The Suitability of Commercial Low-Cost UASs for Forest Assessment

Submitted for the degree of Bachelor of Science with Honours in The Fenner School of Environment and Society, The Australian National University

Rowan Edwards, 2015

I declare that this thesis is my own work, except where otherwise acknowledged

R Edwards

Contents

List of Figures

List of Tables

1. Abstract

This study examines the suitability of commercial low-cost Unmanned Aerial Systems (UASs) for use in assessing arboreal resources. These UASs are small, remotely controlled flying platforms, which have the ability to mount sensory equipment not directly related to the operation of the craft itself. The recent commercialisation of these systems has opened the potential for their use in a number of applications, including in forest assessment.

The key areas investigated are the ease with which a novice operator can pilot a UAS, the suitability of the UAS for assigned tasks, the data which can be gathered, and the use of different processing tools to gain information from that data.

The study allows natural resource managers to assess the potential benefits of incorporating UASs into their management techniques. Additionally, it informs UAS developers of the requirements of natural resource managers.

The technology of the UAS used was found to be suitable for a number of tasks, though specific issues were identified that limit potential applications. The primary technological limitation was identified as the battery life, which served to limit most other facets of UAS implementation. For the model examined during this study, the control software was also a limiting factor, though other packages have been identified which address these issues. The current legal restrictions, especially those associated with line of sight operation, also serve to limit the usability of the system.

The primary role of the UAS is identified as a tool for small scale, *in situ* assessments, including fixed point photography, upper canopy inspection, canopy cover line analysis and sourcing images for subsequent 3D reconstruction. The resulting data is of finer detail than traditional remote sensing techniques, though this is balanced by a comparatively smaller area which can be covered. UASs also provide the ability to assess both individual trees and stands from multiple angles and scales, allowing both fine detail and contextual assessment. This improvement in detail, when integrated with existing methods of data collection, provides the ability to construct better resolution models. With their ability to work inside and outside the canopy, these UASs also provide a novel, low cost approach for the validation of the output of such models.

Seven different software packages were evaluated for the subsequent manipulation of data, with four being chosen for detailed investigation.

In conclusion, UASs are deemed currently suitable for the applications considered, though there are aspects which serve to limit their effectiveness. Specifically, they do not have the capability to replace full scale aircraft, but are best utilised as a tool to augment existing processes.

2. Introduction

Forests provide a wide range of goods and services while varying greatly in size, structure and value. Increasingly, effective management and understanding of forests requires more and more precise, accurate, and up to date information over smaller and smaller pieces of land. Such information, especially when collected over a long period of time, can monitor attributes such as the progress of stress or disease within a forest, the rate of deforestation and degradation, forest based carbon sequestration, and the commercial timber and non-timber production of a forest. This information is not only important to the activity of commercial businesses but also to national and international governance. Australia has many obligations which concern its forests, as it is part of a number of international organisations including the Montreal Process (Department of Agriculture and Water Resources, 2015), Asia Forest Partnership (UN Partnerships, 2015), and the International Tropical Timber Organisation (ITTO, 2015). Each of these organisations stipulates multiple conditions and requirements which require monitoring and taking inventory of multiple facets of arboreal resources on a periodic basis.

Systematic collection of information regarding forests has been occurring for many hundreds of years. William the Conqueror, who conducted the last successful invasion of England in 1066, ordered a famed series of surveys which became known as the Domesday Book (The National Archives, 2009). In addition to noting details such as the names of villages and their farmland, it noted the size and condition of wooded areas. This included the creation of a new forest for the purpose of the king's hunting which still survives today: the New Forest. These early record keepings were primarily based on the experience and subjective knowledge of local landholders, who were principally concerned with the size and value of the area. Such information can be easily measured with simple instruments, but as our understanding of forests grew there developed a demand for more information, and a higher quality of that information. Over the last 200 years in particular, more advanced methods and technologies have been adopted to conduct surveys, as they became available and practical in their execution.

The current methods of surveying forests use a combination of accurately measured on-the-ground statistics and remote sensing techniques, in order to deliver a result at an acceptable level of accuracy and cost. Accurate measurements of trees are extremely time intensive, as every individual tree possesses different characteristics. In addition, measuring attributes such as carbon by mass or commercial volume require the destruction of that tree in order to obtain a result. The commonly used solution is therefore to use formulae to relate easily measured, correlated attributes (such as diameter at breast height, tree height, or crown diameter) to the desired, yet unknown, statistic. Measuring carbon is a common example of this, in which a small number of trees are dried and weighed to determine their carbon mass (Montagu et al, 2005).

Prior to the advent of remote sensing, the total value for the area of interest was determined by multiplying the result of the allometric by the number of trees present in a hectare to arrive at a measurement/ha. This figure was then multiplied by the total area in ha of the subject of interest to arrive at an end result. Due to the variation in forest structure over a geographic area this single average over a large area was relatively imprecise, which led to the addition of statistical methods such as stratification of the area in order to fine-tune the equation for a more accurate result. With the advent of remote sensing by aerial photography, stratification became a more powerful tool as it was easier to identify the different forest strata. Further improvements in remote image acquisition, from both aerial and satellite, led to the development of double- and multi-phase sampling techniques. These techniques rely on a combination of measurements of the individual and measurements of the sum of the individuals. In this case, measurements of the individual trees (i.e. diameter at breast height) are combined with measurements from satellite imagery (i.e. RGB pixel value) and related to the parameter of interest (i.e. Carbon mass). These metrics can then be used to construct a model which can be applied over remotely sensed data without the requirement for stratification, leading to increased accuracy.

Whilst double- and multi-phase sampling are more accurate than single-phase, even with stratification, there is still a measure of error (Stehman, 1997). This measure is defined by: sqrt(a^2 + b^2-2(covar(ab))
Where:

a denotes the error in the allometric equation (%)

b denotes the error in the estimation of the mean value from remote sensing

The covariance of (*ab*) is generally assumed to be 0

As a result of this equation, the error is dominated by the largest error source.

Current remote sensing techniques are dominated by aerial and satellite surveys, using both LIDAR and digital photographic imagery (Poso et al, 1999). The overall accuracy of the estimates produced by a multi-phase model is therefore partially determined by the accuracy and quality of data of the remote sensing technique. The greater the number of features that can be accurately measured and related to on-ground features, the greater the accuracy of the model. The most common features for remote sensing techniques used to be crown/canopy cover and stand height; however the introduction of LIDAR has increased the number of parameters that can be utilised as metrics.

The recent commercialisation of small unmanned aerial systems (UASs) may provide an impetus for a change in the current forest measurement techniques, similar to the way in which LIDAR has. The UAS platform provides a new set of operational parameters for data collection, in particular the rotary wing variants as they are able to take images from a greater variety of angles and heights. The variability of rotary winged UASs allows the use of 3D reconstruction software to recreate a digital model of the surveyed resources, though the accuracy of such models is largely unknown.

This thesis will explore the potential for the currently commercially available UASs to change the way forest inventories are performed. It will explore the practical capability of an existing system, including operation in remote areas; examine opportunities to replace or enhance existing systems; as well as any changes or further research required to adapt UAS technology for forestry use. Specifically, I attempt to answer the question: *Is the current status of commercial, low-cost unmanned aerial systems sufficient to augment arboreal natural resource assessment?*

3. Literature Review

3.1 History of Resource Management

Early forest inventory was concerned with singular large scale assessment of the forest, generally in order to place a value on the land which could be used as the basis of taxation (The National Archives 2010). As time progressed, other factors became of importance. In particular was the requirement of the navy for trees that could be used to construct the great ships of the seafaring age, such as the English Oak. The prospect of a shortage of shipbuilding quality timber in England was a frightening thought, so a royal commission was set up to inventory and oversee timber production and forest management to ensure a continuing supply (Middleton et al, 1786). This production and management included the measuring and modification of certain trees to meet desired parameters, determining readiness for harvest, and the replanting of old stock (Mathews, n.d.). With the advent of ironclad warships starting in 1859 (Sondhaus, L., 2001), the importance of timber for naval purposes dwindled, though it was not long before other industries developed specific demands for timber. An example of another critical era of forest management was during World War One, during which timber was used to prop up the trenches for both warfare and mining. Such was the rate of decline in English woodland that in 1916 the Prime Minister of that time, Herbert Asquith, ordered the creation of a parliamentary committee to assess and increase the country's timber producing capacity (Forestry Commission, 2015). The attention to woodland management continued throughout World War Two, and has indeed continued to this day. From the beginnings of land taxation, through suitability for naval construction and mass production for trench warfare and industry, we now have such requirements as the Kyoto protocol to inventory the carbon mass per one hectare plot (United Nations, 2015).

3.2 Incorporation of Technology

The increase in the amount of forestry information gathering, as well as the diversification of data types, has been enabled in a large part by an increase in technological capacity. The advent of flight, starting in 1903 (First Flight Centennial, n.d.) and being hastened by the military during wartime, provided one of the first significant changes from the traditional methods of requiring a person on the ground to make measurements of every tree of interest. Aerial photography provided the ability to get an image of the whole forest, which could then be interpreted to provide a scale, and thus the area of the forest. This enabled both easier and more accurate measurement of forest area, and the introduction of stratification and multi-phase sampling. As camera technology improvements enhanced image quality, the amount of information that could be gained also increased. Colour photography allows easier stratification, whilst the advent of uncooled infrared cameras in 1997 opened another set of potentials (Kruse & Skatrud, 1997). Laser range finders were another advance which impacted on forest monitoring, as it became easier to get exact measurements. Handheld laser range finders are accurate to a few mm (Sala et al 2008) and make the task of measuring tree height far easier, though lasers really created a new field of study with the advent of LIDAR.

LIDAR devices use a continuous stream of laser pulses to determine the distance to their target, similar to a range finder. The difference between the two lies in the fact that the stream in a LIDAR device is constantly moving. When this motion is combined with a laser set to scan an area, it becomes possible to triangulate the position of corresponding points. The triangulation data can then be digitally interpreted to construct a three-dimensional model of the scanned area, the accuracy of which depends greatly on the accuracy at which the movement of the source and the pulse return of the laser can be measured. This need for accuracy helps make LIDAR units expensive: one plane-mounted system costs €355,000 (~$55,500AUD) with training included (Aerial Surveys n.d.), though their price is decreasing. Such systems can be mounted on flying platforms (such as a plane or helicopter) or on ground based platforms, such as a ute. The cost of airborne LIDAR ranges from USD$0.05-0.20 per hectare (Asner, 2009), though the cost of the total study typically resides around USD$20,000, regardless of study area, due to the associated aircraft maintenance and set up costs (Erdody & Moskal 2009). This cost makes airborne LIDAR surveys financially impractical for making frequent assessments over a period of time, organisations with low funding, or small study sites. An alternative is to use the handheld LIDAR system currently being developed, the Zebedee (CSIRO 2015). Whilst this does not have the coverage nor penetration power of vehicle-mounted LIDAR systems since the power of the pulse is not as great, if the area of interest is not large it is a suitable alternative. Additionally, ground-based LIDAR can have problems in reaching the canopy through dense foliage, particularly if low power (such as the Zebedee). What is therefore required is a low-cost, low-maintenance platform, which can reach above the canopy layer upon demand. Enter the Unmanned Aerial System, or UAS.

3.3 Unmanned Aerial Systems

Unmanned Aerial Systems, also known as drones, Unmanned Aerial Vehicles (UAVs), Remotely Piloted Aircraft (RPA) and many more names, are a recently commercialised flying platform. Whilst the naming convention for these platforms has not yet been finalised, the term UAS will be used for this paper, and is defined as a vehicle which is capable of flight; autonomous, manual, or a hybrid of both. A UAS also possesses the ability to mount sensor equipment and can directly record information from that equipment whilst in flight. As with many technologies, the origin of the UAS is in military application, where it is usually referred to as a drone. Numerous technological developments, particularly in miniaturisation, have enabled the construction of privately affordable UASs.

Such UASs come in two distinct forms: fixed and rotary wing. As with full-sized aircraft, the differences are much the same, but on a smaller scale. Fixed wing craft are more fuel efficient in terms of distance covered per fuel unit, whilst rotary wing craft provide much greater flexibility and mobility. This mobility is the key driver behind the use of rotary (as opposed to fixed wing) craft for forestry observation, as it enables takeoff and landing in areas which would be far too restrictive for fixed wing craft. This is particularly important when surveying natural resource sites which are not guaranteed to have a clear strip to use as a takeoff and landing zone, even by the more rugged fixed wing designs. A camera gimbal installed under the fuselage increases the need for a smooth landing zone for fixed wing craft as they can no longer belly slide, the common 'rugged terrain' landing method. Rotary wing craft also have a lower skill level for use, an example being that the operator can take their hands off their controls of the DJI Phantom and it will hover, whereas a fixed wing craft like the Bixler would remain heading at throttle.

3.3.1 Increases in computer processing speed

A key component that enabled the development of small UASs was the continuation of Moore's First Law, which states that the number of transistors in a given area will roughly double over the course of a year. This has led to not only more powerful computers, but equally powerful computers of less weight. Moore's Second Law states that the cost of such devices will also decrease over time, with the result of increasingly powerful computers at decreasing cost (Moore 1965). This has led to the development of a system powerful enough to control motor speed and servo settings at a fast enough rate to enable flight, at a weight which allowed the system to leave the ground.

3.3.2 Phone miniaturisation

As the UAS shares many components in common with cellphones (cameras, light-weight batteries, compact GPS), the research and development which has led to the 'smartphone revolution' has accelerated UAS development. An example of this is in the development of a GPS refining technique which can run on a mobile phone processor (Phys.org, 2015) to greatly increase the accuracy of the determined position.

3.3.3 Power technology

The fuel which UASs use varies, though for the systems of interest in this study the primary sources are two-stroke and electric. Miniature jet engines do exist, though their use as photographic platforms is primarily for First Person View (FPV) flight setups. Since this study is to determine the condition of user ready, commercially available small UASs, the focus will be on the battery powered systems. This is because it is the power source for both main contenders for the title of 'user ready UAS': DJI's Phantom series and 3DRobotics's IRIS. The reasons behind this are many, but the key problems with liquid fuelled craft are in the engine vibration produced and the exhaust fumes blocking the camera.

The key development for battery technology was in the commercialisation of lithium ion cells. These cells produce more power over time than metal acid batteries of comparable weight, enabling the power/weight ratio required for powered flight. Whilst often called lithium polymer, or LiPo, these are not true LiPo batteries or cells, as the polymer does not take place in the reaction (Ogrin, 2015).

Whilst not as susceptible to combustion as lithium polymer batteries, the use of lithium ion cells in a flying object, which can fall some considerable distance, is still a safety concern. When this is coupled with a lightweight casing used to reduce overall weight, this means that these batteries could ignite in a serious crash, should one be punctured. However, no fuel source for a UAS is entirely safe from combustion, therefore this risk is not inherent to lithium ion batteries. A number of safeguards exist in the batteries of a UAS to reduce this chance of fire, including safety shutoffs and intended energy dissipation; however the technical information on their workings is outside the scope of this study.

3.3.4 LIDAR

Efforts to miniaturise the LIDAR equipment have been relatively successful (Wallace et al, 2012), but the system is not currently available commercially and therefore does not meet the criteria specified for this study.

3.3.5 Ease of use

The primary advantage concerning the use of a UAS over that of a simple RPA is that the bulk of the high-skill flying can be handed off to the on-board system. Using an accelerometer, a UAS can hover by itself with an accuracy that only the most skilled operators can match. A UAS can also manage user input, allowing it to not bank above or below a certain angle, for example, or moderating excessive user input. In turn, this allows the traditional throttle control to be replaced by height change control, reducing the skill threshold of a rotary wing UAS significantly.

The secondary advantage of the UAS is that it can be programmed autonomously.

Programs such as Pix4D (Pix4D, 2015) and Mission Planner (APM DroneCode, 2015) allow a user to specify a number of commands that can be uploaded onto the UAS and executed at the operator's discretion. Additionally, it is possible to modify some of these programs to add features such as customised presets and flight patterns.

3.4 3D Visualisation

3.4.1 Photogrammetry

Photogrammetry is the use of photographs in order to obtain measurements of objects or landscape features (Walford, 2007). In forestry this is mainly done from a top-down perspective or orthogonal perspective, traditionally from a plane. Aerial photography, whilst it produces some extremely useful images, does have a number of drawbacks. Most notably, it is at the total mercy of the weather. Strong winds can ground an aircraft, while cloud cover can make images useless, yet all the while the aircraft is on standby to take images it is costing the operator. A run of unexpected bad weather can thus take a severe financial toll on a survey.

