAVs) have been suggested as an ideal way to collect high quality spatial, spectral and temporal data that can assist in productivity gains. A small fixed wing design is suitable for the grains industry.
- Some potential use cases include crop scouting, site specific weed control and high accuracy topographic mapping.
- UAVs are essentially a remote sensing platform. The operational function of the UAV needs to be understood, but the most complexity lies in the sensor and data processing.
- A modified handheld camera (Canon S100) has generally been the sensor of choice but several weaknesses have been identified such as spectral limitations and limited image calibration options. A new generation of more suitable sensors is emerging.
- Several challenges exist that need to be considered before relying on UAV technology. Some include repeatability and data calibration, spatial accuracy, handling data processes and integrating with existing precision agriculture systems.
- Fortunately there are several UAV manufactures innovating in this space. A suitable UAV, including sensor, but not processing software, for broadacre agriculture could cost anywhere from $2000 if built in house, up to over $100,000.
- Recommendations for further research include a focus on the new sensor development including rigorously evaluating calibration processes, GPS position improved for better spatial accuracy and making solid links between all professionals involved for an effective and efficient workflow.

Contents

Foreword

Being passionate about technology and farming from a young age, at university I studied agricultural science and geographical information science followed by a short stint working for precision agriculture consultants and John Deere. I then landed back on the farm, where we crop 2200 ha of wheat, barley, chickpeas and sorghum. I was constantly learning but equally always searching for what is next. When not farming I can usually be found at my computer or workshop researching or having a go a developing the next big thing for agriculture. This is turn led me down the path of the coveted Nuffield Scholarship.

I felt restricted by existing data collection methods for precision agriculture. The dream of being able to collect data at unprecedented temporal, spatial and spectral resolutions for a reasonable price with full ownership and control made the study of Unmanned Aerial Vehicles (UAV) a topic that could not be overlooked. If this technology worked I knew it would open up a myriad of opportunities in advancing precision agriculture. Before even applying for the scholarship I was busy first building an unmanned ground vehicle, and then graduated to building a UAV. Many an hour was spent researching and building these machines with much frustration in crashes and unexplained faults and celebration when completing autonomous flights and utilising the captured data.

I began my Nuffield travels on the Global Focus Program (GFP), travelling through South Africa, Kenya, Russia, Czech Republic, Poland, Germany and USA. I returned to the USA and travelled up to Canada to study the development of UAVs in North America. Once back in Australia I visited University of Tasmania and the Outback UAV Challenge at Kingaroy, QLD. Some highlights in USA were the InfoAg conference in St Louis, Missouri and the Precision Aerial Ag Show in Decator, Illinois.

None of this would be possible without the generous support of my sponsor the Grains Research and Development Corporation (GRDC). They had the foresight to recognise the potential of UAVs before they became a buzz topic in the media. In addition, many thanks for the hard work from those in Nuffield Australia that organise GFPs, scholarship selection, sponsor relationships and all the other people that make it a great organisation.

Acknowledgments

My wife, Olivia, and the rest of my family deserve a special mention for sticking with me for the busy, eye opening year that was 2014.

Abbreviations

PA – precision agriculture

VRT – variable rate technology

GIS – geographic information science

UAV – unmanned aerial vehicle

NDVI – normalised difference vegetation index

FOV – field of view

GCS – ground control station

GPS – global positioning system

HUD – heads up display

DEM – digital elevation model

DSM – digital surface model

IMU – inertial measurement unit

MVS – multi-view stereopsis

SfM – structure from motion

SIFT - Scale Invariant Feature Transform

CASA - Civil Aviation Safety Authority

RPA - Remotely Piloted Aircraft

COA certificate of authorisation

FAA - Federal Aviation Authority

NIR - near infrared

DVI – difference vegetation index

SAVI - Soil Adjusted Vegetation Index

Objectives

1. Investigate the perceived benefits of UAVs
2. Understand the individual components that contribute to a UAV solution
3. Consider strengths, weaknesses and standout features of different UAV manufacturers
4. Describe challenges facing UAV adoption
5. Record current development and future use for the technology

Chapter 1: Introduction

The grains industry in Australia grows several crops in a diverse range of growing conditions. The sub-tropical regions of Australia are suitable for summer and winter crops and other areas focus on one season – winter or summer depending on dominant rainfall. The forecast winter crop area for Australia for 2014-15 is 22.575 Mha. Primary winter crops are wheat, barley, and canola. Some other winter crops grown are chickpeas, oats and lupins. The forecast summer crop area for Australia for 2014-15 is 3.705 Mha. Primary summer crops are grain sorghum, cotton and rice. Other summer crop includes corn, soybeans and sunflower. In the 2012-13 year Australia produced 22 856 kt wheat of which 18 644 kt was exported (ABARES, 2014).

In the last 100 years Australian cropping systems have improved wheat farm yields substantially despite periods of intense drought. The average farm yield has climbed from about 0.5 t/ha to almost 2 t/ha. Figure 1 shows three periods of dramatic yield increase and the main drivers for this upsurge. It is worth noting that other factors not identified in Figure 1 have probably contributed to this phenomenon including minimum tillage and controlled traffic. From 2000 onwards, the yield improvement gain from genetics, rotation and nitrogen is tapering, causing another plateau period for Australian wheat yields.

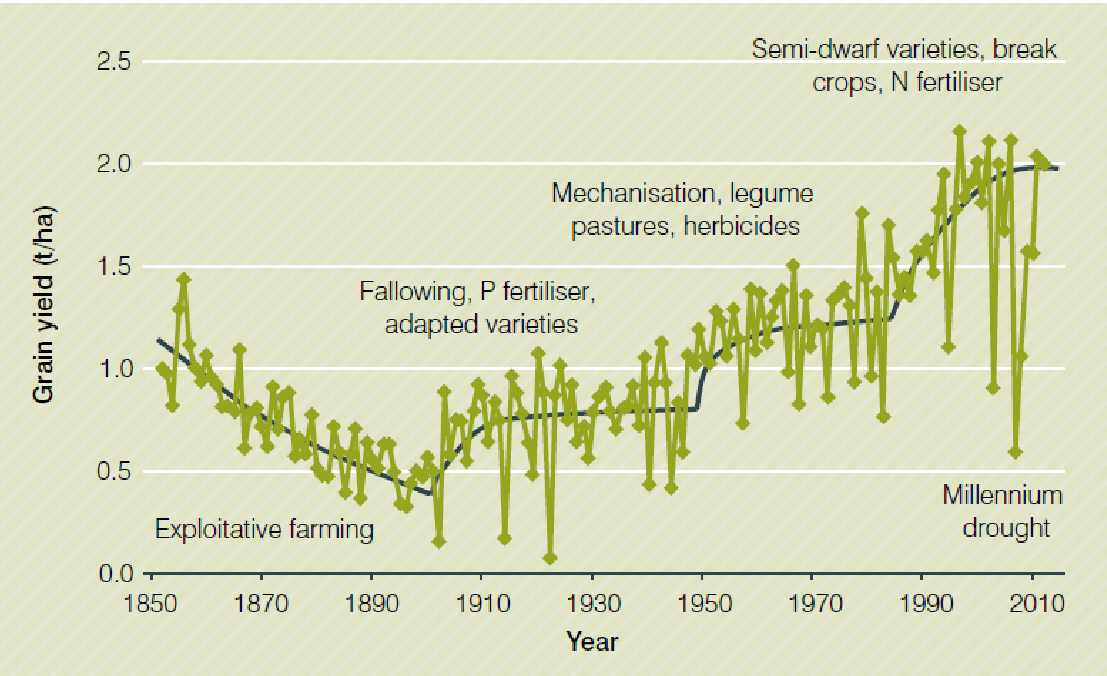

Figure 1: Average farm yield of wheat in Australia (Fischer, Byerlee, & Edmeades, 2014).

Considering that by 2050 the world will be demanding 40% more wheat with one 1% extra harvested area (Food and Agriculture Organization via Fischer et al., 2014) there will need to be another significant leap in yields to meet this target. One way to gauge where the next leap will come from is to look into where the large agricultural companies are investing. For example, Monsanto, traditionally known for their work in crop protection and genetics has acquired Precision Planting (Monsanto, 2012) and more recently Climate Corporation (Monsanto, 2013). This would suggest new technologies improving agronomy precision, understanding climate science and allowing for 'big data' opportunities may be the driver for the next yield leap.