Aerial photography operates at high to medium scale resolutions, typically between 90cm and 2.5cm per pixel, over medium to large scale areas. This overlaps with another photogrammetric data source, satellite imagery, which typically operates at anywhere up to 50cm per pixel over a larger surface area than aerial imagery (Aerometrix, 2012). Satellite imagery suffers from overcast weather more than aerial photography, as it cannot evade it by flying below high cloud cover. Satellite photography is, however, not generally subject to waiting costs whilst doing so, as the satellite will typically fly a set orbit. If the satellite needs to be re-routed or re-targeted to obtain the required images, a waiting cost may however apply. Usually satellite imagery companies have a level of cloud cover which is deemed acceptable when applied to an image. If a target area is small enough to be covered under that acceptable percentage, then satellite imagery may not be the best solution.

The measurements from photogrammetric images can take on multiple forms. One of the basic applications is to determine the size of an object or area of interest from photographs. This is done by triangulating the position of the plane at the point of capture, which provides a reference scale. In order to do this the position of the plane must be known in detail, which generally is accomplished by the use of high accuracy GPS. Other uses include the analysis of ground cover by measuring the vegetation cover categories, either by local 'unit' scale in the case of percentages, or using the above mentioned triangulation to achieve absolute values such as m^3. This can be digitised by categorising RGB values, then using the computer to count the number of pixels in each category.

3.4.2 Structure From Motion (SFM)

An alternative method of utilising photogrammetry is to combine multiple images together in order to extract enough information to enable construction of a 3D model of the target area. This is done digitally with two primary techniques: Simultaneous Location And Mapping (SLAM) and Scale Invariant Fourier Transformations (SIFT). These two processes share some techniques, but the source images and requisite metadata differ substantially.

SLAM relies on image tiling, a set of images which overlap by a large amount, supported by accurate GPS coordinates and headings. An algorithm is used to match photos to each other, supported by the knowledge of where exactly each photograph should be placed via GPS information. In order for this to work, images need to be taken orthogonally, in order to minimise any parallax that may occur. This gives an optimal flight pattern of a grid of overlapping squares (see Fig. 1).

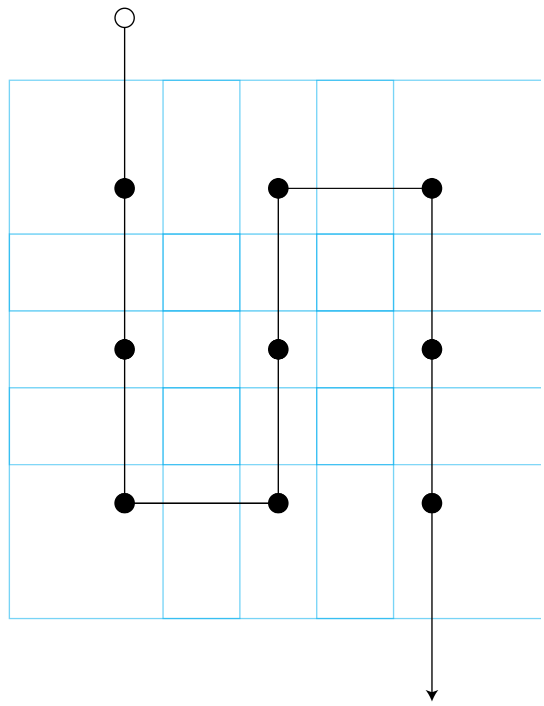

Fig. 1. Ideal SLAM flightpath with minimal overlap

SIFT likewise requires image overlap, but instead of requiring accurate positional data on multiple images to compute angles and distances, SIFT works by feature recognition. By comparing the same feature from multiple angles and positions, the size and shape of an object can be determined. For this reason, the use of SIFT technology is also referred to as Structure From Motion, or SFM. However, due to the lack of any relational spatial frame to reality, provided by the GPS coordinates in SLAM, the resulting SIFT-derived model has no relation to any real-world measurements.

SIFT and SLAM are both considered computationally intensive, though research is progressing to allow them to run in real-time (Ling 2013). Their expanded use has been driven by the continuation of Moore's Law, as well as the development of distributed computing, as performed by Autodesk's 123D Catch (Autodesk 2015). Additionally, the leverage of the Graphical Processing Unit (GPU) instead of the Central Processing Unit (CPU) has enhanced performance by delegating tasks to where they are best performed. The exact technical details of these enhancements are not directly relevant to the study; it is enough to understand that they have enabled the technology to run on modern consumer machines, though the machine will need to be more powerful than the average word processing terminal.

3.4.3 UAS photogrammetry

There exist many examples of SLAM (Miettinen et al 2007, Öhman et al 2008, Tsubouchi et al 2014) and SIFT (Dandois & Ellis 2013, Ecosynth 2015, Lingua et al 2009) being used in forestry. These studies use a range of data collection mechanisms, from simplified LIDAR to UAS sourced photogrammetry. Other disciplines have utilised the UAS approach, often favouring SIFT over SLAM. The most advanced of these seems to be archaeology, where it is used it to map excavation sites (Chiabrando et al, 2009).

The UAS equipment used in these studies, both hardware and software, tends to be ad-hoc and highly customised for the specific task at hand. This high degree of customisation tends to increase the level of skill required for the entire production pipeline, from flying through to postprocessing. This is detrimental to the adoption of UAS technology by a more general audience, which delays the generalisation of use. New technologies often experience a number of problems which can slow down their adoption, even in fields where they show excellent potential (Moore, 1994). Of particular note here is the potential reluctance of employees to learn a new, fairly substantial, skill set, though there will undoubtedly be many early adopters who seek out the technology for the enjoyment of flying.

3.5 Barriers and Social Constraints

3.5.1 Regulation

Usage of a UAS is not an unregulated activity, as the misuse of one could interfere with other flight traffic causing an accident. For this purpose, the Civil Aviation Safety Authority, or CASA, maintains regulations that apply to UAS operators (CASA, 2014). The key points of the regulations which apply to the category of UAS used in this study are outlined below:

- *Aircraft must remain within visual line of sight at all times.* This means that pure First Person View (FPV), such as flight by Oculus Rift, is not allowed as it does not count as visual line of sight. A screen with an FPV display on it is permissible however.

• *Aircraft must remain below 400ft (120m) above ground level.* How ground level is measured in regard to topological variation is unspecified.

• *No operation within 20m of an uninvolved party.* Again, what an involved party consists of is not defined precisely.

• *The aircraft shall not pose an unreasonable safety or fire risk.* No direct standards or metrics have been defined for this regulation. In essence, it requires that the power source be capable of withstanding an impact from crashing without catastrophic failure.

• *No flight within restricted zones.* Restricted zones generally consist of airports, governmental buildings and military infrastructure. It is the responsibility of the operator to know where these zones are.

These regulations are extremely generalised, as the document which outlines them was primarily designed for full-size aircraft operating autonomously. CASA has been in the process of devising a modernised set of regulations which simultaneously protect from misuse but open up the potential of UASs for commercial use. This has, however, been the case for a number of years, with no sign of a finalised document. Other countries are facing similar issues, an example being America, where regulators are attempting to construct legislation that would allow delivery by drone (Law360, 2015). By the time the safety authorities had given permission to test a drone, that model was already far outdated (Wall Street Journal, 2015).

3.5.2 Licensing

With CASA seemingly unwilling to take on the role of both setting the guidelines for UAS use and enforcing them, insurance companies have stepped into the breach (Austbrokers 2015). This indicates confidence that UAS use will continue to grow as more and more applications will be found for them, which will be aided by a solid financial underwriting of risk. With assurance against loss or accident, commercial UAS usage can begin to grow.

3.5.3 Safety features on a UAS

Insurance and regulation are not the only measures of safety present on a UAS. The on-board system itself typically has a number of key features which aid the operator in following regulations and keeping the UAS safe. These features are available on at least two of the main UAS operating systems: DJI and 3DR/ArduPilot.

Geofencing, or the ability to restrict UAS access over certain areas at a software level, exists in two forms. The first and simplest is called a hard fence, which is considered a line beyond which the UAS is not allowed. Should a UAS determine that it has crossed a hard fence, the general response is for the UAS to perform an emergency shutdown as it is then considered out of control. As this is a somewhat drastic response that may have serious consequences (fuel leak, fire etc.), a hard fence is usually used in conjunction with a soft fence. Unlike a hard fence, violation of a soft fence is not considered a critical failure. The usual reaction to crossing a soft fence is for the UAS to enter Return To Launch mode (RTL). When a soft fence is used in conjunction with a hard fence, the soft fence is deployed within the confines of the hard fence. This allows the UAS to cross the soft fence, which will then cause RTL to activate. If this fails to activate, the UAS will continue until it hits the hard fence. At this point, the UAS is correctly considered out of control and will execute an emergency landing (Fig. 2).

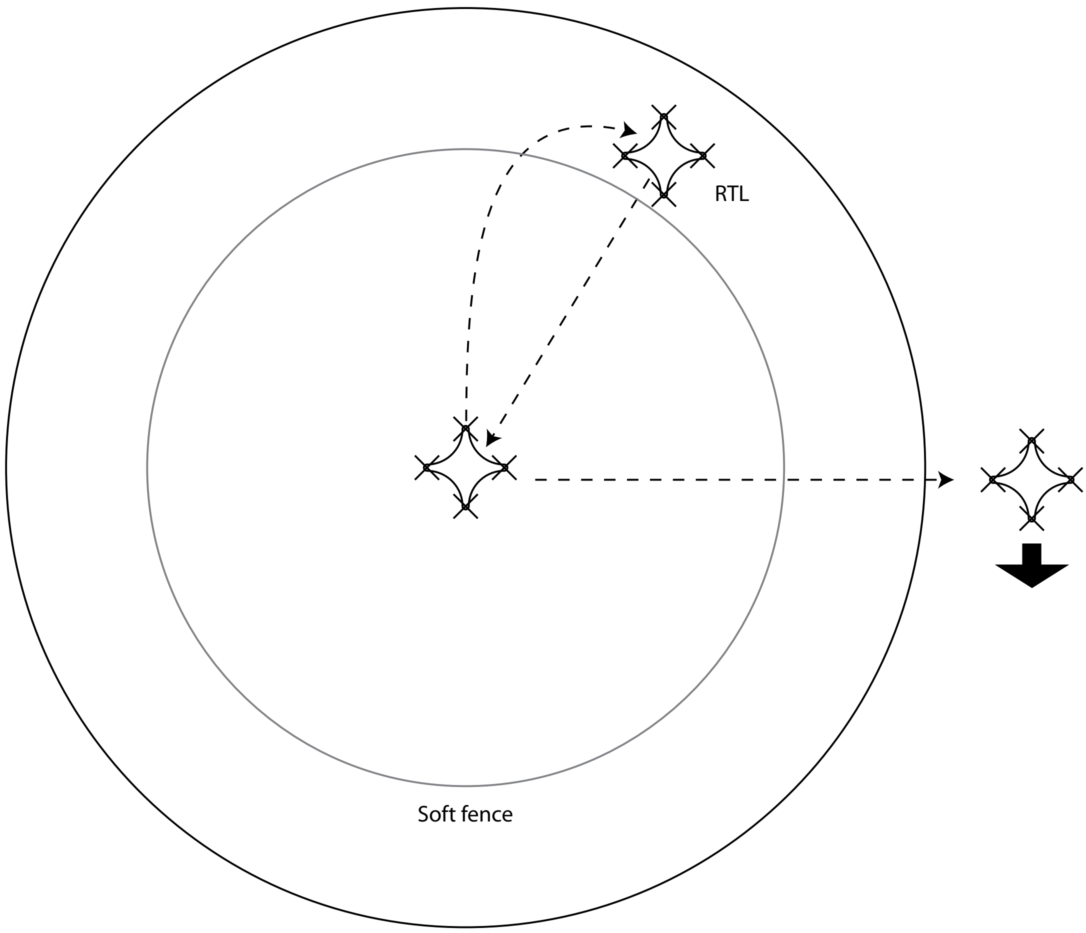

Fig. 2. UAS soft and hard fencing

UASs also tend to possess multiple software fail-safes to ensure that a battery does not fail or run out of power in such a way that it could cause damage or harm. In addition to the ground station battery readout (usually in volts), a UAS often has a series of audio and visual cues that alert the operator to a low battery. Should the operator fail to heed these warnings, the UAS can be programmed to perform an emergency landing, safely shutting down the UAS before it can cause damage.

3.6 Summary

The information gathered for forestry is dictated by both the needs and technological limitations of that time, from simple information such as the size of a forested area, to complex data such as the carbon mass of specific hectares. Certain technologies, such as the invention of flight and GPS, have enabled leaps forward. Such leaps inevitably pose challenges to their adoption, which in more recent terms frequently takes the shape of regulatory requirements. Such leaps forward start off as customised solutions, which, if proven capable, make the transition to stand-alone protocols. The question therefore is whether UAS technology is at a level at which it can transition from being a customised application of a set of technologies to a technology in its own right.

4. Method

4.1 Assessment Criteria

Using opportunities provided by current research and management projects, this study evaluated UAS technology, its practicality, and any legal or social barriers encountered during use. Of the available projects four were selected to cover a feasible range of potential uses, each with their own focus on an identified key area. These key areas were identified as:

- The ease of use and handling of the UAS
- The ease of maintenance of the UAS
- The software used to fly the UAS
- The hardware that makes up the UAS and associated base station
- The ease of use of software used to process the data obtained
- The output data produced by the processing software

4.2 Selection of Sites

Three study areas were chosen to aid assessment of the criteria.

4.2.1 National Arboretum, Canberra
(http://www.nationalarboretum.act.gov.au/)
Latitude -35.287797 Longitude 149.069324

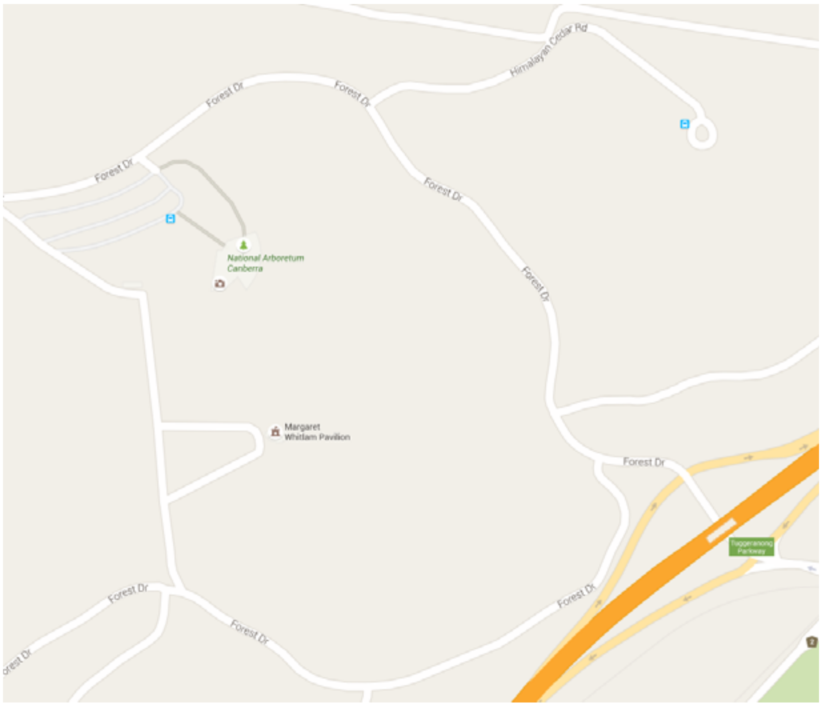

Fig. 3. National Arboretum (www.google.com/maps)

The National Arboretum was chosen as it is a local, well-studied site with a variety of tree species and growth stages. This diversity provides a rich set of opportunities to test what results are obtained from different canopy types at different stages of life. The initial test flights were performed at this location, with the goal of assessing the ease of use for a new operator and to familiarise the operator with the system and what data might be gathered. The site is also useful in this regard as it is possible to find areas which are sufficiently far away from people to mitigate any hazard posed by an inexperienced operator, whilst remaining within a short distance of the base of study.

4.2.2 Peniup Farm, Western Australia

Latitude -34.081636 Longitude 118.856006

Fig. 4. Peniup Farm (www.google.com/maps)

Peniup Farm is the site of ongoing Carbon sequestration research by Greening Australia (http://www.greeningaustralia.org.au/), involving natural re-vegetation of areas of land. This site was specifically chosen due to the ongoing studies performed here, which offered the opportunity to obtain immediate feedback on the usefulness of various data types, mainly fixed point aerial imaging at different altitudes. Peniup formed the basis of the majority of extensive flight testing under real-world survey conditions, as well as the primary assessment of fixed point monitoring capabilities. In addition it provided an opportunity to test the capability of the UAS to operate in remote areas, where all repairs and maintenance must be carried out without access to the internet or additional tools or equipment.

4.2.3 ANU Campus, Canberra
Latitude -35.278231 Longitude 149.115200

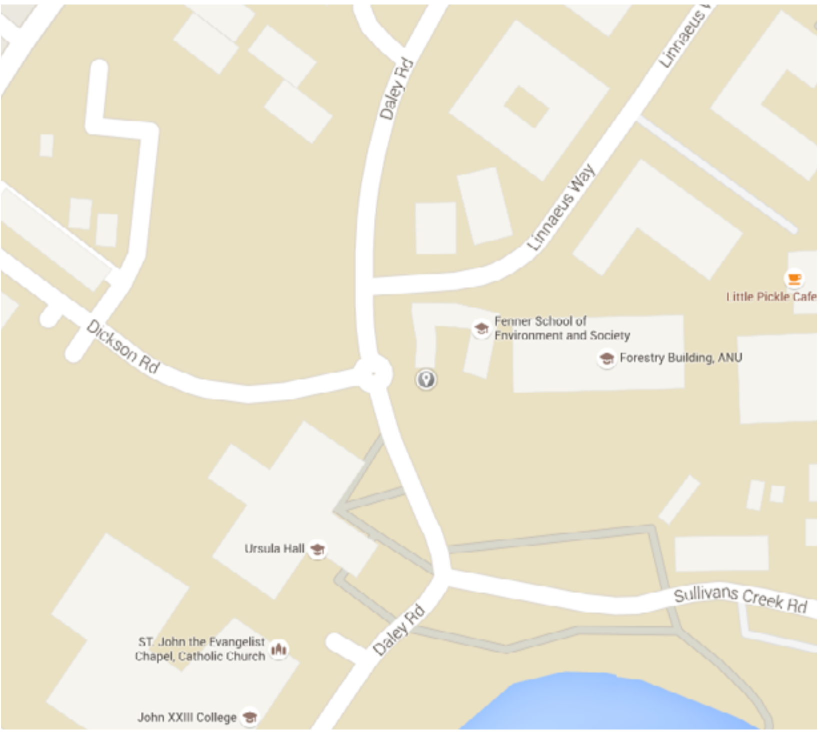

Fig. 5. ANU Campus (www.google.com/maps)

The ANU Campus provided an opportunity to get immediate feedback on the use of the UAS and its ability to gather the required data, all at a local location. The task presented was to aid the grounds maintenance staff in the assessment of a eucalyptus with suspected fork damage, a task which would usually require a climbing team to climb up and manually inspect for damage. This task had the secondary benefit of testing the fine grain control of the UAS when flying in sub-canopy conditions, as well as attempting flight inside the canopy itself.

4.3 3D Software Testing

With the establishment of the capacities of the UAS, the next step was to assess the viability of different methods of constructing a 3D model from the data that the UAS can collect. This step involved the selection of a process based on which better suited the capabilities of the UAS. Once a process was selected, it was tested by attempting the reconstruction of a simple geometric shape placed against a true random noisy background. This model was then placed in a spatial reference frame in order to extract measurements to determine the relation of the model to the real object.

Parrallax influence was measured by using corrected images in Adobe Photoshop to perform line analysis. A sample of fixed height *k* was taken at the full width of the image, with the required sample line forming the lower bound. The value is *k* is unimportant; it is there to provide context for the sample to aid determination in canopy cover. Once the sample is extracted, a new layer was created in Photoshop and the areas deemed under cover (remembering that only the lowest line of pixels can be sampled to decide cover upon) blocked off in solid colour. With this complete, the readout of the number of pixels on the blocked off layer can be divided by the number of pixels on the base layer (which provides the total pixels in the image) to provide a percentage cover. This works as $kM/kN = M/N$, where k is the height of the sample, M is the number of blocked off pixels, and N is the total pixels in the sample.

For the final stage, the goal was to draw on all information learned in the previous steps to create a 3D model of a canopy. For this, the National Arboretum was revisited and a small test plot chosen (Dairy Farmer's Hill) in which to attempt this reconstruction.

4.4 Selection of Equipment

For this experiment a DJI Phantom 2 Vision was the UAS used (Fig. 6). It is a quadcopter design, with an integrated camera stabilised by a 1-axis gimbal. The camera is rated at 14 megapixels and has a very high field of view as a result of the use of a fisheye lens. The extent of gimbal rotation is 0-60 degrees, starting at 0 (horizontal) and looking down to 60. The entire system weighs 1,160g, including the 5,200mAh lithium ion battery. This was expected to deliver around 25 minutes of flight time, though the amount varied depending on the style of flying and the condition of the battery.

This system is controlled by two components: a two-control joypad to control motion and a mobile app to control the camera and provide feedback. WiFi communication for the mobile app is achieved by the use of a WiFi range extender, which allows for 300m range between the mobile device and camera. The mobile device used for this was running iOS 8, allowing the use of either an iPad or iPhone depending on the size of image feedback required. The two programs used to control the UAS were the DJI Vision app, which acts as a miniature base station application, and the Pix4D Capture app, which is an autopilot designed to fly the UAS in a set pattern (Fig.1). This entire system is commercially available at a cost considered appropriate for even small-scale natural resource managers.

Fig. 6. DJI Phantom 2 Vision (dji.com)

4.5 Safety and Operation

The DJI Phantom 2 Vision comes with a number of preset safety features. These include Return To Launch (RTL), battery amp warning, battery voltage warning, automatic hover (within parameters) and No Fly Zone (NFZ) functionality. The use of the NFZ feature is not applicable to this study, as there were no locations in any planned site that featured any nearby restricted zones. Canberra Airport, in particular, was noted as absent from the preset list.

Technical operation of the UAS should be consistent with the recommendations from DJI. These include vertical and horizontal speeds and wind speed brackets. Functional operation is required to conform to the Civil Aviation Safety Authority (CASA) regulations for drones weighing under 7kg. Of main import are the following:

- *System must remain within visual line of sight at all times*
- *400ft (~121m) flight ceiling*
- *No operation of the system within 20m of persons who are not directly involved with the operation of the system*
- *Give way to all other air traffic, even if they deviate from a registered flight path*

5. Results

The following tables (1 to 4) summarise the findings of the four test flights, following the first four categories outlined in Chapter 4.1

Table 1. Assessment of ease of use and handling of the UAS

Assessment of	Assessment Issues at Test Site in Order of Execution			
	Arboretum	**Peniup**	**ANU Tree Inspection**	**Dairy Farmer's Hill**
1.1 **Ease of flying**	• Very easy to start and learn	• Wind speed limits operation to under Beaufort 3 • Gusts throw off camera stability • Drone doesn't fully return after a strong gust • Have to stop the UAS moving to get SLAM compatible images • Trees never a significant obstacle to takeoff or landing • Long grass can wrap itself around motors at takeoff • Can takeoff from and land in back of ute without problems	• Much more challenging circumstances • Air current going through fork was pulling the UAS into the tree • Second person giving directions from iPad was useful	• Easy to fly • Taking photos took too long • Failure due to inability to turn off .RAW

(Continued)

	Arboretum	Peniup	ANU Tree Inspection	Dairy Farmer’s Hill
1.2 Response to joystick	• No real issues detected • Unfamiliar to response so no baseline yet known	• Noting lack of fine control • Drifting whilst moving • Increased confidence in general flight so able to notice detail • UAS attempts to maintain smooth movement; desirable for film, not so good for surveys • Slight increase in drift at around canopy level	• Lack of fine grain control obvious • Controller dead zone is too big • Air current in branches made any amount of inherent drift impossible to discern	• Drifting noticed again
1.3 Setup of supporting equipment	• iPhone used	• Makeshift mount for iPad • Lanyard required for joystick to free hands to take photos • Routine established: 1. Set up flag pole 2. Set up ground station 3. Photo of plot tag to ID following photos 4. 10m height 5. 20m height 6. 50m height 7. Rotation at 90° intervals	• iPad used, but given to specialist inspector so that they could see the result	• Minimal • Use of iPhone is easier and more mobile than iPad • As area was largest attempted, the mobility was useful to keep track of the UAS

(Continued)

	Arboretum	Peniup	ANU Tree Inspection	Dairy Farmer's Hill
1.4 **First Person View (FPV)**	• Familiarised with the ability to fly by FPV	• FPV imperative for taking photos • Situational awareness still required • Bird attack demonstrates this	• FPV not ideal, need awareness of surroundings • Eventually handed iPad to another person and concentrated on flying	• FPV required again for photos
1.5 **Visibility of UAS to operator**	• Easy to lose track of in the sky	• Operator doesn't need to rely on seeing the UAS • Flown by instrumentation and checking photo alignment	• Flying very close to operator • Very easy to keep track of location and orientation, even without FPV	• Very easy to lose track of against sky, especially with frequent WiFi dropouts • Compass is handy
1.6 **Additional issues**	• None	• Bird attack: resolved by flying UAS to ground and keeping it still	• Public area: required warden to minimise pedestrian traffic	• Bird attack: flew down and stayed still. Worked again.

Table 2. Assessment of ease of maintenance of the UAS

Assessment of	Assessment Issues at Test Site in Order of Execution			
	Arboretum	**Peniup**	**ANU Tree Inspection**	**Dairy Farmer's Hill**
2.1 **UAS battery**	• Precharged	• Recharge was shorter than expected in the ute, as it was on mains. 1 hour to charge from 30% to full • Flight time estimated at 30 minutes total	• Precharged	• Precharged
2.2 **WiFi battery**	• Precharged	• Lack of accurate charge indicator very inconvenient	• Still using charge from Peniup	• Precharged
2.3 **Controller battery**	• No problems	• No problems	• No problems	• No problems
2.4 **Assembly**	• Already assembled	• Easy to fit blades on • Prop guards easy to attach • Battery is a bit hard to get out at times	• Simple steps, especially having done them before	• Already assembled
2.5 **Storage in transit**	• Can't be put back in the case once the prop guards are in place	• Air travel restrictions regarding carry on of UAS not clear • Batteries must be carried on • Turned away at gate on return flight	• Location on campus, no storage required	• Strapped into vehicle seat out of case, fits well

Table 3. Assessment of UAS Flight Software

Assessment of	Assessment Issues at Test Site in Order of Execution			
	Arboretum	**Peniup**	**ANU Tree Inspection**	**Dairy Farmer's Hill**
3.1 Ease of use	• Couldn't get autopilot to work at all • DJI app worked without flaws	• Taking hands off to take photo is awkward • Locator compass is very handy when taking rotational photos • Lack of camera angle readout hampers SLAM imaging	• Only able to connect one iPad; would have been preferable to have two showing the camera feed	• Problems getting system off .RAW mode and keeping it off • Camera timer was therefore 30 secs • Had to revert to manual
3.2 Bugs	• None found	• Black bar appears on screen, very annoying as it covers the connection status • Takes a while to find the WiFi network; workaround used was to spin up the motors and then shut them down • Unknown if that causes a refresh or if it was just a time-delaying placebo	• Still black bar on screen • Network discovery time not monitored	• Black bar made another appearance • Takes a while to find the WiFi network • Couldn't get .RAW to turn off and stay off
3.3 Crashes	• None	• Couple of iPad app failures, unknown reason • Instant restart of app	• None	• One iPad app crash, unknown reason • Fixed by restarting app

(Continued)

	Arboretum	**Peniup**	**ANU Tree Inspection**	**Dairy Farmer's Hill**
3.4 Photos	• None	•Fisheye removal successful • Bit fiddly to get the camera profile into Photoshop •Photos taken from north looking south so as to negate as much sun glare as possible	• .RAW very useful for allowing post-image exposure modification • High postprocessing exposure modification allowed an insight into the tree hole	• .RAW takes a very long time to write to disk • Terminal was amazingly useful for separating .jpg and .RAW (mv command)

Table 4. Assessment of UAS and base station hardware

Assessment of	Assessment Issues at Test Site in Order of Execution			
	Arboretum	**Peniup**	**ANU Tree Inspection**	**Dairy Farmer's Hill**
4.1 Non-terminal failures	• None	• Accidental descent feedback from maximum height, recovered • Provoked descent feedback to determine cause; full recovery and cause established	• None	• Descent feedback, recovered • Descent feedback loop, saved by terrain undulation
4.2 Terminal failures	• None	• First occurrence of descent feedback crash, able to manoeuvre to bush • Bush broke one blade • Battery failure crash • Potentially provoked by fail-safe exceeding feedback • Energy dissipation through disconnecting parts succesful	• None	• None
4.3 Battery	• No problems, but very short flight	• Critical failure at 26%, warning sounded at 28%, then crash before UAS fail-safe (24%) • See battery discharge graph (Fig. 7) • US->AUS adaptor is very loose; suggest changing plug • Adaptor tendency to come loose in moving vehicle	• Flight short enough that battery life not an issue	• Requirement of continuous flights made recharging between batteries impractical • Multiple batteries best thought of as a block of flight time to be used and then all recharged

(Continued)

	Arboretum	Peniup	ANU Tree Inspection	Dairy Farmer's Hill
4.4 Controller	• Intuitive to use	• Lack of controller trigger for taking photos becomes awkward	• Joystick dead zone is too wide • Input from just outside of dead zone too strong, makes fine-tune flying hard	• Competent use
4.5 WiFi	• WiFi dropout	• No problems	• No problems	• WiFi dropout • WiFi drops out on writing of .RAW; suspect processor speed is insufficient • WiFi drop-outs seem to be linked to site, not just when taking photos
4.6 GPS	• Suspect great inaccuracy in height measurement	• Inaccuracies of 1-2m in height • Height callibration based on point at which the system is switched on • Distance estimation accurate to within 10m	• Flight area and adjustments too small to make any comment	• Inaccuracies in tens of m in height • Seems to not be using the launch point as reference as it did at Peniup

(Continued)

	Arboretum	Peniup	ANU Tree Inspection	Dairy Farmer's Hill
4.7 Marker	• None required for task	• Flag pole is insufficient, too narrow to show on photos • Tried reflective plastic; just reflects the trees making it very hard to see • Hi-Vis jacket is slightly better, but flops down • Hi-Vis + backing good, but tends to face into wind, which was from same direction as taking photos • End result was still hard to see • Particularly hard in high tree plots • Possible to use vehicle for scale reference	• None required for task	• Use edges of canopy as marker to be referenced against map
4.8 Other	• None	• iPad screen area was useful, but a bit impractical to carry/use • Lack of carry case for assembled UAS was inconvenient	• iPad screen area very useful for showing others	• None

Fig 7. shows the typical discharge profile for lithium ion batteries, featuring a descent from fully charged to the more gentle slope of the main discharge, culminating in a sharp voltage drop as the battery nears full discharge. The batteries used in this study followed this profile, but reached their voltage drop before expected.