Changing the focus to a particular region in Australia, it gives perspective as to which technologies have achieved consistent growth in uptake and why. The average area of crop grown per farm in 2011 for the northwest New South Wales and southwest Queensland area was 1718 ha. In 2011 75.9% of grain growers in this region were using some form of autosteer. In comparison only 6.8% of farmers had adopted variable rate technology (VRT) (Edwards, Umbers, & Wentworth, 2012). Admittedly, these technologies are at different stages of maturity but it does show some precision agriculture (PA) technologies have a broad scope and others quite specific. It is also prudent to ask why the uptake of VRT seems low despite evidence that it can increase margins (Robertson et al., 2012). It may be a combination of lack of availability of timely and accurate data collection, systems to apply incoming data, upfront cost and that the technology may only suit certain farm types.

The next leap in yield could be a combination of technologies that offer less than 10% yield improvement but combined offer a significant leap. One consistent need that most new technologies and existing require is data. The timely rise of unmanned technology could potentially fill this gap.

Considering the much needed bump in the grain industry productivity, and more specifically, the need for timely high quality data to bolster existing PA technologies and the ability to broadly improve crop monitoring and in crop trails, the unmanned aerial vehicle (UAV) is a technology that can and inevitably will add value to the grains industry. In addition, considering quality and timeliness of the data on offer, this is unlimited potential for processes, applications and technologies to develop that do not exist in this industry.

Chapter 2: Theory of Operation

As with any new technology, it is important to understand the current theory of operation. The systems covered here focus on small UAVs to collect data and therefore exclude systems designed for other applications such as chemical spraying.

In its most basic form there is some type of UAV carrying a sensor to capture data from an aerial viewpoint. A common example in the media is a small quad rotor machine (e.g. DJI Phantom) carrying a GoPro camera. This setup is not suited to broad acre agriculture due to the low efficiencies of the multi-rotor design and the sensor captures video rather than spatially aware (georeferenced) still images. Looking more closely at UAVs for broad acre agriculture it is possible to pigeon hole common components and operations in a typical system for covering large areas to produce a georeferenced dataset. A common method to collect data using a small fixed wing UAV consists of:

1. Determine data requirement to select sensor. It is important to know what type of information needs to be generated from the data collected. One sensor will never fulfill all requirements. For example, a high resolution red-green-blue Canon camera would be a good choice for 3D modelling, whereas a true multispectral sensor is a better fit for determining Normalised Difference Vegetation Index (NDVI) or similar indices.

2. Plan survey area and flight path based on sensor and UAV characteristics. In most circumstances several hundred scenes or images will need to be collected over survey area. The flight path will take into consideration the flight elevation, field of view (FOV) of the sensor, flight speed and desired overlap. More overlap is required for tasks such as 3D modelling.

3. Load flight path, take-off and land sites and geo-fences into UAV autopilot. This can be done at any stage, even the night before, although an unexpected wind change or take-off/land site characteristics may change mission parameters requiring the plan to be reloaded to the autopilot.

4. Once on site set up ground control station (GCS) and check conditions (wind, visibility, rain etc.). Adjust flight plan if necessary (as discussed above). An optional step for high accuracy imagery is to lay out ground control points and mark these positions with a high accuracy GPS.

5. Launch, monitor and land UAV. Allow the onboard autopilot to navigate the flight path while the operator monitors the UAV visually by line of sight and via the heads up display (HUD) from the ground control station. Information such as the autopilot sensor values, GPS position, mode of flight (e.g. autonomous or return to launch) and wireless link are all available live through the GCS.

6. Recover UAV and transfer raw data to computer for processing. In most situations several gigabytes of images is transferred from a SD card. There are some UAV systems that upload data to a server as they map but the bottle neck here is the mobile internet bandwidth available.

7. Begin data processing to generate an orthomosaic. The first step in data processing is to check data quality and that the entire area of interest is covered. Next, the images are 'stitched' together to form a mosaic, in essence one large continuous image generated from several hundred individual images. This is an advanced computer process that requires large amounts of processing power and expensive software. There are remote services that allow the user to upload raw data and have a server process the imagery and then server it directly as an interactive map or send back to the user. Ground control points used in this step if included in step four.

8. Generate information. The orthomosaic can now be further processed to build actionable information. Examples include vegetation indices such as NDVI, 3D digital elevation model (DEM) or plant stand count.

The above steps are a general guide to how as to how someone may, in theory, operate a UAV to collect and process data to actionable information. As the technology develops and changes this process may change.

Chapter 3: UAV System Components

UAVs are complex systems that rely on several technologies working together. It is important to consider all aspects pertaining to the agricultural UAV (aUAV) Solution which this report defines as a robust, timely, cost effective way to collect usable data to improve productivity in farming systems. Consider the following formula:

aUAV Solution = platform + GPS + autopilot & communication + sensor + data processing & integration + legal & operation

All components of the formula need to be working well and working together for the product to be successful technology.

Platforms

There are two main platforms available: fixed wing and multi-rotor. A fixed wing platform has the advantage of covering large areas efficiently, whereas a multi-rotor shines in being able to remain very stable in challenging conditions with large payloads. Due to the scale of broadacre grain growing in Australia, this report focuses predominately with the fixed wing platform type, as paddocks often exceed 250 ha.

Figure 2: Multirotor

Figure 3: Swift Radio Planes Lynx fixed wing UAV

In addition to these common, usually electric driven platforms, there is active development on traditional helicopter style UAV as these are the most efficient rotor style aircraft. Once the traditional helicopter style UAV are able to be reliably controlled using common autopilots such as the Ardupilot (APM), these platforms may replace the now common multi-rotor systems and even exceed fixed wing designs for heavy payload situations. As of September 2014 proof of concept of traditional helicopter style UAV running on gasoline has been shown in DIY Drones – the community that supports the development of the APM family of autopilots (Lefebvre, 2014). Figure 4 is of a gasoline powered UAV manufactured by AutoCopter. This is a production unit available now but outside the price range of most agricultural applications.

Figure 4: AutoCopter

Global Positioning System / Inertial Measurement Unit

Global Positioning Systems (GPS) are the backbone of most spatial technologies. The GPS serves two purposes – navigation and georeferencing data. For autopilot control and navigation the GPS on the UAV works in conjunction with the inertial measurement unit (IMU). An IMU is a combination of sensors that together can determine the velocity, orientation and gravitational forces of the UAV. For example the 3DR Pixhawk has a three axis gyroscope, three axis accelerometer / magnetometer, three axis accelerometer / gyroscope and a barometer (3DR, 2014).

In addition, GPS links the data collected to its spatial position (i.e. geo-referencing). Many UAVs are equipped with a u-blox GPS receiver or similar which is compact and provides les than 5 m horizontal accuracy. These systems are affordable and accurate for most autopilot navigation but often do not provide sufficient accuracy for georeferencing (Paul, 2014). This is discussed further in Chapter 6: Challenges.

An exciting development is the Piksi (Swift Navigation, 2013), which is a low cost Real Time Kinetic (RTK) GPS receiver that promises to sell for around $1000 which is significantly lower than the current price point. The Piksi offers centimetre level accuracy inside a compact design, ideal for small UAVs. The improved accuracy will be invaluable for autonomous landings and improved accuracy of georeferencing data.

Autopilot & Ground Control Station

UAV autopilots are improving very quickly with increased reliability, especially within the open source community. Autopilots are essential for being able to effortlessly fly over a whole area to collect the desired data removing human error.

There are several autopilots available, both proprietary and open source. An example proprietary autopilot is the Micropilot (MicroPilot, 2014). A well-known user of the Micropilot is the Trimble UX5. The most recognized open source autopilot is the Ardupilot, also known as APM. By definition the open source autopilots are freely open for anyone to copy, modify and use both privately and commercially. It relies on a community of likeminded individuals to contribute to the project (with a few generous key contributors). Hardware to deploy the Ardupilot software is available from many different manufacturers but most developers seem to use the 3D Robotics Pixhawk. Some conflict does exist around hardware, see discussion at DIY Drones (2014). Since hardware-software link is pivotal in the autopilot, Gardner (2014) recommends using the Pixhawk with the Ardupilot. Commercial UAV platforms using the Ardupilot include RoboFlight (Burchfield, 2014) and Swift Radio Planes (Rayleigh, 2014). These companies acknowledge the few criticisms of the Ardupilot but in their experience it is capable of reliable operation for commercial mapping operations. The Micropilot price ranges from US$1500 up to US$6000 not including ground control software (US$1500), cables and other accessories. In comparison the 3DR Pixhawk and all required accessories can be bought for about US$500 (3DR, 2014). Inevitably support provided would vary between autopilot providers.

A Ground Control Station (GCS) is the main point of contact between the UAV and operator. The GCS is usually a software package installed on a notebook computer or tablet. It serves several functions including, but not limited to mission planning (UAV flight path), autopilot tuning and flashing, and in flight monitoring via the heads up display (HUD). The GCS connects to the UAV via a radio modem. A commonly used radio modem is the RFD900 from RFDesign (2014). MicroPilot offers a proprietary GCS that pairs with their autopilot, known as HORIZON (MicroPilot, 2014). There are several open source options which are under active development including Mission Planner and APM Planner.