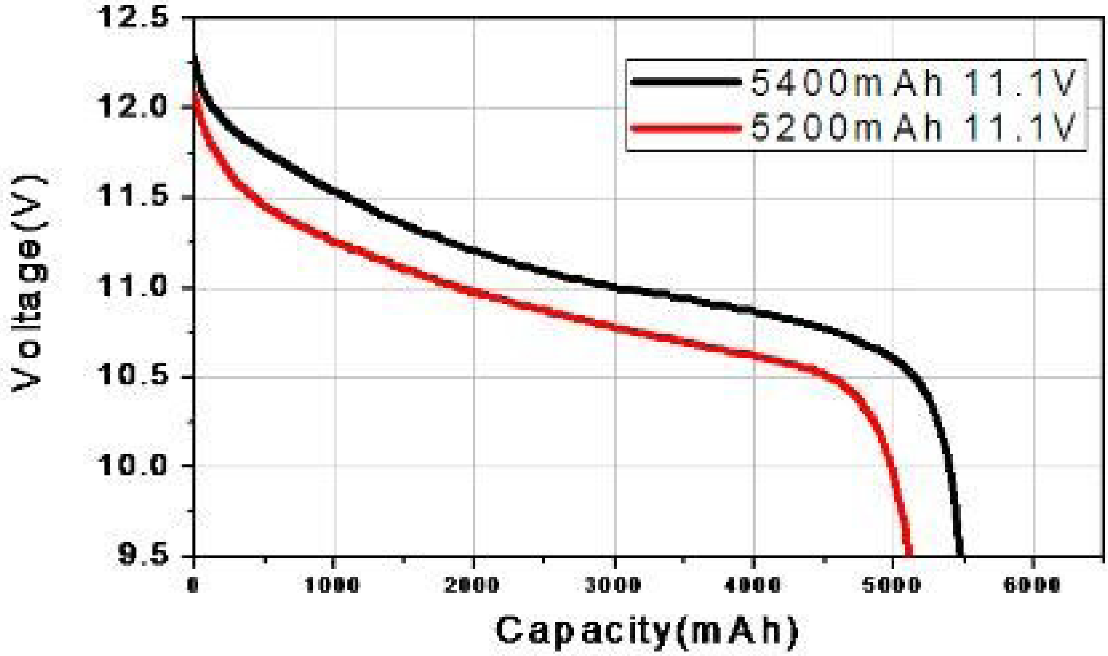

Fig. 7. Battery discharge graph for two types of lithium ion batteries used by the Phantom 2

(http://www.unmannedtechshop.co.uk/5400mah-dji-phantom-2-compatible-inteligent-battery/)

The raw photographs from Peniup, WA (below) demonstrate the difference between photographs from differing heights, as well as the marker used to identify photo sets (Fig. 8a). Images from lower altitude (Fig. 8b) show the immediate structure of the subject, whilst those from a higher height (Figs 8c, 8d) show the subject in increasing landscape context. The images are then corrected to remove lens distortion (Fig. 9).

Fig. 8a. Raw image: marker

Fig. 9a. Corrected image: marker

Fig. 8b. Raw image: 10m

Fig. 9b. Corrected image: 10m

Fig. 8c. Raw image: 20m

Fig. 9c. Corrected image: 20m

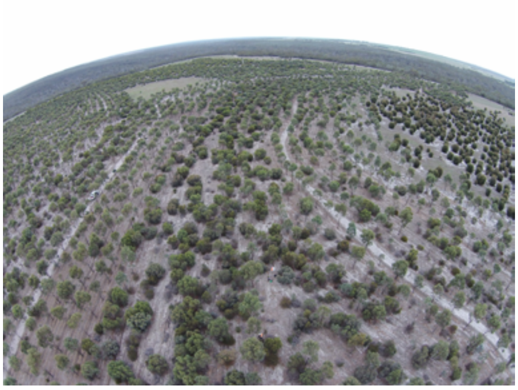

Fig. 8d. Raw image: 50m

Fig. 9d. Corrected image: 50m

Due to the limited gimbal axis of the Phantom 2, images often possess unwanted rotation. Fig. 10a demonstrates this with an image from Peniup, WA, taken at 20m altitude. Fig. 10b shows the result of correction to the true horizontal axis (blue line) in Photoshop, as estimated from the horizon.

Fig. 10a. Image pre-correction

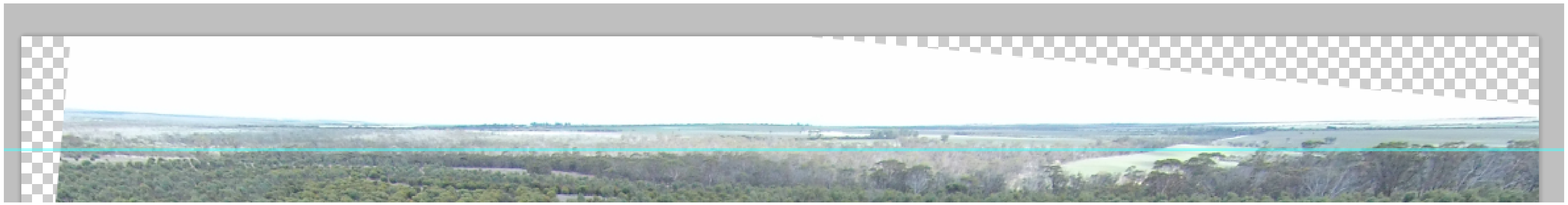

Fig. 10b. Image post-correction for rotation

The multi-line sampling aims to determine the effect of parallax by extracting samples from three points with increasing parallax on a 20m image from Peniup (Fig. 11). The same set of 20m Peniup images was also used for single-line analysis, using the centre sample.

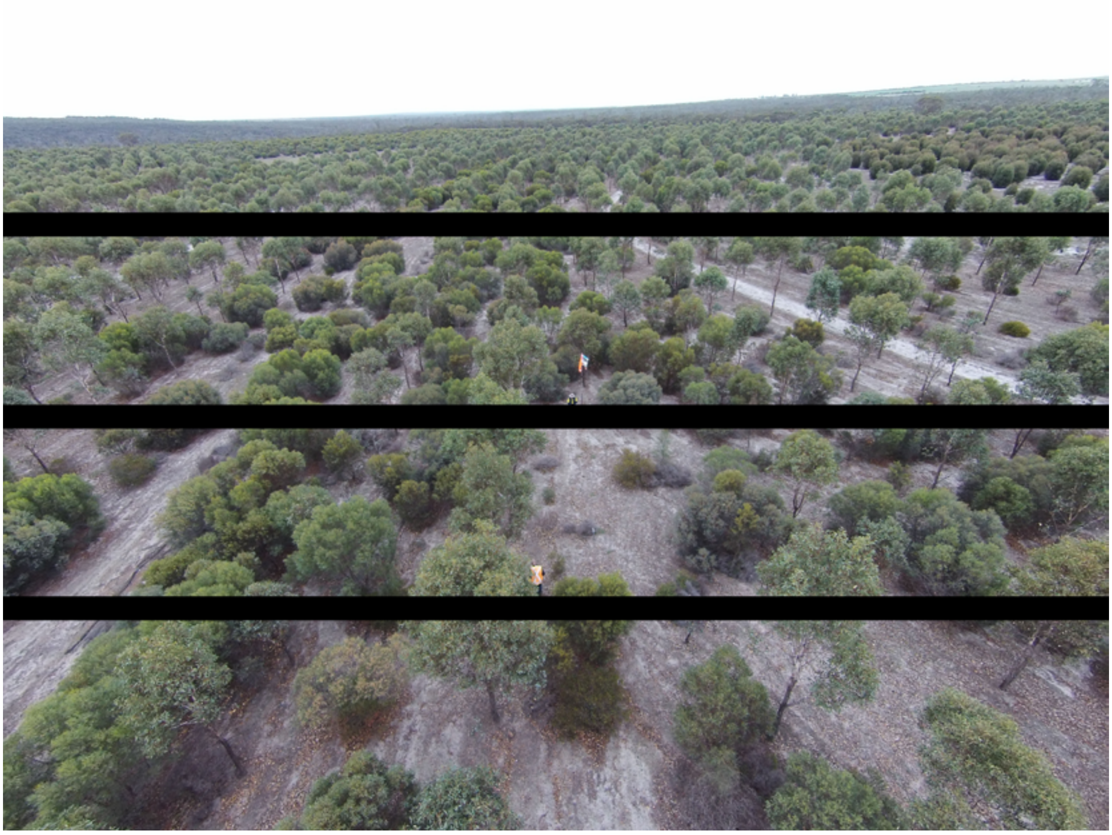

Fig. 11. Multi-line analysis example from a 20m altitude image at Peniup

Successful single-line analysis demonstrates the potential for UAS use in canopy cover measurement. Sites were grouped according to soil type and planting to examine their influence on percentage cover. This was only moderately successful, as there existed some overlap between groups in a number of the sample images. Site 109 is an obvious outlier, reflecting the random nature of the planting within the sites.

Table 5. Single-line analysis results

Site Group	Site	Total Pixels	Blacked Out	Remaining	Percent Cover
1	101	230400	161800	68600	70.2
1	106	230400	154350	76050	70.0
1	107	230400	116184	114216	49.6
2	109	230400	14250	216150	6.2
2	110	230400	66700	163700	28.9
2	111	230400	126750	103650	55.0

An example is shown of the black-out method of line analysis (Fig. 12) performed in Photoshop, using the 20m altitude image of site 101 at Peniup. If the lower edge of the sample is covered by canopy (Fig. 12a, b), the area is blocked off at full height (Fig. 12c). A count of the blacked out pixels divided by the total pixels gives the percentage coverage.

Fig. 12a. Line analysis sample

Fig. 12b. Line analysis sample with extent of canopy cover indicated

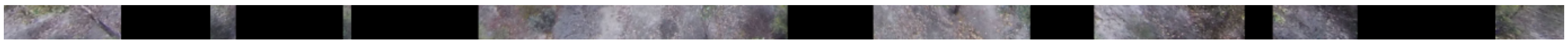

Fig. 12c. Line analysis with canopy cover blacked out ready for analysis

Line analysis was used to examine the effect of parallax on canopy cover, using the three sample points shown in Fig. 11 and the technique demonstrated in Fig. 12. Sites are grouped grouped according to soil type and planting, as in Table 5. As parallax increases (lower sample to upper sample in Fig. 11), the percentage cover also tends to increase (Table 6). This looks like it resolves into two groupings (Fig. 13), though this is not relevant as the groupings do not correspond to the site group.

Table 6. Multi-line analysis results

Site Group	Site	Total Pixels	LowerCount	MidCount	UpperCount	Lower %	Mid %	Upper%
1	101	377856	258956	237062	302252	68.5	62.7	80.0
1	106	115200	66900	71700	113850	58.1	62.2	98.8
1	107	115200	47350	57350	92100	41.1	49.8	79.9
2	109	115200	39000	56500	70000	33.9	49.0	60.8
2	110	115200	56750	71300	97450	49.3	61.9	84.6
2	111	115200	37950	59400	90050	32.9	51.6	78.2

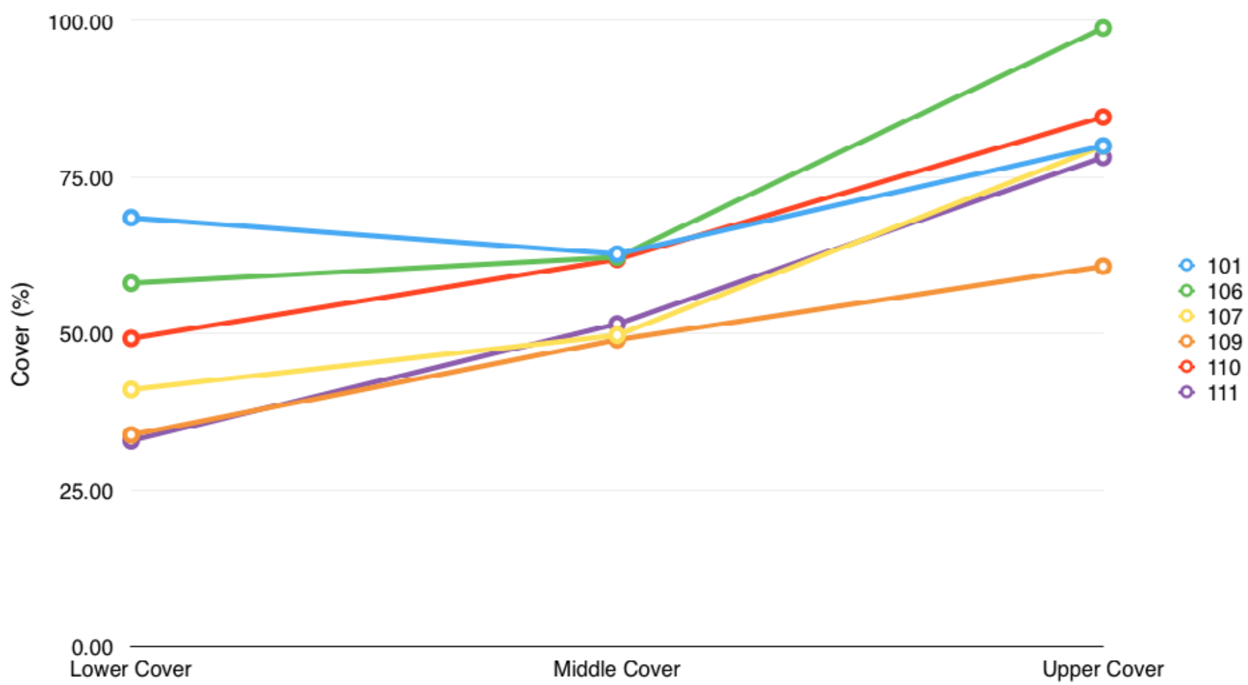

Fig. 13. Multi-line analysis percentage cover for different samples

Table 7. Overview of processing software and use

The following tables (7 to 9) summarise the findings of the use of the five post-capture data processing packages used. Of these, 123dCatch was suspended by the manufacturer during the study and its use was discontinued. Insight3D proved to be inferior to VisualSFM and usage was likewise discontinued. Table 7 introduces the packages, their purpose and the platforms on which they run. Tables 8 and 9 evaluate the use of the packages following the final two points identified in Chapter 4.1

	Software Package				
	Photoshop	**VisualSFM**	**Insight3D**	**Meshlab**	**123dCatch**
1 Purpose	• Preprocessing of images • Remove fisheye distortion • Normalise exposure	• Construction of point cloud from image sequence	• Construction of point cloud from image sequence • Manual reconstruction of 3D model assembly of individual planes	• Generation of 3D model from point cloud	• All in one package for image sequence to 3D model
2 Applicable platforms	• Computer	• Computer	• Computer	• Computer	• Computer • Mobile • Cloud

Table 8. Overview of ease of processing software use and performance

	Software Package				
	Photoshop	**VisualSFM**	**Insight3D**	**Meshlab**	**123dCatch**
3 Ease of loading images	• Very easy • Use batch processor • Set image conditions and let it process • Use Unix Terminal to move images around based on file extension	• Moderately easy • GUI is a bit odd at times • Can select multiple images to load at once	• Clumsy to use • Cannot select multiple images • Have to write a '.ifl' - image file list in order to load multiple images	• Moderately easy • GUI is a bit odd at times • File structure of requisite data difficult to learn	• Moderately easy on computer • Very easy on Mobile/ Cloud, but cannot load images from external source • Mobile no use to UAS • Can take a very long time to load as images are being uploaded • Maximum number of images allowed

(Continued)

	Photoshop	VisualSFM	Insight3D	Meshlab	123dCatch
4 Ease of performing task	• High, but familiarity already established	• Moderately easy • Complex options available, but easy to ignore • Excellent tutorial • GUI is a slim wrapper on commandline	• More complex than VisualSFM • Tutorial not nearly as good as VisualSFM • GUI is slim wrapper on commandline; might have been better to use commands • Commands have higher learning curve than GUI	• Awkward to navigate model/scene • Options for model generation are complex • Saving system isn't intuitive • Model saved separately from scene • High level of skill required for accurate/efficient use	• All tasks hidden from end user
5 Speed of execution	• Fast	• Far faster than expected • Under 5 minutes on all tasks presented • Progress constantly updated and obvious • Timestamps for everything, very useful	• Far faster than expected • Progress not as apparent as VisualSFM	• Highly variable on model generation parameters • Requires better understanding of the tessellation process to optimise speed/quality • Tutorial guide recommended model quality (still good) was fast to complete • Progress apparent, easy to cancel large tasks	• Slow • Low upload speed • Low processing speed • Progress not transparent

Table 9. Overview of processing software output and observations

	Software Package				
	Photoshop	**VisualSFM**	**Insight3D**	**Meshlab**	**123dCatch**
6 Output files	• Image files, familiar to most users • Advanced users can use Terminal commands (cp, mv) to organise files easily	• Confusing mix of base images, basic point cloud, and advanced point cloud • Able to generate multiple models from one set of photos if insufficient data • Difficult to swap between multiple generated models	• Reconstruction option no use for study as it cannot handle organic shapes • Point cloud output complicated to export	• Complicated saving system • Saves scene and models separately from different "save points" • Loss of data almost inevitable due to save process • Multiple file formats, including industry-standard .obj	• Model only • Multiple file formats including .obj • Linkage to other Autodesk modelling products
7 Observations	• Industry default • Powerful • Easy • Automated	• Superior point cloud generation to Insight 3D • Huge potential to expand point matching capability	• Extremely clumsy to use • Powerful, but can't really use that power due to GUI problems	• Powerful • Awkward to use • Poisson generation of model is not optimal • Attempts to make smooth surface, but conifer points are not smooth • Capability to write custom generation algorithms present, but highly complex	•Beta service suspended during mid project; unable to fully test

(Continued)

<table>
<tr><th></th><th>Photoshop</th><th>VisualSFM</th><th>Insight3D</th><th>Meshlab</th><th>123dCatch</th></tr>
<tr><td rowspan="2"></td><td></td><td></td><td></td><td>• Might work better with broadleaf trees as they have a softer shape
• Secondary, more user-friendly modelling package would be useful for manipulation
Free: Blender
Paid: Max, Maya
• Other packages have some degree of generation control
• Weren’t tested due to cost of said packages and time available</td><td></td></tr>
<tr><td></td><td colspan="2">• Pattern matching on natural noise was far better than expected
• Need to be careful not to allow the ISO to increase on the camera, as that would add artificial noise that doesn’t match between images
• Lower image size increased speed of results and quality of results
• Needed more points per area unit
• Needed more connective angles on the area
• Spiral flight path might be better than straight lines</td><td></td><td></td></tr>
</table>

In order to assess the accuracy of the 3D model generated in the VisualSFM/Meshlab workflow, a test run was performed using a box as the subject. Fig. 14 shows the dimensions of the box, which was used as the reference to compare with the generated 3D model.

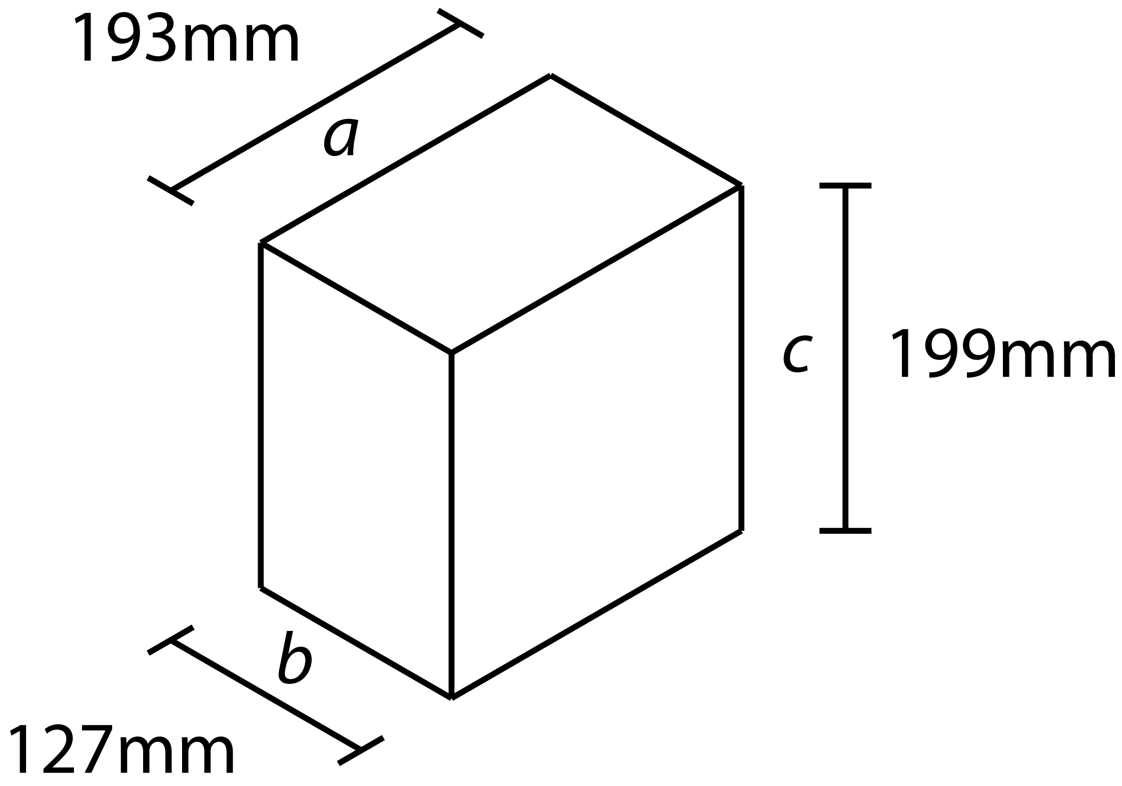

Fig. 14. Dimensions of the test box

The first step in the VisualSFM/Meshlab workflow was to use VisualSFM to create point clouds from a set of photographs. The images below are from the inital test run with the box, showing the screen display, with the match time to the right (Fig. 15), and the sparse point cloud which results from this process (Fig. 16). Also present in Fig. 16 are the calculated viewpoints which the photographs were taken from, which can seen in the upper half.

Fig. 15. VisualSFM interface showing source images

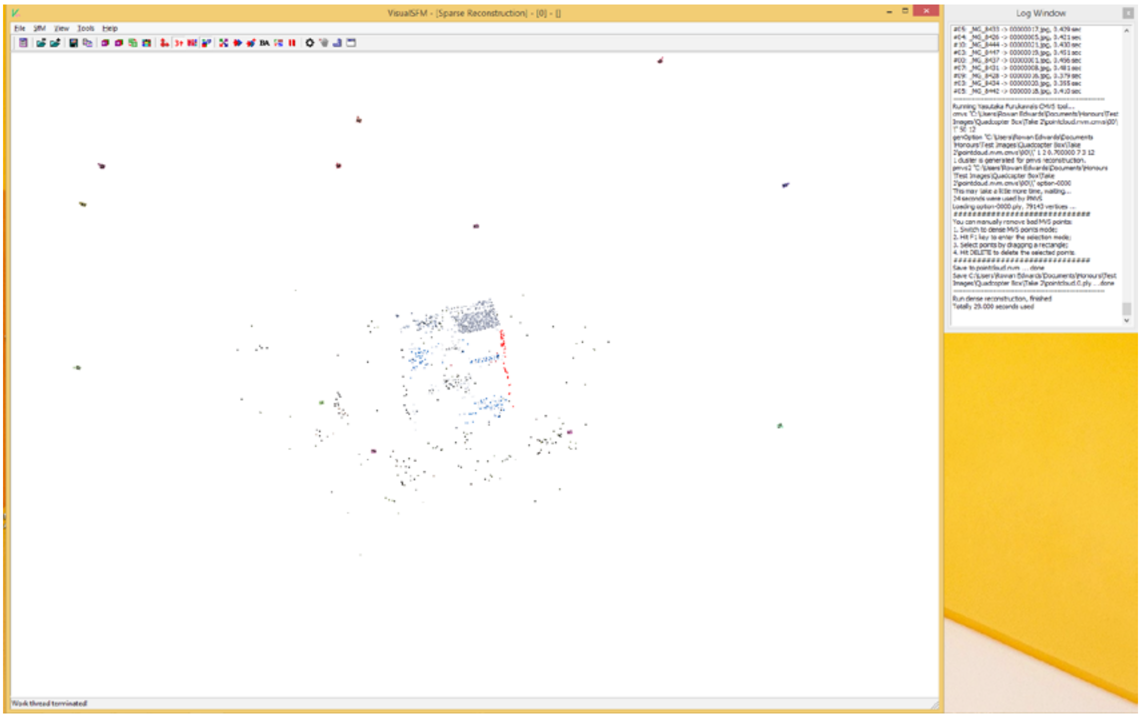

Fig. 16. VisualSFM interface showing generated sparse point cloud

The next stage of the process was to generate a dense point cloud in VisualSFM, which needed to be exported to Meshlab in order to be viewed (Fig. 17). A Poisson reconstruction algorithm was then used on the point cloud to generate the surface of the model as a mesh of triangular surfaces (Fig. 18). The model was then cleaned to remove the distortion that occurred at the model edge, sealed to form an enclosed shape, and then textured by using the adjusted images from VisualSFM (Fig. 19). The sealed underside does not have a texture, as it is not present in the original point matching.

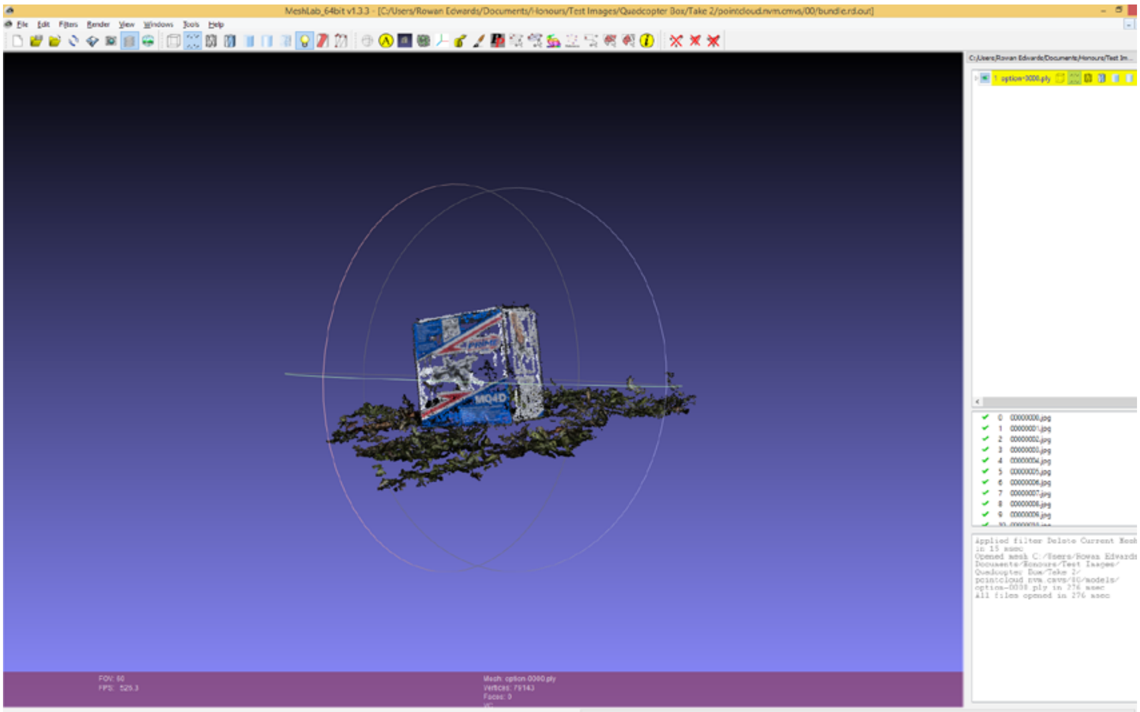

Fig. 17. Meshlab interface showing dense point cloud

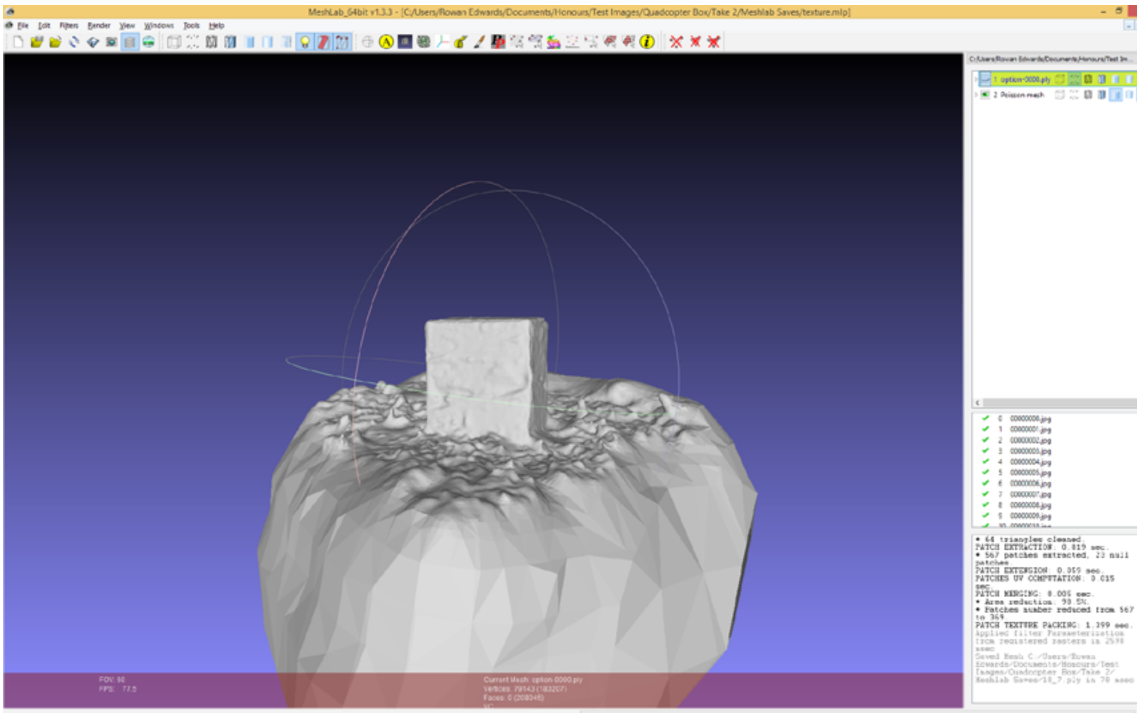

Fig. 18. Meshlab interface showing Poisson mesh reconstruction

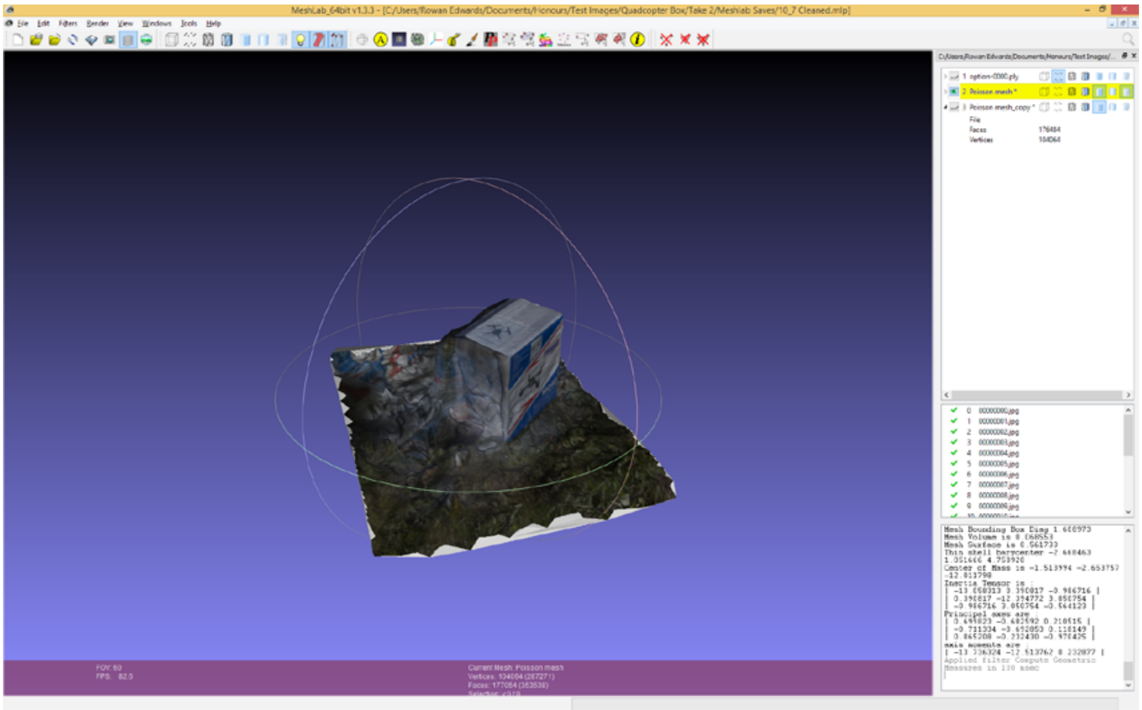

Fig. 19. Meshlab interface showing cleaned, sealed and textured mesh

The model generated (Fig. 19) was then compared to the measured dimensions (Fig. 14). The results are displayed for each dimension of the box in Tables 10, 11 and 12. These tables show the measured value from the model, in arbitrary units, and the ratio of that measurement to the actual measurement from Fig. 14.

Table 10. Measured values (dimension a)

Value	Ratio
0.250939	0.01300202
0.260895	0.01351788
0.253392	0.01312912
0.251937	0.01305373

Table 11. Measured values (dimension b)

Value	Ratio
0.161674	0.01296646
0.164328	0.01293921
0.164296	0.01293669
0.166952	0.01314583

Table 12. Measured values (dimension c)

Value	Ratio
0.258694	0.01299970
0.246998	0.01241196
0.261514	0.01314141
0.261531	0.01314226

The results of tables 10 to 12 were then analysed by creating eight equally sized categories, 0 to 7 (Table 13), which were then applied to every ratio (Table 14). The resulting distribution appears to be normally distributed (Fig. 20), though it should be noted that the sample size is not particularly large (n=12). For the correct determination of the required sample size for a level of accuracy, the sample size needs to be greatly increased. Table 15 shows the level of accuracy which the distribution of ratios provided, which far exceeds initial expectation.