Sensors

Essentially a UAV is a remote sensing device and pertinent to any remote sensing system is the on board sensor. The sensor is detecting certain parts of the electromagnetic spectrum reflected from the target, but inevitably has light interference from other sources. For plant biomass data, the most important spectral range is near infrared. Other spectrum including the ‘red edge’ are also known to provide relevant data (Mather, 2004). Two common examples used in UAVs for agricultural purposes include the Tetracam ADC Lite (Tetracam, 2014) and a modified Canon S100 digital camera (Event38 Unmanned Systems, 2014). There are some new purpose built multisprectral, global shutter sensors now available and more in the pipeline. Examples include the Multispec 4C (Mainfroy, Faroux, & Cheron, 2014) available in the Sensefly Ebee, and offerings from MicaSense (Torres, McAllister, & McBride, 2014) and Sensilize (Stark, 2014). See more information in Chapter 5 – Sensing Vegetation.

Universities are experimenting with sensors for UAVs using scientific processes. For example, TerraLuma, is a research group at the University of Tasmania. Projects of interest include high accuracy geo-referencing of imagery 'on the fly' (Turner, Lucieer, & Wallace, 2014) and correcting six band multispectral data collected from a UAV (Kelcey & Lucieer, 2012).

It is worth mentioning that it is very common for UAVs to have a GoPro camera (or similar) mounted to capture high definition video footage. This video footage is valuable for visually monitoring crops from the sky but is generally not processed to geo-referenced data. There is of course a couple of exceptions such a demonstration where video footage is used to generate a 3D surface model of a construction site (Dunk, 2012). The basic process involves removing still images from the video to conduct 'structure from motion' processing mentioned below.

Data Processing & Integration

Collecting high quality raw data is challenging, but the most time consuming (and often unexpectedly expensive) part can be processing it to a point where it can be integrated into precision agriculture systems. Generally the UAV will follow a lawn mower track collecting images at a defined interval with a generous set overlap. The raw data will usually be images (many hundreds – several gigabytes) with a single GPS position and sometimes pitch, yaw and roll values. The challenge for the data processing is to stitch these images together to generate one homogenous data set. Every image is affected by the differing roll, yaw and pitch of the UAV as the image is captured.

Typically, technology known as multi-view stereopsis (MVS) and structure from motion (SfM) is employed for processing UAV imagery. These processes have been examined closely and evaluated for accuracy by Harwin and Lucieer (2012) and Lucieer, Jong, and Turner (2014).

An example workflow could be: SfM estimates where sensor/camera is in a 3D space. Commonly, SfM employs a technique known as Scale Invariant Feature Transform (SIFT) to pair overlapping images by finding matching points between images. SfM output is used in Multi-view Stereopsis (MVS) is to generate a point cloud. The points are connected to generate a mesh and finally a texture laid over the surface. An orthomosaic can then be exported.

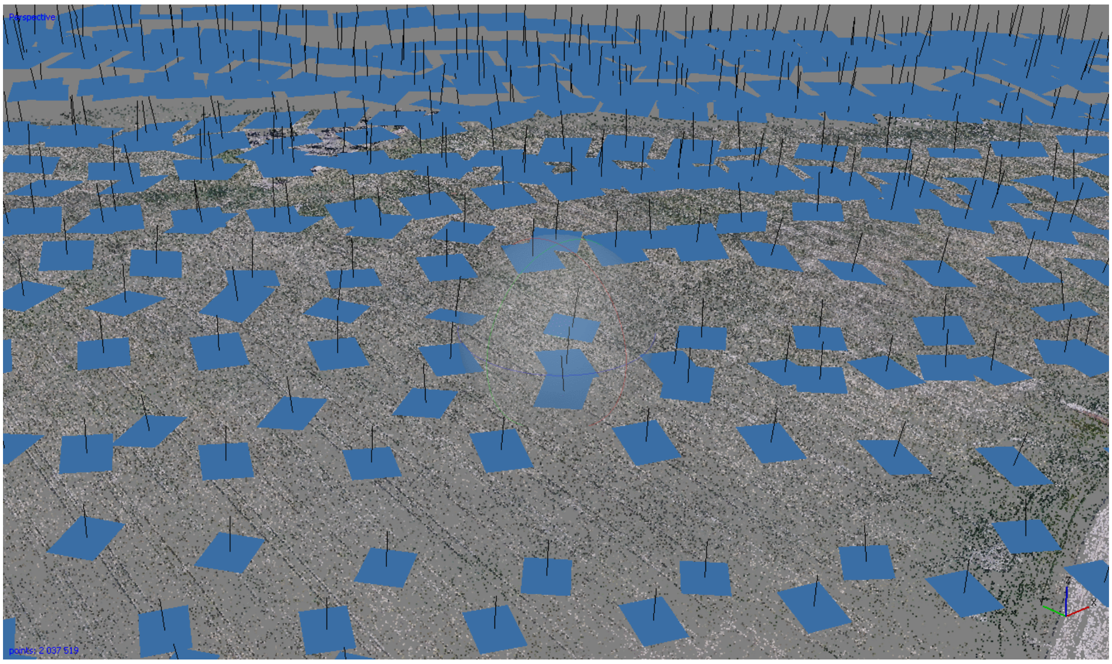

Figure 5: Point cloud showing image footprint in Agisoft Photoscan

Some of the more common desktop applications for UAV imagery processing include Agisoft Photoscan Pro and Pix4D. There are not many open source options when it comes to UAV image processing. The primary example is a combination of projects including VisualSFM, CMVS and CMPVMS. Duffy (2013) illustrates by video and explains the somewhat complex process. Unfortunately no matter the choice of processing software, there is high computer power demand. There is a trade-off between investment in computer capacity, intensity of the data processed (i.e. spatial resolution), area of interest size and time.

The alternative to desktop processing is a 'cloud' based solution. Examples include Precision Mapper and Drone Mapper. These applications require the user to upload the raw images to a remote location with purpose built, high power servers to conduct the image processing. These servers often use software the same as or very similar to desktop applications. Some of these applications will build a web based map using the output data to allow the user to easily view and share their data with others. There is expectation that once UAV processing becomes more than experimental and large areas need to be processed that cloud processing services will be the predominant option of choice, especially as broadband internet services continue to expand and improve (Lohman, 2014).

DroneDeploy is an innovative cloud solution which is involved in the complete UAV operation workflow – including flight planning, data processing and data sharing. As the UAV is collecting data it is uploading it via 4G mobile broadband to be processed on the fly so that processed data is available instantly (reference).

Once a geo-referenced, homogenous, data set over a paddock is achieved it could possibly undergo further post processing to determine NDVI. This raster data may then, for example, be used to define zones for in crop variable rate fertiliser application. Three dimensional models could be used to create digital elevation models (DEM) which is valuable in farming for determining water movement. Further processing may also include classification of image to determine location and area of weed species. In the example below, imagery was collected over wheat using a Trimble UX5 and processed in Agisoft Photoscan Pro. A section was then imported into the free software package, Multispec (Biehl & Landgrebe, 2002), where Supervised Classification was run to attempt to quantify exact area of rye grass and map how the weed is spreading.