Table 13. Definition of ratio class ranges

Class	Min ratio	Max ratio
0	0.01241196	0.01256994
1	0.01256995	0.01272793
2	0.01272794	0.01288591
3	0.01288592	0.01304390
4	0.01304391	0.01320189
5	0.01320190	0.01335988
6	0.01335989	0.01351787
7	0.01351788	0.01367585

Table 14. Classification of ratios

Dimension	Ratio	Classification
a1	0.01300202	3
a2	0.01351788	7
a3	0.01312912	4
a4	0.01305373	4
b1	0.01296646	3
b2	0.01293921	3
b3	0.01293669	3
b4	0.01314583	4
c1	0.01299970	3
c2	0.01241196	0
c3	0.01314141	4
c4	0.01314226	4

Table 15. Analysis of ratio distribution

Range	0.00110592
Standard deviation	0.00025072
Coefficient of variation	1.92%

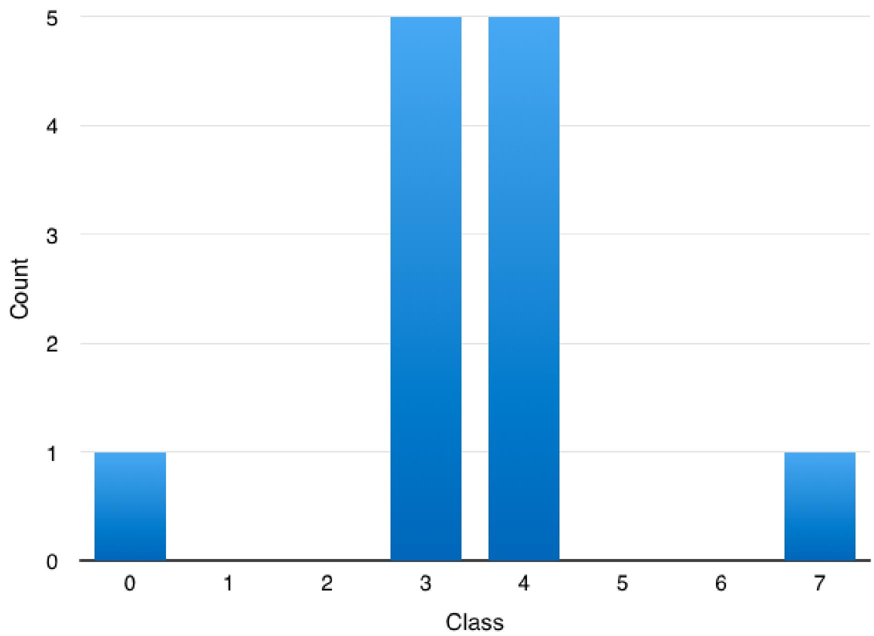

Fig. 20. Distribution of classes of model:actual dimension

The culmination of this study was to attempt the reconstruction of a 3D model of an arboreal area (Dairy Farmer's Hill). The main restriction of this attempt was the lack of sufficient data to enable VisualSFM to create a full construction, though the process did produce some usable results. The resulting point cloud clearly shows the terrain undulation and the distinction between the ground and canopy layers (Fig. 21). Fig. 22 shows the area from approximately the same viewpoint as Fig. 21b, to provide a visual comparison. See Chapter 6.4.3 for the discussion on this topic.

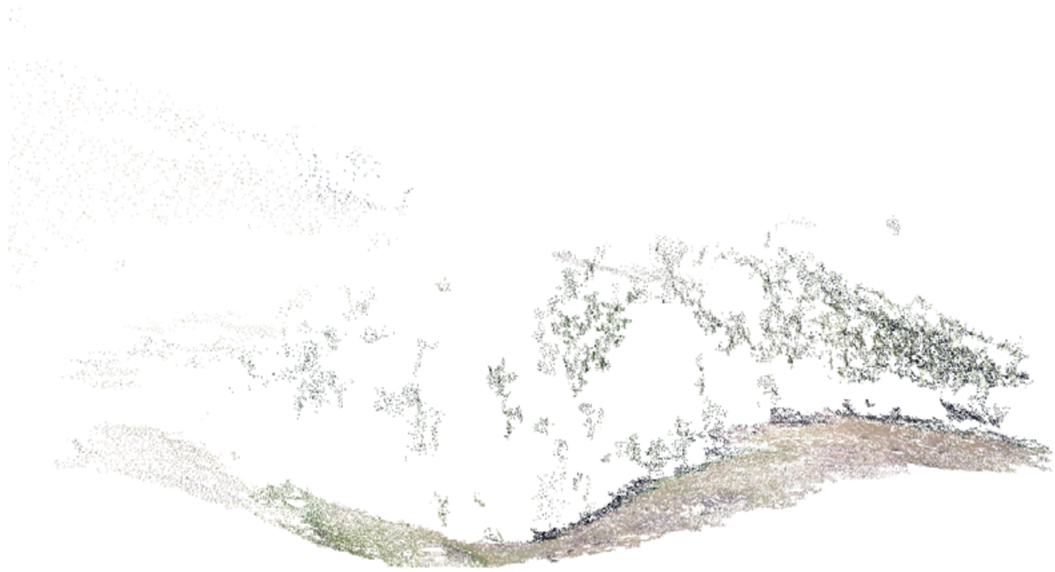

Fig. 21a. Dairy Farmer's Hill point cloud output showing the high density of match points on the ground, compared the comparatively sparse number of match points in the canopy

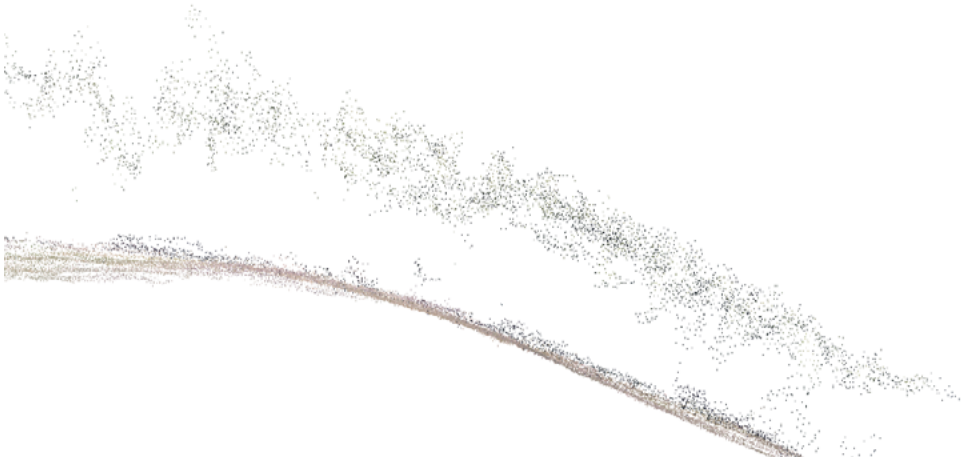

Fig. 21b. Dairy Farmer's Hill point cloud output detail of side perspective. The ground layer is visible as the more solid line at the bottom, whilst the canopy is shown as the more dispersed upper layer

Fig. 22. Dairy Farmer's Hill photograph

The images below show the eucalyptus tree on the ANU campus which was examined for suspected damage in the branch forks. Fig. 23a shows the unadjusted image, in which damage can be seen, but the extent of damage is obscured. Adjustment of the image in Photoshop reveals the true extent of the damage (Fig. 23b), the most noteworthy of which are the two areas in the upper image where the damage has created cavities inside the fork. This amount of postprocessing would be much harder to achieve in .jpg format as opposed to the .RAW format used here, mainly due to the data lost during the .jpg compression.

The UAS is approximately 10cm away from the right hand branch at the closest point, demonstrating the ability of the UAS to navigate the canopy with a moderately experienced operator.

Fig. 23a. Tree inspection .RAW image, pre-adjustment

Fig. 23b. Tree inspection .RAW image, post-adjustment

6. Analysis & Discussion

6.1 Flight Testing

6.1.1 Flying

Flying the UAS was overall an easy skill to acquire since the controls are intuitive and simple. However the lack of fine-tuned control over movement was an issue when attempting to fly in confined areas, due to the large dead zone on the joystick (Table 1). The resulting movement of the UAS once the dead zone was passed was simply too large to enable minute movement. This has a simple fix; scale down the movement parameters (Fig. 24), though this is not possible on the Phantom due to the closed software and design of the controller. As the Phantom was able to move at greater speed than the guide suggested possible, this would not have any significant effect on high-speed performance. If more room is needed for movement, reducing the dead zone by around half would provide more space for control.

The lack of fine-tune control was exacerbated by the smoothing algorithms present in the flight control, as the UAS would coast to a stop after the controls were released. Whilst this smoothness is an advantage when filming, the slow and smooth stop is not ideal for survey work, which would benefit from a more aggressive algorithm. The ideal solution would be a mode in which the UAS is able to centre itself over the point where the controls were released, as well as a 'lock' function which locks specific axis of movement. If a full autopilot and ground station were available, this would be much easier to do with that functionality than on a joystick/controller.

Most image capture was done by looking through the FPV feature of the UAS, therefore UAS position relative to the operator was not as imperative as it might have otherwise been. However, having taken your eyes off the UAS it was often difficult to visually re-acquire. The directional compass in the app was the most beneficial solution to this problem, as it provided an axis upon which to look. It could potentially be enhanced by making it three-dimensional, using the relative positions of the handheld device and UAS, coupled with the inertial sensor in the handheld. This would enhance the current system by allowing the operator to find the height of the UAS as well as the direction from the operator's current position.

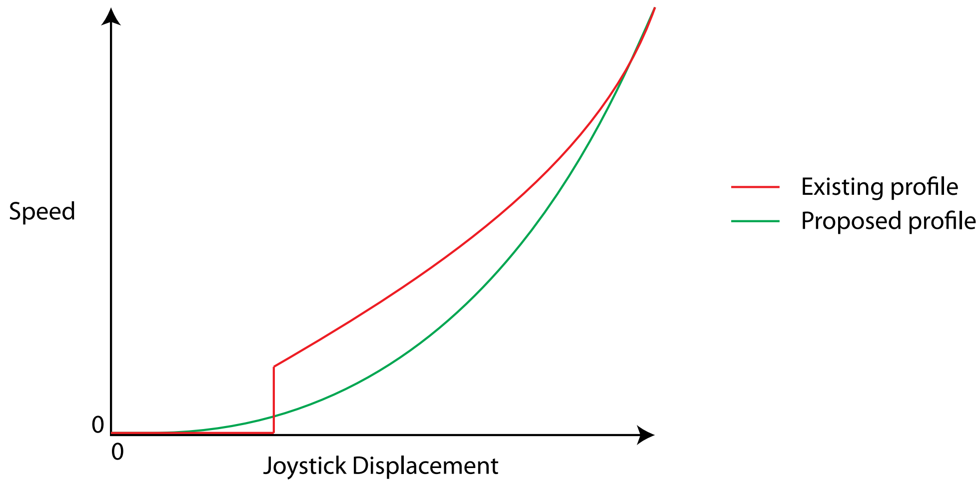

Fig. 24. Joystick response curves

One major issue which arose when using FPV mode was the incidence of bird strikes. Whilst published literature suggests that bird attacks will happen mainly to fixed wing craft, the quadcopter UAS used in this experiment was twice attacked by small hawks. Further investigation has revealed other occurrences of this happening, primarily by birds of prey. A notable exception to this rule is, unsurprisingly, the Australian Magpie, *Cracticus tibicen*. The attacks experienced in this study were not hard to avoid; by simply descending and staying near the ground the birds lost interest and flew away. However a key point to note is not to exceed the maximum descent speed in avoiding these attacks, as that may trigger a stall and subsequent crash (see Fig. 25).

6.1.2 Maintenance

The UAS battery recharge rate was far faster than expected, both when charging from mains and from a car battery (Table 2). With a flight time limit of 30 minutes, this fast recharge was essential for continued use when surveying Peniup. It was less useful when flying Dairy Farmer's Hill, as the flights here were back to back as opposed to the single short flights in Peniup. This gave no opportunity to make the trip back to the vehicle to put a battery on charge, nor was there a period of fieldwork between flights to give the battery more time to charge.

Another issue with battery life was the lack of fidelity on the charge indicator of the WiFi extender. When this indicator turned orange/red to show low battery, the battery expired only minutes after. As this unit cannot have the battery itself replaced in the field, it must be charged via a USB cable. Fortunately, the base station vehicle was equipped with USB ports, and the required charge time until use was very low. Still, it was an unwelcome thing to discover whilst out performing survey flights.

Travelling on an airline with the UAS presented another set of problems. The Canberra Airport staff allowed the UAS case as carry on luggage, which made life simpler as the batteries are required carry on due to the lithium content (restrictions on lithium content and the number of batteries will be discussed Chapter 6.1.4.) However, when returning via Perth Airport, the case was not allowed as carry on due to the content. No information was obtained as to what particular aspect determined this, only that it was a UAS and must be placed in hold luggage. Thankfully the case used is highly durable, so this was not an issue in that regard. The main issue was that it resulted in one member needing to postpone their flight in order to stay with the case.

Though the case is durable it has one design flaw: it is not possible to store the UAS with the prop guards attached. Once the UAS has been assembled, it must remain out of the case until disassembly.

6.1.3 Software

The software was a critically weak area of the UAS. There was no functioning autopilot, despite assurances that it existed and much testing over multiple platforms. This meant that none of the autopilot features could be used, which limited the capabilities and ability to program set sequences (such as the 10m, 20m and 50m sequence used in Peniup). This limited flights to manual mode, so the effect of different flight paths could not be reliably investigated.

The software was also lacking features on the mobile app. In particular, a numerical readout for the camera pitch would been extremely helpful in providing replicable photo points (Table 3). Another useful feature would be the ability to slave a second mobile device as a viewer, to allow a second person to see what the UAS is seeing. This became particularly evident when performing the tree inspection, when the pilot had to give the mobile device to the inspectors so that they could guide the camera into position.

The stability of the mobile app is also lacking. The black bar effect persisted through three software updates and the app itself is prone to the occasional silent failure, requiring a restart of the app. As this is a silent error, no information can be gained as to the cause or a potential solution by the user.

6.1.4 Hardware

The hardware too is prone to occasional problems. The lack of a camera trigger on the controller was a key failing that stood out. The need to switch to the mobile app to take photos became irritating, mainly as an interruption to the flow of flying. A finger trigger would streamline the entire process and remove the need to take hands off the controller.

A key failing of the UAS itself was a condition that presented itself many times over the course of the study, often resulting in a crash (Table 4). As the props are directly vertical, this creates an area of downward moving air directly below the rotors. If the UAS should descend into this pocket of downward moving air at greater than a critical rate, it will act as a downdraught. Any attempt to increase motor power to lift out simply creates a larger downdraught, exacerbating the problem (see Fig. 25). This is the situation which caused the feedback loop crashes.