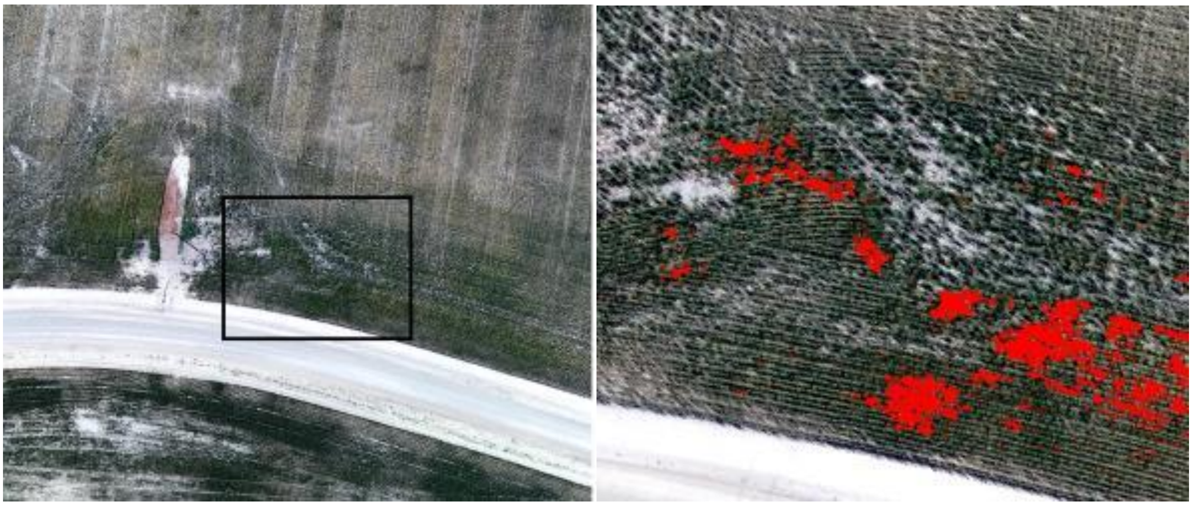

Figure 6: Supervised classification attempting to identify ryegrass in wheat from UAV imagery

Legal & Operation

Whenever operating an aircraft, manned or unmanned, there is a framework of governing rules which need to be followed. In every country the laws surrounding the operation of UAVs differ. There has been a spike in interest surrounding how the various national governing bodies have revised or are in the process of rewriting their rules and regulations in response to the surge in UAV operations in both the private and commercial areas. An important aspect of UAV regulation worldwide includes defining the difference between a hobby/model remote controlled aircraft and a UAV used for commercial gain. In many situations, hobby aircraft can operate without certification within some regulations surrounding aircraft size, line of sight, maximum elevation and right of way to manned aircraft. When a UAV is used for commercial gain the regulations are much more controlling, often requiring the pilot to have some sort of certified manned aircraft pilot qualification in addition to other government required permissions.

In Australia, the Civil Aviation Safety Authority (CASA) has been very proactive in governing UAVs or as termed by CASA Remotely Piloted Aircraft (RPAs). In 2002 CASA developed the first operational regulation in the world for unmanned aircraft (CASA, 2014). CASA requires commercial UAV operators to have a Remote Pilot Certificate or a UAV Controller Certificate and a UAS Operators Certificate. A Remote Pilot Certificate is a standalone qualification that focuses solely on UAV operation. A Remote Pilot Certificate does not require a manned aircraft pilot license. Alternatively, for those with a Private Pilots License, a UAV Controller Certificate is an option. In addition to either a Remote Pilot Certificate or UAV Controller Certificate a UAS Operators Certificate is required. This necessitates the formulation of manuals, flight assessment and interviews. At the time of writing (October 2014) CASA is currently reviewing the RPA regulations. One of the proposed changes is to allow UAVs under 2kg to operate within standard regulations without any form of certification.

Australia is fortunate to have a framework in place to operate UAVs. The United States, where several of the leading agricultural UAV companies are established, does not yet have set regulations for individuals to operate a UAV in a commercial capacity (FAA, 2014). There is provision for experimental UAV operations, Certificate of Authorization (COA) for some government and university institutions, and model aircraft for safe non-commercial flying. There is an exception; the Federal Aviation Authority (FAA) has recently allowed six companies to fly small UAVs to operate for TV and movie production under Section 333 “Special Rules for Certain Unmanned Aircraft Systems”. Section 333 is an interim way for some commercial UAV operations to proceed in the US while the FAA is finalising new UAV rules.

Service delivery

Consideration needs to be made for what structure will evolve to deliver a UAV service. The challenge is to complete the entire workflow – including understanding the information required, collecting data and processing – requires strong integration of several skill sets. Agronomy, UAV piloting, UAV service and maintenance, Geographical Information Science/ Remote Sensing and Information Technology are some areas that need to come together for successful workflow. Considering the complexity, a custom service provider may be best suited to deliver this rather than an individual farmer or even agronomist but time will tell which model is successful. The most important part is that clients and service providers understand each other's expectations.

UAV Providers

This report broadly defines four tiers of civilian UAV providers for large area mapping. Obviously there is a great deal of overlap between tiers but categorising helps understand which solution best suits a particular problem or customer.

Tier 1: Do It Yourself (DIY) / Hobby ($1,000-$2,000)

Taking advantage of the massive amount of information available freely on the internet combined with cheap online hobby stores it is completely feasible to build a fully functional UAV for mapping for less than $2000 including all equipment except processing software. This Tier interacts substantially with Tier 2 as most components are identical. There are several blogs which document success with DIY UAV. Boughton (2014) is a related example.

Tier 2: Budget Professional ($2,000-$10,000)

A Tier 2 UAV is where an individual or group experienced in UAV construction leverages much of the technology (components and software) from Tier 1 and builds ready to fly UAV platforms that a UAV operator could purchase and fly without knowledge of how to complete the build themselves. In addition, since Tier 2 providers need to operate for a profit, they often further the development of core technologies which, due to the nature of Open Source, are made available to Tier 1 builders.

Tier 3: Professional ($10,000-$100,000)

There are several companies that operate independent of the budget components in Tier 1 and Tier 2. Examples include Fourth Wing and Trimble.

Tier 4: High-end Professional ($100,000+)

Generally Tier 4 UAVs evolve from military to civilian applications. These are extremely reliable and robust solutions that are generally only sold with complete training packages. An example is the AeroVironment Puma.

The most overlap is seen between Tiers 2 and 3 since components that were once considered hobbyist or experimental are becoming robust enough to be used in professional platforms. The predominant example is autopilots as discussed above. The Tier 2 platforms are attractive because they are inexpensive, often as capable as a Tier 3 and often have an easier upgrade path. Tier 3 have the advantage of a generally more reliable system, better support and usually are larger companies that have the capacity to remain in existence with a down turn in sales or equivalent challenges.

Chapter 4: Making use of UAV data

Perceived benefits come from applications that improve farm business productivity (productivity is the ratio of inputs to outputs). This section aims to cover some of the popular applications for UAV technology in the grains industry.

Scouting

Given the most attention, and easiest to apply is the ability to aid in scouting paddocks. Consider the perspective from a flight in a manned aircraft over farm land. A UAV provides a similar perspective with additional advantages, such as every point geo-referenced, low cost and ability to fly not limited by an aircraft operator. The process is discussed in Chapter 2. The resulting map would show the variability of crop health over the entire paddock and allow you to concentrate on areas of poor health. In addition, human driven variation is obvious such as planter problems, compaction, chemical application etc.

To make this process even easier there are a couple of iPad and Android tablet applications (e.g. PDF Maps) that allow the map to be imported and with the use of a GPS position, locate areas on the map that is of interest (Ferrie, 2014). In addition, the user is then able to add notes and photos by putting down place marks on the maps.

Site specific weed control

In a similar process to Scouting, making sure a sensor with high spatial resolution is used, the resulting map could be used to identify where large individual weeds are located in a paddock. This could work in a fallow or in crop situation. In our farming environment we face glyphosate resistant weeds that require high chemical coverage to kill. Again an app like PDF Maps could be used to find single weeds in a paddock to mechanically or chemically eradicate.

Variable rate applications

Precisely placing inputs where they are most needed rather than blanket applications could increase yield and reduce wastage. Variable rate spreaders, sprayers and air seeders have been around for while now but the uptake use has been less than many expected. A rapidly developed georeferenced NDVI omap from a UAV in combination with in paddock examination of what is causing variability puts the grower in a good position to generate a suitable variable rate fertiliser application map.

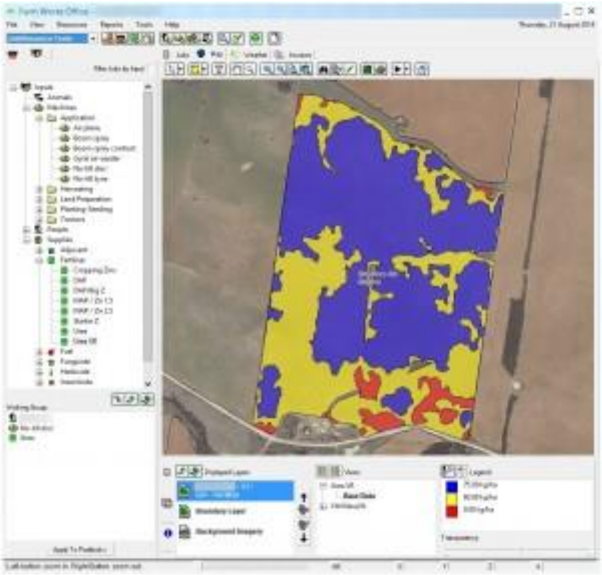

Figure 7: Example variable rate application map

Insurance/Drift/Environmental regulations

In many countries, none more than North America insurance is a major part of farming. If an adjustor from an insurance company is able to rapidly access a map that correlates closely with what they see on the ground then they are able to adjust the area much more accurately than a ground assessment alone, which is better for everyone involved. Accurately mapping areas of drift damage and ability to map areas of environmental concern has similar benefits.

3D/DEM/DSM

Employing the SfM technology, digital surface models (DSM) can be generated from still images collected with a UAV. Trimble Geospatial Division (2013) has published a white paper which describes at length the potential of DSM in surveying and agriculture. In summary, with ground control points, survey grade information can be rapidly generated in their photogrammetry software with data collected from a UAV. Agisoft Photoscan and Pix4D offer similar functions.


Figure 8: 3D Digital Surface Model from Pteryx UAV

Plant stand

Corn being a pillar crop in the mid-west USA, there is interest in the ability for UAV data to be used to determine site specific plant stands in row crops. Fourth Wing and Precision Hawk have examples of Feature Extraction whereby each plant is able to be identified. The application is making the decision to replant, early yield potential and to evaluate planter performance.

Other applications

Above are applications for UAV data than you can reliably apply right now for a reasonable amount of money. Some future applications that are beyond the scope of this report include thermal, Lidar, five plus band multispectral and hyper spectral. Many research institutions are in the process of testing these new sensors.

Chapter 5: Sensing Vegetation

When considering the target when collecting data from a UAV in a grain farming situation, it is usually vegetation. Collecting spatially referenced data of vegetation is by no means a new endeavour. This information has been collected as vastly as Landsat satellite imagery (U.S. Geological Survey, 2013) and as specific as a GreenSeeker (Paulson, 2011). Generally, for vegetation, similar bandwidth reflectance is measured irrespective of proximity to the target. The same is true for sensors used in UAVs. The reason why is photosynthesis. In a plant that is photosynthesizing, the chlorophyll will absorb large amounts of 'visual' light, particularly blue and red, and reflect near infrared (NIR) light. The more photosynthetic activity, the more NIR light is reflected and less visual light absorbed. Conversely, inactive vegetation will reflect more visual and less NIR (Ashraf, Maah, & Yusoff, 2011).

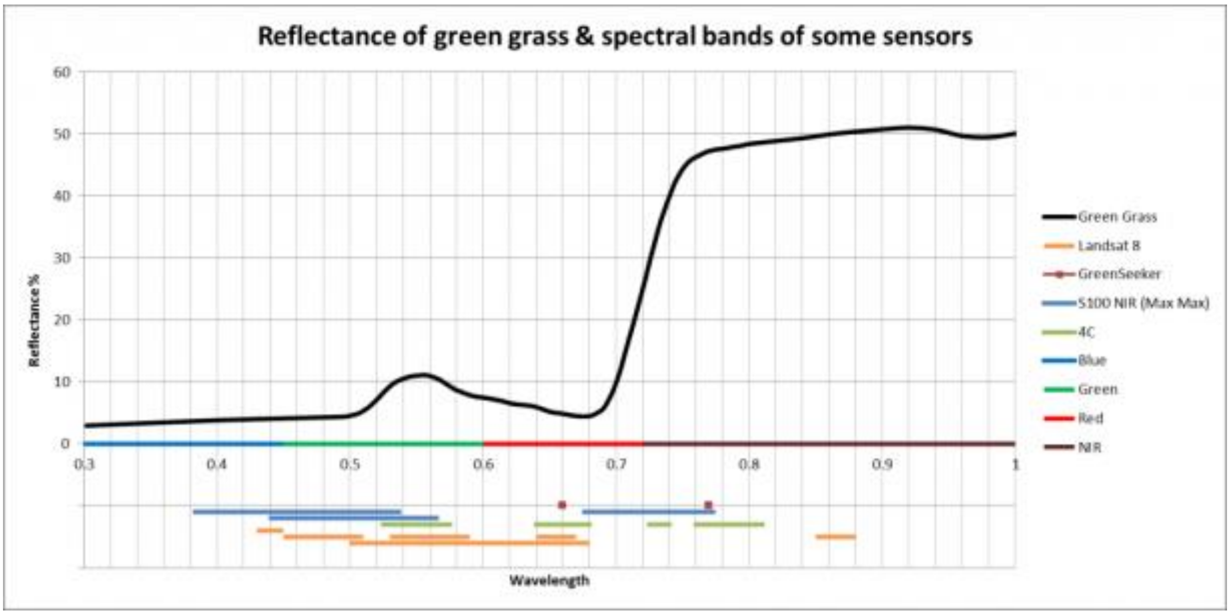

Figure 9: Sensor spectral bands and reflectance of green grass

A useful contrast is between red and NIR light which is what is generally used when calculating the Normalised Difference Vegetation Index (NDVI). NDVI is a good indicator of plant health and measure of biomass. Consequently, most sensors used to determine NDVI look into the red and NIR bands – some more accurately than others. Figure 12 shows the reflectance curve of green grass over different wavelengths. Below the X axis is a rough spectral guide to some of the well-known sensors available.

What is most notable is the wavelength spectrum or band at which each of the sensors read. The GreenSeeker is extremely specific at capturing a certain wavelength in the middle of the red spectrum and similarly specific in the NIR. At the other end of this comparison the S100 modified camera has very broad spectrum for each channel that it reads. Consider (what was before modification) the S100's 'red' channel which reads roughly from 0.67um to 0.76um with the modified filter. Post modification, this channel is renamed NIR and measures reflectance in an area that covers red right through to NIR. The S100 modification retains the blue and green channels which replaces red when calculating NDVI. Another significant point that this chart does not show is the interference that can occur between the different bands in a point and shoot camera.

It has to be noted that it is hardly fair to compare the S100 and GreenSeeker in a practical sense for several reasons with the main one being that you would not mount a GreenSeeker on a UAV as it needs to be close to the target (the GreenSeeker is an active sensor meaning that it emits light and measures that reflectance, the S100 is a passive sensor just reading reflectance from the sun). In addition, the GreenSeeker measures only one point whereas the S100 collects data on 12 million pixels. The reason they are compared is they can both be used to produce an NDVI map. In fact, despite the spectral differences from each of these sensors and the proximity to the target, RoboFlight claim from their tests that NDVI data collected from a GreenSeeker and modified S100 correlate in a linear fashion very closely (r squared > 0.9) (Burtchfield, 2014). So we know that the two sensors correlate well but the correlation will never be a fixed formula because sunlight reflected will always be different based on sun angle, atmosphere conditions, cloud etc. The S100 and GreenSeeker would probably work best as tools which complement each other. For example, map a large area with the S100 on a UAV. The resulting dataset could be calibrated using GreenSeeker data collected in the field at the same time as the flight. Potentially if S100 data is always calibrated against the GreenSeeker, inter-paddock and inter-season comparisons can be made.

As mentioned in Chapter 3, there is a new wave of sensor development designed specifically for UAV and agricultural and environmental industries. An available example is the Airinov Multispec 4C. This sensor captures four distinct, narrow spectral bands with no interference. These bands include green, red, red edge and NIR. What makes this package special is that not only does this sensor package look down at the vegetation; it is also looking up measuring sunlight with a lux meter. This should facilitate data collected that can be calibrated without the need for ground truthing with a GreenSeeker or similar 'active' device. Another feature of this sensor is that it uses a Global Shutter which means all pixels in a photo are captured at exactly the same time eradicating any motion blur. The 4C has much less spatial resolution than the S100 (1.2MP vs 12MP). Expect to pay over US$10,000 for this sensor package, not including UAV or processing software.

In summary there is more to a UAV sensor than just megapixels. It is important to understand the spectral response of vegetation and how this can impact your sensor choice. A modified Canon camera such as the S100 is a great option for UAV but its limitations must be understood. Work needs to be done to analyse the results and accuracy of the new sensors such as the Multispec 4C.

Chapter 6: Challenges

Chapter 5 discussed some issues specifically around sensing vegetation. In this chapter, the challenges facing data collection using UAVs is covered more broadly.

Repeatability and Calibration

To map a paddock at 11am and then again at 2pm, the resulting pixel values would be different. Even using the Normalised Difference Vegetation Index (NDVI) which by definition gives a normalised value, the data will be different. This is due to the variability in the atmosphere and sun angle. The variability in the different bandwidths does not change in parallel amounts either. We see this effect in satellite imagery where the image is affected by cloud shadow. The table below is pixel value of Red and NIR from two points in the same barley paddock that has minimal variability. Despite crop growth activity and biomass being very similar, these areas produce significantly different NDVI value due to the cloud shadow.

	No Shadow	Shadow
Red	37	32
NIR	128	51
NDVI	0.55152	0.22892

Figure 10: Cloud shadow versus no shadow NDVI in barley, Landsat 8

This can be applied to UAV imagery. The atmosphere, clouds and sun angle is constantly changing throughout the day affecting reflectance of all wavelengths differently. Therefore for data to be compared like to like it needs to be calibrated.