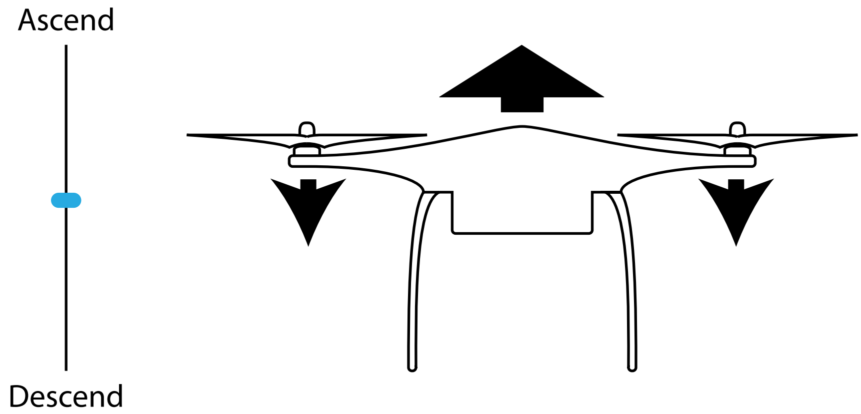

Fig. 25a. Initial hovering state, the thrust from the props to keep the UAS in the air creates downdraughts from each prop

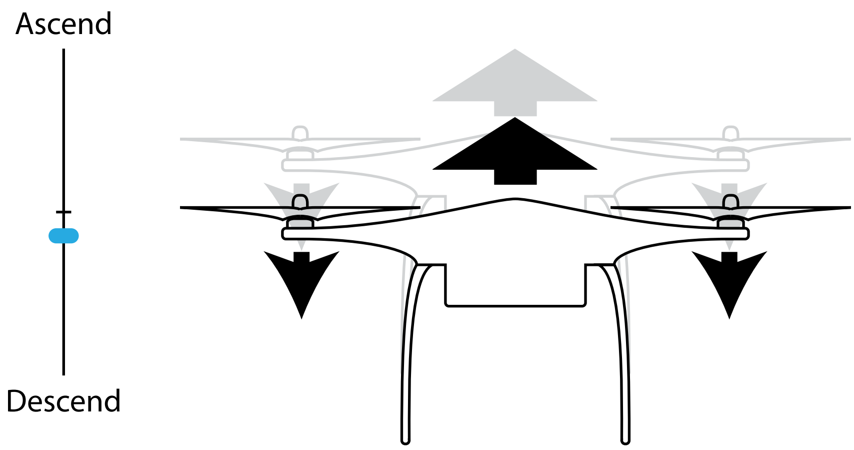

Fig. 25b. If the descent speed of the UAS exceeds a critical value, the prop enters the downdraught causing descent speed to increase

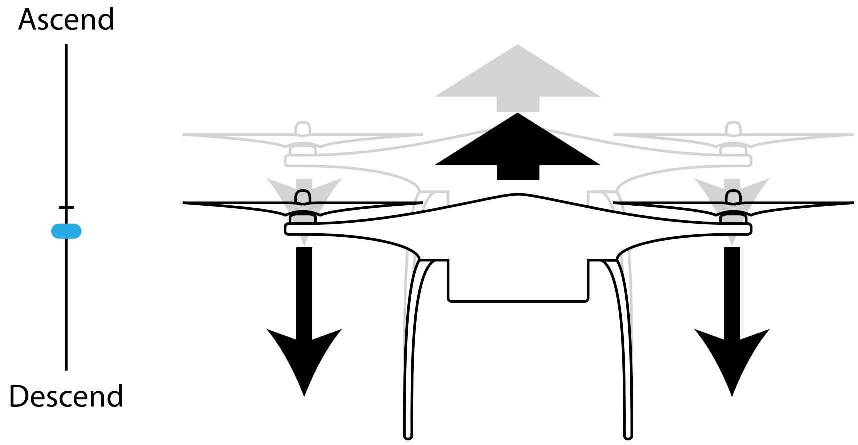

Fig. 25c. This causes the UAS to increase power, creating a larger downdraught

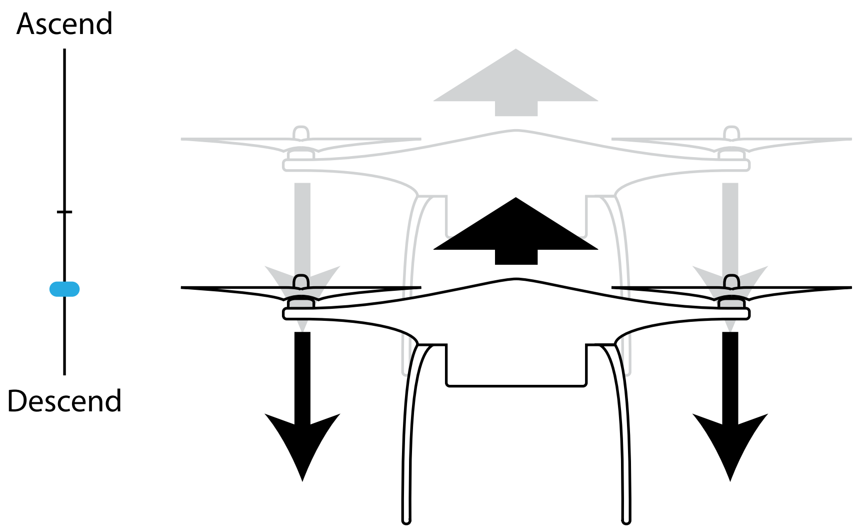

Fig. 25d. This then causes the UAS to increase power, creating a larger downdraught

The resulting crash from this situation did not cause any significant damage during testing. One crash was landed in a bush, another landed directly on the ground. The bush crash resulted in a destroyed rotor blade due to a piece of plant material passing inside the blade radius whilst still operational. The ground crash successfully dissipated the energy by disconnecting components. The battery and gimbal were thrown around 1m from the point of impact, a significant energy expenditure especially when considering the strength of the battery clip. The components were re-attached in the field, taking around 5 minutes to check all connections and power. The UAS was then launched again and did not suffer any negative effects.

Blade breakages are not a significant problem to general maintenance. Spare blades can be carried around and replaced in the field in case of any damage. A spare set of blades should be carried at all times as they are very easy to damage, especially the very thin outer third. The ease of damage does not, however, result in a significantly increased operating cost. Two blades cost $19AUD from the DJI store, though some users have used 3D printed rotor blades. These do currently take a significant amount of skill to finish and balance, though with the speed of advancement in 3D printing technology this may well change. The ability to print blades and replacement parts on demand would be a significant bonus to remote sites, reducing the need to rely on expensive and slow shipping.

Most severe of all technological problems was the battery life span. The life span dominated all factors: how fast to fly, how long you could fly for, how high you could fly, how much weight could be carried, in turn limiting the amount of data that could be gathered per flight. This limitation was further exacerbated by the premature voltage drop experienced, which caused a crash. Lithium batteries are used for their stable discharge profile as much as for their capability to store large amounts of power (see Fig. 7). When this plateau ends, the voltage reading takes a sharp drop. The DJI software is designed to monitor the output and provide two warnings on low battery. The first warning is triggered at 30% battery life, the second at 15%. On the second warning, it will trigger a fail-safe, which brings the UAS straight down to land. There is a third fail-safe which monitors the voltage reading and triggers the same landing procedure when a threshold is crossed. In an ideal situation, this would never trigger, as the first two warnings should be reached first. In one flight, however, this warning was triggered 10 seconds after the first low voltage warning, whilst the battery readout was at 28% capacity according to the mobile app. This resulted in the fail-safe descent triggering, which unfortunately exceeded the design parameters for the maximum descent speed, in turn triggering the feedback loop, resulting in a crash.

The lack of power contained in one battery can be mitigated by using multiple batteries, as was done in this study. However there are problems when transporting large banks of batteries by air. International regulations are in place which limit the total amount of lithium that a passenger can take on-board, which in turn limits the number of batteries that can be brought on. There are ways which could be used to safely transport large numbers safely: storing the batteries in isolation from each other in fire-retardant hard containers would be far safer, as any failure in one battery would be prevented from reaching others. This would also remove the risk of short circuit, a particular potential issue with UAS batteries, as they often have the short circuit protection that most lithium batteries possess removed. This is due to the need to shed weight, and the need for the batteries to provide a comparatively high voltage output, which cannot be as easily achieved when the short circuit protection is in place. Airlines also have restrictions on whether this type of battery can be transported, but these seem to be largely outdated. This was not an issue with the DJI battery as they do possess the capability to detect short circuits, upon which the battery shuts down.

An issue, which was in appearance most when flying at the National Arboretum, was the WiFi connectivity. This would frequently drop out, the cause of which is unknown. It is suspected that the undulations played a part, though the signal was sometimes lost when there was direct line of sight between the UAS and ground station. Distance from one to the other was not a factor, as it was well within the tolerance and distances used in Peniup. It is possible that, being high up, there was a measure of radio interference at the National Arboretum which was not present in other sites, though the equipment and knowledge required to measure this was not present. There are no known high strength emitters present near the sample site, especially on the frequency used (2.4Ghz range). This issue could potentially be resolved by the use of different WiFi specifications, as well as increasing the transmission strength, which would provide the ability to operate in more cluttered environments, both in radio space and physical obstructions. Any increase in power needs to fall within the legal requirements, as signals over a certain strength in the 2.4Ghz band will cause interference with other applications and may be subject to restrictions such as the requirement for a radio operator's license. This is undesirable, as it increases the cost and training required to be able to operate the UAS.

A probable secondary cause of WiFi dropout was the overload of the UAS CPU, particularly evident when saving .RAW images. Without access to the core CPU and diagnostics package, this is impossible to verify. It is hypothesised that in the situation of saving a .RAW file, the CPU cannot handle the flying, saving, and live video transmission simultaneously, thus the stream gets dropped to prioritise cycles for the two key tasks. This theory is supported by repeatedly saving a .RAW image and observing the subsequent drop out of WiFi communications.

Another technological issue with the UAS is the accuracy of the GPS module. Whilst not a failing, as there exist alternatives to the use of the GPS, this did limit the scope of the UAS in some areas. Such inaccuracy is typical of mobile GPS solutions which do not have access to a triangulated base stations system, at some times reaching errors of 2m, with greater spikes observed. At this point, physical interference was not considered an issue and the UAS was in contact with 12 satellites, so the problem was not in the lack of transmission but rather in the inherent GPS inaccuracy. This could be resolved by the use of a triangulated base station, which typically increases accuracy to within a few cm, but requires skill, power, and time to set up. The power of such a solution would need to increase depending on the density of the surroundings, making this a difficult solution for mobile surveys. However, commercial forestry plantings often have triangulated GPS on site to monitor ground equipment, which could be leveraged for use by any UAS in the area at no extra cost.

A further advancement in this area is the recent development of a technique which can use the same inaccuracies that cause GPS drift to resolve the signal and provide a far more accurate reading. Designed for use on mobile phones, this solution has potential to be utilised on a UAS, especially a more modern one with a greater CPU capacity. The CPU capacity and use of the Phantom are unknown, however it is known that the 2nd generation PixHawk used by 3DR uses ~40% of available CPU when running ArduPilot.

An existing alternative would be the use of an inertial measurement unit, or IMU. This is capable of tracking the movement of the UAS from the point where it is switched on, so whilst it is able to tell exactly how far the UAS has travelled and where it is currently, that information is only useful when considered relative to the starting position. If the starting position is inaccurate, the data set gathered will also be exactly as inaccurate. If the launch site were triangulated via GPS this could be negated, and there exist several vehicle mounted GPS units. As proven during this study, it is possible to take off from and land in the back of a ute, meaning that if the ute were to know its precise GPS coordinates, these could be offset for the takeoff position and then used to place a UAS with an IMU in a spatial reference frame.

Whilst the UAS may be in a spatial reference frame, there is still the need to place any resulting imagery or model in a reference frame. During the study, a flag pole was used to attempt to mark a known reference point. However, many factors impacted upon the usefulness of this marker. There was a tendency for it to respond to the wind which often ended up with the marker in line with the pole, rendering it almost invisible. Similarly, the highly reflective surface used with the intent to reflect the sun, simply reflected the surroundings and merged in with the canopy. The most useful was a stiff-backed shape with a high-vis jacket on, though this still had a tendency to follow the wind. An improvement on this would be to construct a rigid cross constructed of a material similar to hi-vis jackets (Fig. 26).

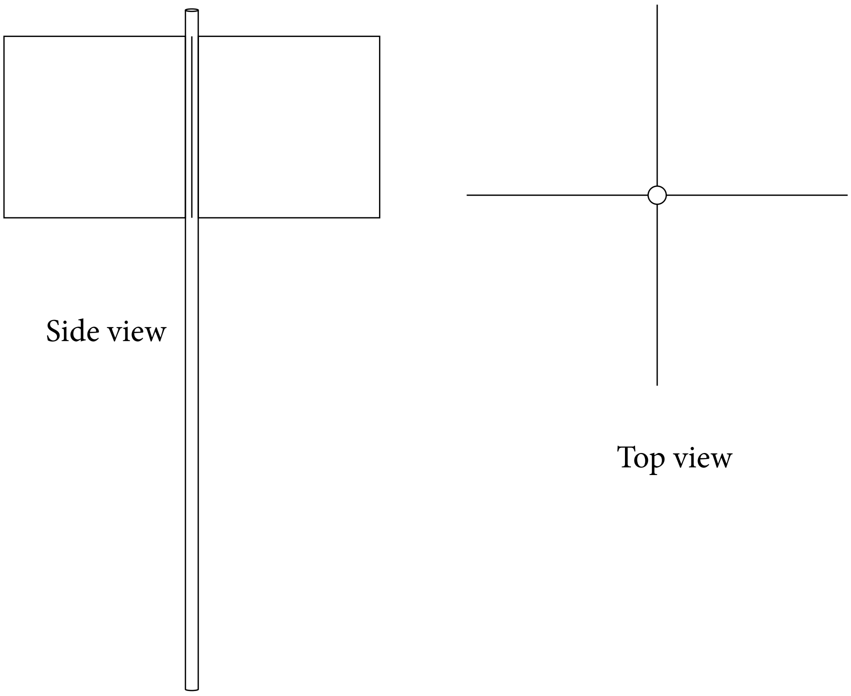

Fig. 26. The proposed hi-vis marker shape

6.1.5 Alternatives

The primary alternative UAS to the DJI Phantoms is 3DR's IRIS, featuring the PixHawk. Using this would change the software available and in turn modify the parameters of what is and isn't possible. While 3DRobotics are a new entry to the end-user market, they have much experience in UASs. The on-board controller for their new UAS uses the PixHawk, an electronics package also designed at 3DRobotics which has been used in many successful UASs. The key difference between the offerings of DJI and 3DRobotics is the the level of customisation that each allows. While DJI's UAS is entirely self contained, 3DRobotics built their name by providing the parts to customise other craft to become UASs. This is reflected in the PixHawk, which has the ability to use the open source ArduPilot software modules, as well as anything else it has the capacity for, to run the UAS. This allows complete customisation of all modules, as well as the ability to attach new hardware to the UAS and configure it accordingly.

The second benefit of using a PixHawk-based UAS is the fully functioning autopilot MissionPlanner, which again is open source. This autopilot allows completely autonomous control of the UAS, including of any upgrades or new hardware added to the UAS. This autopilot can be coupled with a programmable controller, enabling a far greater customisation of controls and responses, such as reducing the dead zone, or a button to trigger a camera. However, all this customisation comes at a cost: greater customisation means a higher skill level is required to operate the UAS efficiently. This can be overcome by 'condensing' the modifications back to an end-user solution, a task made easier by the PixHawk modular design. As mentioned in 6.1.3, the second generation PixHawk has plenty of space for upgrades, and the third generation model is expected to have even more.

6.2 Still Image Acquisition and Interpretation

6.2.1 Image rotation

Though care was taken to keep the camera as stable as possible, images still had a degree of rotation in them (Fig. 10). Without a camera readout to display the intended angle of the gimbal, it is impossible to truly understand the amount of rotation in that aspect. As the UAS can hover and rotate on the spot, it is also impossible to determine the total rotation with regard to that axis without the use of an IMU. This leaves the side to side tilt as the factor which can be controlled.

This degree of rotation was managed by bringing the UAS to a standstill at each photo point, as well as monitoring wind conditions to avoid gusts. However, as can be seen in the example image, this did not eliminate the effect. The residual wind was enough to create a significant amount of error, in this case 7°. This has severe implications for the use of SLAM, as there are boundaries beyond which the algorithm is likely to cause error as it attempts to compensate. Whilst an aircraft might be able to cope with an effective error of 5m due to the height flown, this would represent a great portion of the image given the low height of the UAS.

The even greater issue when dealing with rotation is the lack of spatial information present in the photo itself. If the image carried details as to the angle it was taken, the height etc., it might open other avenues for image processing. This data would be best stored in the EXIF tags of the image.

6.2.2 Canopy cover line analysis

Canopy cover line analysis is a simple method for measuring the canopy cover from a still image, usually taken in orthogonal projection. The initial test was to see if it could indeed be performed. To do this, a sample was taken from rotationally corrected images (such as seen in Fig. 11) at the height of the operator's head in a 20m height image (example given in Fig. 12a, which is the sample from the middle mask of Fig. 11). If the bottom of the sample was under canopy cover, it was blocked off in black (Figs 12b, c). The total blacked out pixels were subtracted from the total pixels present, to give a standard percentage figure which can be used in existing analysis (Table 5).