If data is going to be used for more than just scouting then some sort of calibration will need to take place. As discussed in a Chapter 5, calibration of NDVI could be potentially be achieved using an active ground device such as a GreenSeeker. There is also the new payloads that are true multispectral and have upward looking sensor to measure irradiance which could be used to calibrate data for true reflectance. Other forms of calibration/ground truthing include biomass cutting and weighing, tissue testing, the list goes on.

Algorithms & Indices

When it comes to remote sensing and vegetation, NDVI is the most recognised index, but it is not without its concerns. NDVI has been used to estimate several vegetation properties include Leaf Area Index, biomass, chlorophyll concentration in leaves, plant productivity, fractional vegetation cover, accumulated rainfall, etc (Wikipedia). This in itself highlights a problem. Correlating one index to so many different variables suggests that all these plant variables are directly related themselves, which is a dangerous assumption as this is not always (or even often) the case. Another concern with NDVI is discussed in Repeatability and Calibration above.

There are other vegetation indicies apart from NDVI. Agribotix claim they get better results using the Difference Vegetation Index (DVI). Another example is Soil Adjusted Vegetation Index (SAVI).

Position

Without ground control points, the positional accuracy of data will be mediocre at best. Expect horizontal accuracy of a few meters and even more on the vertical axis. GPS will record the position each frame is captured (+/- delay error), but the pitch, yaw and roll of the UAV which affects how the image is framed on the ground, is determined by an inertial measurement unit (IMU). The quality of the IMU will have a bearing on the positional accuracy if the processing software takes these variables into consideration. Expect to have to lay out minimum of 4 ground control points for high accuracy data or utilise an RTK GPS as discussed in Chapter 3.

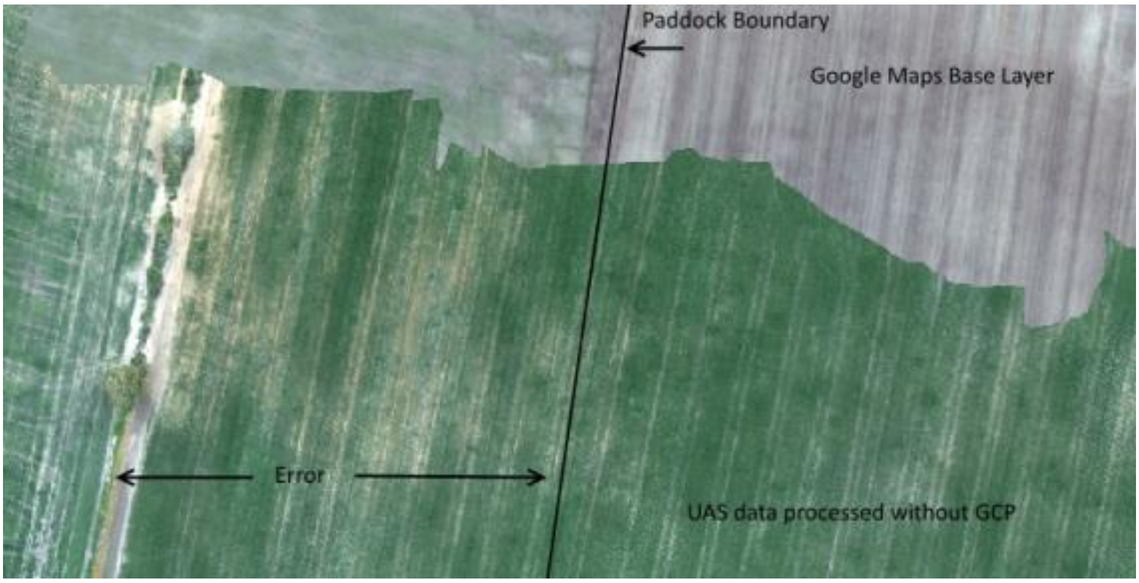

Figure 11: Error in UAV image processed without ground control points or RTK GPS

Reliable data collection

As a consequence of the process involved in collecting data with a UAV there are several factors that contribute to the ability to reliably collect data. The process is outlined in Chapter 2.

An example of environmental factors impacting reliable data collection is when in flight if the UAV is hit by a gust of wind, it may put 2 or 3 images off target, while the autopilot adjusts for wind. This can lead to a hole in the data set. This is not uncommon. Some UAV manufacturers allow you the rapidly transfer the raw data off the vehicle to a laptop in the paddock to check data coverage and quality in field (e.g. Precision Hawk).

If a UAV manufacturer claims their machine can fly in high winds, it is probably true, but the quality of the data being collected may not be of much use.

Data processing, storage and sharing

Data processing is explained in detail in Chapter 2. Data processing often brings new challenges when there is a change such as environmental conditions or hardware such as a new sensor that the software was not originally designed for. An example is that the 2014 corn crop in the Midwest USA was excellent which meant the crops were extremely uniform. This led to some of the desktop image processing software having problems stitching the images together. Another example is if a sensor has a slow rolling shutter, due to the speed a UAV is flying when collecting data it can cause distortions. Generally problems such as these are not identified until after the images are collected and data processing begins.

Once the data is processed it needs to be stored somewhere and somehow distributed. Often one stitched scene can be more than a gigabyte. If the processed data is not compressed or further processed (e.g. resampled to lower resolution or cut into tiles) it can require a powerful computer just to view it. This is where online solutions come into play. Again there are issues around bandwidth requirements but UAV data could be viewed in similar for to Google Maps which is familiar environment for most users. At some point if the data is going to be used for more than just looking at it will most likely need to be transferred onto a local machine for further processing. If for some reason the data is to be printed, it needs to be formatted as such which takes time and GIS software.

System integration

Integrating data generated from UAV into existing precision agriculture software should be possible but not likely in its highest available spatial resolution. Software such as FarmWorks and SST were not designed for such intense data sets which are able to be generated from UAV sensors. Resampling data to 0.5m resolution may be required.

Chapter 7: UAV Marketplace

There are several UAV options available. Listed here are just a few small fixed wing UAVs that are available to purchase now.

senseFly: eBee

The eBee is probably the least intimidating UAV. It is almost a true turnkey system – the user just provides a laptop for ground control station and PC for data processing software. It is a compact, lightweight (0.7kg) flying wing design which is hand launched. All packaged up, the case is small enough to be classed as carry-on luggage. There is a few payload options including the typical Canon S110, but more interestingly the Airinov Multispec 4C is also available. The included processing software is top notch as it is based on Pix4D.

Other eBee facts and functions include:

- The motor is turned off whenever an image is being captured to reduce image blur from vibration.
- Multiple eBee planes can be operated from the one ground control station with an automated collision avoidance system.
- The eBee can be optioned up to RTK GPS.

Figure 12: senseFly eBee pair

Precision Hawk: Lancaster

The Precision Hawk (Lohman, 2014) Lancaster platform uses a traditional fixed wing design. Two processors running Linux handle flight management and any other in flight processes such as real time data assessment. The platform is easily hand launched and weighs about 1.4kg not including the payload. Precision Hawk offer several sensors ranging from the humble Canon S series camera through to many of the Tetracam options and can also carry Thermal, Lidar and Hyperspectral equipment. To Precision Hawk, the Lancaster platform is just a small part of the workflow. Data processing and sharing is an even bigger part of their business. They offer Precision Mapper, a cloud based system which allows raw data from any UAV to be uploaded, processed and shared.

Other Lancaster facts and functions include:

- Precision Hawk plan to have an API system for sensor integration so 3rd parties can integrate their own sensor into the platform.
- The Lancaster creates its own flight plan after it has been launched and determined weather conditions.
- Precision Mapper is excellent value at about 25 cents a hectare.

Farm Intelligence/Fourth Wing: Vireo

The Vireo is marketed as a tool to provide high quality data for the online farm management platform WingScan. In its own right it is a still a UAV worth looking at. It is a sort of hybrid flying wing cross traditional plane but does not have any control surfaces on the tail. It is hand launched and weighs 1.4kg total. The whole system including laptop packs into a provided travel case. They claim it can fly for an hour or more. The Vireo does not use a modified point and shoot, instead a dual-imager sensor payload which captures NIR and Visual (RGB) in a single pass at 10MP.

Other Vireo facts and functions include:

- The Fourth Wing online store is available to the public to price their products. They sell the dual-imager sensor separately.
- The Vireo does not use any foam in its construction, only carbon fiber and Kevlar.

Swift Radio Planes: Lynx

The Lynx is the largest of all the UAV mentioned here and also the system you would part with the least cash for. It weighs in at about 4.5kg, but is still hand launched. The Lynx will fly comfortably for 90 minutes. The plane is controlled by an APM 2.6 but has the ability to completely isolate itself from the autopilot for full manual control. Despite the in flight size of this system it packs down into a single case. Swift Radio Planes have developed a roll stabilised camera mount with sensor options from Sony, Canon and Tetracam.

Other Lynx facts and functions include:

- It has the unique ability to deep stall meaning it can land in very tight spaces.
- The plane is entirely encased in Kevlar.
- Swift Radio Planes offer a server based platform for data processing and sharing.

AgEagle

AgEagle's UAV (Chilcott, 2014) is a flying wing launched from a slingshot style launcher to ensure consistent take-off every time. They pride themselves on a system that is tough in design, built especially for agriculture. It comes standard with a modified Canon camera, but soon available with true multispectral camera. AgEagle supply Agisoft Photoscan Standard and AgPixel in the standard package to process imagery.

Other AgEagle facts and functions include:

- AgEagle describe a simple process of exporting a non geo-referenced JPEG from Photoscan, through AgPixel, into SMS for variable rate application maps
- AgEagle are establishing a dealer network throughout the US and even sell their system in Australia

Figure 13: Bret Chilcott explaining the benefits of the AgEagle

Trimble: UX5

Most people would recognise the brand Trimble as they are well established in the surveying and precision agriculture market place. Trimble offer the UX5 UAV, which is a flying wing design weighing in at 2.5kg, made from EPP foam and carbon fiber and is and catapult launched. At the time I looked at the system they offered both standard and modified versions of a Sony mirrorless 16MP point and shoot camera. The systems comes with a rugged handheld computer for the ground control station. Trimble provide their own software for data processing which is a Photogrammetry Module for their Trimble Business Center Office Suite. This integrates with existing surveying processes but the link to Trimble's agricultural products does not seem as complete. But this is just a matter of time. Interestingly, the UX5 uses reverse thrust when landing to allow more predictable and accurate landings.

Figure 14: Trimble UX5 ready for take-off

Event38 / 3DR

Event38 and 3DR are separate companies but use similar components. They offer a much cheaper solution that is capable of performing many of the functions of the above UAV. The reality is that they do take some more learning to become familiar with their operation, but as far as value for money is concerned these are excellent products that are rapidly improving.

Agribotix: Hornet

Agribotix (2014) build a UAV based on similar technology to Event38 / 3DR, so it can be built in house quickly and cheaply. They believe that too much attention is given to the flying machines and not enough to application of the data. Agribotix offer a UAV lease structure where the UAV is essentially free to use and the cloud based data processing is what incurs a fee – therefore minimal capital outlay to get UAV up and running. This is a unique model.

Chapter 8: Travel Details

In researching this report, extensive travel was necessary to seek out the necessary people and see first-hand how they are using the technology and discuss their further plans and expectations. This section describes some of the places and people I met with.

The Nuffield planned Global Focus Program, designed as a capacity building general look at many facets of Agriculture on a global scale, took me through South Africa, Kenya, Russia, Poland, Czech Republic, Germany and USA. This trip was not focused on UAVs but it did give an amazing perspective on how technology is used and where it could be implemented to improve productivity. Those who I did come across that had embraced the UAV technology were not exactly where I expected. Stuart Barden in Kenya, who grows broadacre crops using Australian developed farming practices, had been experimenting with the technology with mixed results.

My second lot of travelling was focused exclusively on UAVs. This led me to USA, Canada and Tasmania, Australia. It was helpful that when in the US I was able to attend several conferences which congregate several key contacts into a specific area. Conferences attended included the Precision Ag Aerial Show, Delta AgTech Symposium, Farm Journal Drone Fly In, and InfoAg. The first two of these conferences had a particular focus on UAVs in agriculture with InfoAg being more general precision agriculture topics but did cover topics relating to UAV and data management.

Figure 15: Precision Ag Aerial Show - full house to learn about UAVs

At these conferences I was able to chat extensively from representatives from most of the companies discussed in this report. AgEagle were kind enough to invite me to see their manufacturing process and sit in on a training session that they offer new customers. Great to see a grassroots company manufacturing in rural America and the personal approach they had with their customers.

Figure 16: AgEagle training school

Precision Hawk also gave me a flight demo and explained how data (in turn information) was the focus, not so much the UAV platform. Chris Dean was very generous with his time in chatting about this. This company has since received massive funding rounds and secured several high profile clients.

Another small American grown UAV company Swift Radio Planes gave me a demo of their robust Lynx platform out in Arizona. These guys are young and keen to make a dent in the market place. Their platform has amazing endurance times.

Figure 17: Me (left) and Swift Radio Planes team holding the Lynx UAV

While in St Louis for the InfoAg conference I had two valuable meetings. First of these was with Rory Paul from Volt Aerial Robotics & Aerial Farmer Blog. Rory was great in discussing some issues and challenges in applying UAVs to agriculture that not many others are speaking about publicly. Rory also introduced me to the Sensilize cofounder Robi Stark. Robi discussed the core principles behind their innovative UAV sensor and processing facilities designed explicitly for agriculture.

The second meeting in St Louis was at Monsanto where I also met some of the Climate Corp staff. Monsanto are well known for their technological advancements in crop genetics and chemical protection but our discussions were focused more around improving yields and profitability by focusing on the crop agronomy and other technologies that can be applied in this area including UAVs.

My trip lead me to Idaho where I met with Robert Blair who farms in Idaho. Robert operates the blog The Unmanned Farmer and has just launched his very own UAV mapping company. Robert had a passion for first his family, second the agriculture industry and his latest addition: UAVs. Robert is probably the first farmer to fly a UAV in USA for crop monitoring purposes and was building his own platforms before most of the former discussed companies existed.

Figure 18: Harvest beside a canyon at Robert Blair's property in Idaho

When in Canada I met with Nuffield Scholar Daryl Chubb and several of his clients who are farmers. The general consensus from growers was caution to the new technology and uncertainty to whether UAVs could add value to their operation. Daryl's comment to this is that most farmers are generally not searching for productivity improvements as the last decade has seen good levels of profitability in the area. There were some exceptions of course and some farmers very keen to improve profitability with technology. Daryl also mentioned that in his experience with UAVs that the speed of processing had to be improved – down to hours instead of days.

Figure 19: Daryl Chubb and I in field peas

While in Calgary Daryl introduced me to Jan Zalud, who runs the aerial imaging company JZ Aerial. Jan said that while there was some demand from farmers themselves, much of his work was commissioned by agricultural research. One particular project focused on developing a protocol to acquire and process high resolution imagery for the purpose of disease and weed scouting with a UAV and compare the cost and accuracy to conventional methods. At the time the project had not yet been completed but UAV imagery captured by Jan was able to detect weed patches in potato, alfalfa and canola fields by looking for anomalies in NDVI imagery.

In the final stages of my travel I flew to Tasmania to visit Arko Lucier at the University of Tasmania and Will Bignell from DroneAg (droneag.com.au). Arko is heading several projects that relate to UAV data collection. Of specific interest was a project which was examining the accuracy of some of the common sensors available and also the accuracy of point cloud processing. Testing these now common hardware and processes with scientific rigour is important instead of just assuming everything functions as manufacturers claim.

Will Bignell is not only a co-founder of DroneAg, but also involved in a family farm at Bothwell, Tasmania. Will described how the UAV has helped on his own farm, particularly on the high value crop poppies. Will generated a 3D model of one of his fields from which he could use to improve drainage. In addition the field had several soil types which the imagery captured was also able to help map. Will’s ambition was to soon use variable rate inputs such as water and nutrients.

Conclusion

UAV technology is in its infancy but the technology is developing rapidly. The industry is currently in the media spotlight which is great for those promoting a new product but it does cause some significant details to get lost in short attention seeking articles often used by popular media. There are several components that contribute to a complete agricultural UAV solution. Despite manufacturers making UAVs easier to operate all the time, these components each need to be understood by the UAV operator. Already there are several use cases for UAVs in the grains industry, for example, site specific weed control, field scouting and topographic mapping but these are not without challenges. Special attention needs to be given to challenges around, not so much flying the UAV, but more so the sensor and data processing. A UAV is basically a platform to hold a remote sensing device or sensor. That sensor should undergo similar critical examination as other remote sensing devices such as satellite imagery which, at the moment, for UAV is not the case. There are several manufacturers with UAVs available to purchase for varying prices. It is also feasible to a technically savvy person to build their own fully functional UAV based on information freely available.

Recommendations

1. Scientific evaluation of calibrating data collected with modified handheld camera with an active sensor such as a GreenSeeker.
2. Scientific evaluation of new generation sensors such as the Multispec 4C. Do these sensors produce repeatable data?
3. Research more closely data processing, especially in 12 months as more software is in rapid development.
4. More research around spatial accuracy of UAV data. Compare RTK equipped UAV with data that utilises ground control points.
5. Work at making solid links between all professionals involved, such as UAV manufacturer, remote sensing specialist, agronomist and farmer for an effective and efficient workflow.

References

3DR. (2014). 3DR Pixhawk. Retrieved 9 October, 2014, from https://store.3drobotics.com/products/3dr-pixhawk

ABARES. (2014). Australian Crop Report (Vol. June). Canberra: Australian Bureau of Agricultural and Resource Economics and Sciences.

Agribotix. (2014). Agribotix: Actionable Intelligence for Precision Agriculture. Retrieved 8 November, 2014, from http://agribotix.com/

Ashraf, M. A., Maah, M. J., & Yusoff, I. (2011). Introduction to Remote Sensing of Biomass.

Biehl, L., & Landgrebe, D. (2002). MultiSpec: a tool for multispectral--hyperspectral image data analysis. Comput. Geosci., 28(10), 1153-1159. doi: 10.1016/s0098-3004(02)00033-x

Boughton, B. R. (2014). Budget UAV for Aerial Mapping: My Experience in Agriculture. Retrieved 24 October, 2014, from http://agmapsonline.com/?p=713

Burchfield, D. (2014). [Personal Communication].

Burtchfield, D. (2014). Strategies for Faster & Higher Quality Data. Paper presented at the Delta AgTech Symposium, Memphis, TN, USA.

CASA. (2014). CASA and remotely piloted aircraft. Retrieved 19 October, 2014, from http://www.casa.gov.au/scripts/nc.dll?WCMS:STANDARD::pc=PC_100376

Chilcott, B. (2014). [Personal Communication].

DIY Drones. (2014). Game of Clones. Retrieved 12 October, 2014, from http://diydrones.com/profiles/blogs/game-of-clones

Duffy, B. (2013). Flight Riot: Advocating UAV and Geospatial Technologies - Post Process. Retrieved 17 October, 2014, from http://flightriot.com/tutorials/post-process-tutorials/

Dunk, C. (2012). Mapping using Parrot AR Drone 2.0 and AutoDESK 123D. Retrieved 17 October, 2014, from http://www.youtube.com/watch?v=Wl4VWZ2t0-s&sns=tw

Edwards, J., Umbers, A., & Wentworth, S. (2012). GRDC Farm Practices Survey Report 2012: Grains Research & Development Corporation.

Event38 Unmanned Systems. (2014). NDVI Camera - NGB Converted Canon S100 Camera. Retrieved 17 October, 2014, from http://www.event38.com/ProductDetails.asp?ProductCode=CAM-NGB100

FAA. (2014). Federal Aviation Administration - Unmanned Aircraft Systems. Retrieved 19 October, 2014, from https://www.faa.gov/uas/

Ferrie, I. (2014). Sky-High Scouting. Paper presented at the Drone Fly-In, Heyworth, IL, USA.

Fischer, T., Byerlee, D., & Edmeades, G. (2014). Crop yields and global food security: will yield increase continue to feed the world? Canberra: Australian Centre for International Agricultural Research.

Gardner, K. (2014). [Personal Communication].

Harwin, S., & Lucieer, A. (2012). Assessing the Accuracy of Georeferenced Point Clouds Produced via Multi-View Stereopsis from Unmanned Aerial Vehicle (UAV) Imagery. Remote Sensing, 4(6), 1573-1599.

Kelcey, J., & Lucieer, A. (2012). Sensor Correction of a 6-Band Multispectral Imaging Sensor for UAV Remote Sensing. Remote Sensing, 4(5), 1462-1493.

Lefebvre, R. (2014). Arducopter Flies Gas Powered Helicopter. Retrieved 8 October, 2014, from http://diydrones.com/profiles/blogs/arducopter-flies-gas-powered-helicopter

Lohman, P. (2014). [Personal Communication].

Lucieer, A., Jong, S. M. d., & Turner, D. (2014). Mapping landslide displacements using Structure from Motion (SfM) and image correlation of multi-temporal UAV photography. Progress in Physical Geography, 38(1), 97-116. doi: 10.1177/0309133313515293

Mainfroy, F., Faroux, R., & Cheron, C. (2014). AIRINOV. Retrieved 17 October, 2014, from http://www.airinov.fr/

Mather, P. M. (2004). Computer Processing of Remotely-Sensed Images: An Introduction, Third Edition. Chichester, UK: John Wiley & Sons, Ltd.

MicroPilot. (2014). MicroPilot: World Leader in Professional UAS Autopilots. Retrieved 12 October, 2014, from http://www.micropilot.com

Monsanto. (2012). Monsanto Company to Purchase Planting Technology Developer Precision Planting, a Leader in Delivering Yield Through Technology. Retrieved 8 October, 2014, from http://news.monsanto.com/press-release/monsanto-company-purchase-planting-technology-developer-precision-planting-leader-deli

Monsanto. (2013). Monsanto Completes Acquisition of The Climate Corporation Retrieved 8 October, 2014, from http://news.monsanto.com/press-release/corporate/monsanto-completes-acquisition-climate-corporation

Paul, R. (2014). [Personal Communication].

Paulson, B. (2011). Green Seeker Basics. Retrieved 11 November, 2014, from http://www.agvise.com/wp-content/uploads/2012/11/2011-Bernie-Green-Seeker-1-Seminar.pdf

Rayleigh, S. (2014). [Personal Communication].

RFDesign. (2014). RFD900 Radio Modem. Retrieved 13 October, 2014, from http://rfdesign.com.au/index.php/rfd900

Robertson, M. J., Llewellyn, R. S., Mandel, R., Lawes, R., Bramley, R. G. V., Swift, L., . . . O'Callaghan, C. (2012). Adoption of variable rate fertiliser application in the Australian grains industry: status, issues and prospects. Precision Agriculture, 13(2), 181-199. doi: 10.1007/s11119-011-9236-3

Stark, R. (2014). Sensilize: sense. analyze. realize. Retrieved 17 October, 2014, from http://sensilize.com/

Swift Navigation. (2013). Piksi : The RTK GPS Receiver. Retrieved 8 September, 2014, from https://www.kickstarter.com/projects/swiftnav/piksi-the-rtk-gps-receiver/

Tetracam. (2014). Tetracam: Digital Camera Imaging Systems Design.   Retrieved 17 October, 2014, from http://www.tetracam.com/adc_lite.html

Torres, G., McAllister, J., & McBride, J. (2014). MicaSense.   Retrieved 17 October, 2014, from http://www.micasense.com/

Trimble Geospatial Division. (2013). Trimble Business Center Photogrammetry Module White Paper. from http://uas.trimble.com/sites/default/files/downloads/trimble_business_center_photogrammetry_module_white_paper_-_english_final-corrected.pdf

Turner, D., Lucieer, A., & Wallace, L. (2014). Direct Georeferencing of Ultrahigh-Resolution UAV Imagery. Geoscience and Remote Sensing, IEEE Transactions on, 52(5), 2738-2745. doi: 10.1109/TGRS.2013.2265295

U.S. Geological Survey. (2013). Landsat 8 Fact Sheet.   Retrieved 11 November, 2014, from http://pubs.usgs.gov/fs/2013/3060/pdf/fs2013-3060.pdf

Plain English Compendium Summary

Project Title:	**Name of project**
Nuffield Australia Project No.: Scholar: Organisation:	Ben Boughton Nuffield Australia / GRDC
Phone: Fax: Email:	0267548617 bboughton@gmail.com
Objectives	1. Investigate the perceived benefits of UAVs 2. Understand the individual components that contribute to a UAV solution 3. Consider strengths, weaknesses and standout features of different UAV manufacturers 4. Describe challenges facing UAV adoption 5. Record current development and future use for the technology
Background	Australian dryland crop yield increase has plateaued in the last decade. Those involved in the industry are searching for new productivity gains. Unmanned aerial vehicles (UAVs) have been suggested as an ideal way to collect high quality spatial, spectral and temporal data that can assist in productivity gains. A small fixed wing design is suitable for the grains industry.
Research	Potential of Unmanned Aerial Vehicles (UAVs) in the grains industry
Outcomes	A documented body of knowledge covering basic to advanced concepts around applying UAVs to broadacre agriculture including recommendations for further research
Implications	This should facilitate uptake of UAVs in the ag industry and serve as a starting point to those looking to use the technology. The broad scope gives the recommendations value and credibility.
Publications	Presented at SPAA Conference Quirindi 2014, ABARES Armidale 2014