The problem with the images from the Phantom is that there is a degree of parallax present due to the angle at which they were taken. Any residual error from the fisheye lens correction is assumed to be constant across images and therefore not a variable. In order to test this, three samples were taken from each image, starting at 400 pixels above the lowest point, and 300 pixels apart from one another (Fig. 11). These samples were then evaluated to give the information to establish the percentage cover at each sample point (Table 6), which can be seen graphed in Fig. 13. The most important fact is that, although the samples were from two different plantings, the divide in the results crosses that boundary. The point to take away from this graph is the trend of increasing measured canopy closure from the points further away.

With a larger sample set of images, as well as more precise data on the exact height above ground level, angle of the camera etc., it would likely be possible to establish a metric to normalise this data. However, as outlined in 2.1.3, this data is not present in either the UAS or the images. This is further compounded by the artificial nature of the site itself. As can be seen clearly in Fig. 9d, the site is, in most areas, an artificial planting. Whilst the interior of the marked plots can be considered random, should any image cross between plantings it would have a profound impact on the coverage figures. In order to establish a metric, such boundaries would need to be avoided in the interest of keeping the sample as representationally random as possible.

6.3 Image Processing

6.3.1 Photoshop

Still image manipulation for this project was performed in Adobe Photoshop. This is the industry heavyweight for image manipulation, which increases the chance that the user has a degree of familiarity with the package. It is also possible to use Adobe Lightroom, though the options once you leave the Adobe Suite are very limited. Nothing was found that could rival the abilities of either of these applications.

Photoshop is a powerful software package which contains three key features utilised. The first is the excellent .RAW format adjustment. Whilst this is possible to duplicate manually, the Adobe .RAW manager simplified the task of correcting under- and over-exposure greatly. Secondly, Photoshop possesses the ability to correct the distortion introduced by the use of a fisheye lens. This is imperative to all further steps of photo interpretation, as it normalises the metrics. Thirdly, all steps in Photoshop can be automated to speed up the process. This allows the batch processing of images, saving time and effort in performing the same tasks over and over again.

6.3.2 Preprocessing

The first step in the processing of images is to correct the lens distortion introduced by the use of the Phantom's fisheye lens. This profile is included in modern versions of Photoshop, though it can also be downloaded from many places on the internet. The results of this process are impressive (see Fig. 8 compared to Fig. 9), and although an hour was spent attempting to improve on this process manually, no improvements were able to be measured.

To further aid the processing of images, it is possible to automate these steps with the use of Photoshop's built in automation system. When provided with a file directory and a lens calibration profile, the computer will cycle through the images applying the change. Whilst this cannot be run as a background task, it is a reasonably fast task to complete and was by far from the most intensive task of this project. One set of images did provide a slight hitch to this process, which was when the Phantom took both .RAW and .jpg images at Dairy Farmer's Hill. To avoid processing the same image in both .RAW and .jpg, it was necessary to separate them, a tiresome task to do by hand. This was solved by using system terminal commands (mv on the Unix system used) to move everything with a *.jpg file name to one folder, leaving the .RAW images alone to be processed. Whilst Photoshop itself is an intensive piece of software, requiring a decent computer to run quickly, it is one of the least intensive parts of the interpretation workflow.

6.4 3D Model Generation

6.4.1 Generation technique

There are two potential candidate methods which can be used to turn a series of images into a three -dimensional model: SIFT and SLAM. The key difference between the two is in the information that each requires to complete successfully. SLAM is far less tolerant of error and inaccuracy than SIFT is in a number of key areas.

Firstly, as SLAM is based on edge-to-edge matching, the constituent images must be of the same orientation. As shown by the flight testing at Peniup, this is very difficult to achieve in real-world flying. Secondly, SLAM relies on accurate positional location data on each image to correct any uncertainty from image-based mapping. This secondary quality guarantee is impossible to use in the current technology as the GPS accuracy simply is not present. The 1-2m variance in GPS reported position represents such a large percentage of the camera area that it has the potential to cause more error than it solves. Thirdly, SLAM requires a fixed-pattern flight in order to acquire the correct sequence of images, with the correct minimum overlap between (Fig. 1). Whilst this would be trivial with an autopilot, at no stage in this study has the autopilot worked. The requirements of flying this path manually, very slowly, whilst dealing with the low sensitivity of the controller, as well as having to react to wind gusts, put this task well outside the capability of any moderately skilled pilot.

In contrast, SIFT is designed to take in far more noisy data and even uses that noise to enhance accuracy, particularly in the case of positional uncertainty. This immediately makes it far more promising for use with UASs, and further investigation revealed existing uses of UAS/SIFT technology in archaeology to map excavation sites. With these facts in mind, it was chosen to use SIFT as the point cloud generation methodology for this study.

6.4.2 Initial point cloud generation testing

The first point cloud test was interesting. The primary discovery was that the software far exceeded expectations when dealing with random noise, such as concrete or grass. It had been expected that the algorithm would match images based on the edges of the box and its surface detail, and that it would then have difficulty with processing the randomness of the surrounding environment. Instead, the software had difficulty with the majority of the box, as it cannot 'cluster' matched points to the edges. The text on the box, even at very small sizes, was a hotspot for matching as expected. Surprisingly, the best coverage in terms of matches/square unit was achieved in the random noise areas.

A summary of the three packages utilised for this test, VisualSFM, Insight3D and 123dCatch can be viewed on Tables 7, 8 and 9. Due to the withdrawal of the cloud service for 123dCatch during this phase of the study, it was evaluated on the information present up to that point. The key facts were that there was limited control over facets of the generation compared to the other packages considered, and the timeframe for completing a model was far, far greater (around half of attempts timed out and failed to complete). The limit on the number of photographs that could be used (70 for the desktop version, 40 for the mobile version) is a significant drawback to the use of this package, especially when the primary limitation of the SIFT algorithm from the other packages was deemed to be an insufficient number of photo points. In all, though the package was simple to use, it was unable to scale to the level demanded of the study, and the program was deemed unsuitable. This left VisualSFM and Insight3D to be evaluated.

Overall, the simple point cloud results were comparable between these two programs. However, there exist several differences in ease of use. In particular, the graphical user interface, or GUI, for VisualSFM is far easier to use than that of Insight3D. This is particularly true for the loading of images into the program, as Insight3D does not even have the ability to load multiple images at once from the system window. Instead, it requires a file to be written containing the list of images. This suggests that Insight3D's

GUI is a very slim wrapper, or front, to a commandline application.

The primary factor which decided which application to select for continued use was the discovery of an excellent tutorial, which ran the user through the basics of taking the photos, loading them into VisualSFM (Fig. 15), using VisualSFM to create both a low density draft point cloud (Fig. 16), as well as a high accuracy, dense point cloud, then importing the high density cloud to Meshlab (Fig. 17) in order to generate a three-dimensional model (Fig. 18). This 3D model did require some measure of correction to remove anomalies and correct the topology (Fig. 19). To further reinforce the decision regarding which application to use to generate the point cloud, Insight3D's in-application mesh reconstruction was found to consist of manually placed flat planes, rendering it unsuitable for soft organic structures such as trees. With this in mind, it was decided that VisualSFM would be the program of choice for future experiments.

6.4.3 Point cloud accuracy evaluation

Due to the nature of SIFT-generated models, there is no frame of coordinates for the model. This means that measuring size and therefore volume is only possible when expressed in terms of 'units'. In order to translate these units to a real-world reference space, a measurement needs to be taken in both the box's real-world frame and the model's virtual frame. This can then be used to determine the ratio between the two frames of reference, enabling the model to be given real-world measurements. However, the accuracy of this ratio is unknown and must be examined in order to understand the limitations of this method.

In order to assess the accuracy of this ratio, the box generated for the initial point cloud testing in VisualSFM was used. The actual box dimensions (*a*, *b* and *c*) were measured (Fig. 14), and then the box model dimensions (*a*, *b* and *c*) were measured four times (Tables 10, 11 and 12). This provides a sample population of 12 ratios, which is a very small number and should not be considered definitive. However, for the purpose of providing a sample to use as an initial investigation it is sufficient. The range of the 12 measurements was then taken and split into 8 different classes, 0 to 7 (Table 13). Ratios were assigned to these classes (Table 14) and graphed to examine their distribution (Fig. 20). The distribution appears normal, though this is tenuous at best due to the low sample size (n=12).

The resulting ratios are normally distributed (Fig. 20), which allows the use of the standard deviation and coefficient of variation (Table 15) to predict the expected accuracy of measurements. With 1.9% variation expected from one measurement, three such measurements would result in an expected accuracy of 0.6%. This does, however, assume that the operator is competent and understands the nature of comparing measurements from 2D to 3D space, and as such this figure only holds true when this is rule is applied correctly.

6.4.4 Natural feature point cloud generation

Two main points arose from this area of the experiment. Firstly, higher resolution images do not mean a better quality result (more matches), contrary to initial expectation. In every case where there were difficulties in computing enough match points, reducing the resolution of the images by at least half provided a greater set of matches. This was particularly evident when performing the final test, where .RAW images were used to ensure the highest possible fidelity. These images, even after careful preprocessing, did not provide enough match points to generate a complete point cloud of the target area (Figs 21). The tutorial provided an insight by suggesting lowering the resolution of the images, though it was not explained why this would help. Once the image resolution was halved, the point cloud started to take shape. Whilst not completely usable, it was a marked improvement on the previous attempts with higher resolution. Further reduction of the resolution did nothing to improve this, meaning that the remaining divides in the point clouds were the result of a different issue.

This issue is likely to be lack of data. The tutorial and official documentation state that if multiple clouds are generated, the likely cause is lack of data. This is particularly likely due to the issue experienced with trying to turn off .RAW format when taking the images. The use of .RAW format increased the time taken to save images, disrupting the workflow and therefore increasing the time taken to capture one image. This also had a secondary effect of decreasing usable battery time, as more energy was used up in saving the images. With the knowledge of the limitations of high resolution images for point cloud generation, it is a recommendation that .RAW only be used for photographic purposes, such as when inspecting a tree for damage, where the enhanced postprocessing capability of .RAW is directly useful (Fig. 23).

Another main contributor to the lack of data was the flight pattern used. To gather the data, it was attempted to fly the UAS in a series of lines, facing in opposing directions, so as to get continuous cover of multiple sides. This was only moderately successful, partially due to the above-mentioned constraints. Other problems encountered were the potential mis-reporting of the UAS height above ground level, though as this could not be tested it was decided to accept the figure as the truth. Even if not true, there is uncertainty as to what 'above ground level' means, and whether launching from a hilltop constitutes 'ground level'. The flight pattern itself was also problematic, as it tended to prefer one side of the feature to another. This is likely due to the fact that the UAS was launched facing this way, and the operator wished to keep it in close visual range due to the frequent WiFi communication blackouts.

Whilst arguments on the specific definition of ground level must await judicial deliberation, there are potential ways to improve the flight path used for image gathering. A spiral of increasing height, starting at the edge and working inwards, would provide the greatest continuous coverage of a point. This is only of use where the feature is small enough that it can be covered entirely without having to exceed the maximum height restriction. For larger images, a series of horizontal loops might provide the maximum coverage, with the vertical ascent being replaced by an extra loop or half loop on the outside of the feature to ensure a buffer zone (Fig. 27).

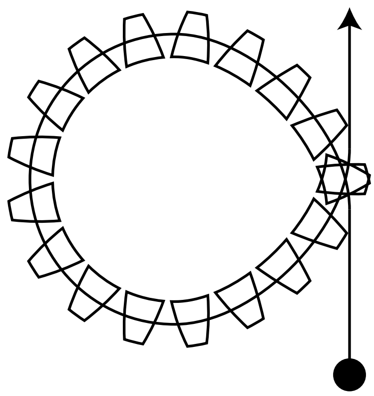

Fig. 27a. One loop of the proposed flight path, showing capture points

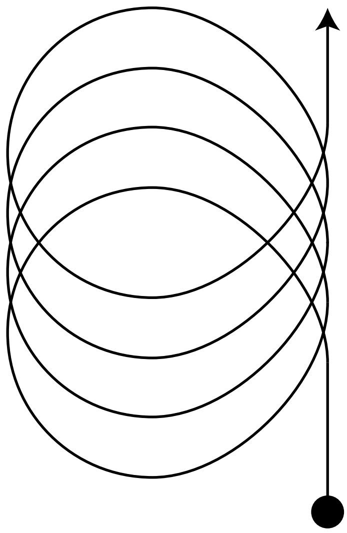

Fig. 27b. Multiple loops of the proposed flight path

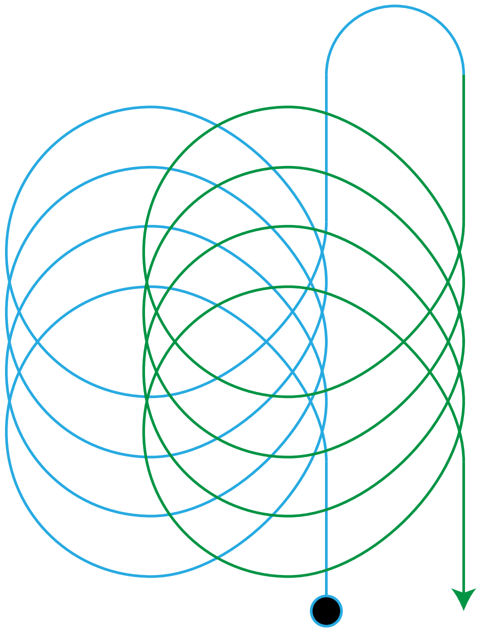

Fig. 27c. Overlapping series of loops provide extensive coverage

6.4.5 Model generation

Although the tutorial was an excellent guide, Meshlab was still an infuriatingly difficult program to use at times. The system for saving is particularly odd, in which the objects are saved separately from the scene in which they are in, much like inserting pictures by reference into a Microsoft Word document. This approach takes some getting used to and will likely lead to loss of data at more than one point, as it did during this study.

Navigation of the scene and mesh is another weak point, especially when compared to mainstream applications such as Blender, 3DSMax or Maya. It might be worthwhile generating the mesh in Meshlab, and then exporting it to a more mainstream package (Blender is free and open source) for navigation and postprocessing. This would also eliminate confusion over the save mechanics of Meshlab and hopefully lead to fewer instances of lost data. An additional benefit would be the enhanced mesh selection options, as well as the more advanced mesh management options such as reconstructing a mesh using corrected topology. Meshes formed by concentric closed loops are much easier to manipulate, though this is an extremely intensive task which should be reserved for end-product models which really require it.

The options for the Gaussian model generation were fairly obtuse in how they impacted on the resulting model. An operator more familiar with the algorithm might be able to obtain better results, but it is likely that the algorithm itself is not suited to mapping coniferous woodland. This is due to the nature of Gaussian algorithms, which attempt to smooth out bumps and spikes in data. This is not beneficial at all to coniferous stands, as each tree comes to a point naturally. It may, however, be of greater benefit when dealing with broadleaf trees, which have a more amorphous nature.

The shape of coniferous trees, and indeed any other tree that tends to a singular point, may provide an alternative model generation algorithm. Techniques exist for LIDAR point clouds that can extract tree shape (Pyysalo & Hyyppä, 2002) which could well be applied to point clouds generated through SIFT. Once this point is known, it is possible to measure the angle of the crown and height of a tree, which in turn can be combined with other metrics to give an estimated point above the ground at which the canopy begins. This would provide the ability to generate sub-canopy dynamics using only above-canopy data.

6.5 Guidelines On Use

6.5.1 Flight

Controlling the Phantom is an easy task even for a beginner, and it is simple to takeoff and land. Long grass caused the most issues as it wrapped around rotor blades, but this is easily remedied by pulling out chunks to make an area of shorter grass. The UAS can be sent into the canopy, or above, though care should be taken to avoid any air currents that may exist. Flying sub-canopy in gusty conditions is also not recommended, due to the lack of speed of the correction routine on the Phantom.

The task of flying could be made significantly easier with the use of an autopilot, especially when flying preset flight patterns or when flying above-canopy. It is often easy to lose visual track of the UAS if line of sight is broken, even momentarily (Table 1), which may often be the case when launching through a gap in the canopy. Allowing an autopilot to fly the UAS, instead of relying on an operator whose view is frequently obscured by branches, is a far safer method. Using the UAS in autonomous mode would result in a consistently higher quality of data, as well as more easily replicated procedures. An alternative to autonomous flight when line of sight is obscured would be to switch to first person view flight (where the pilot flies by looking at what the UAS sees), but this has been deemed to be 'not line of sight' by CASA.

6.5.2 Still images

For still images, the UAS can start to be thought of as a small-scale aircraft. However, the rotary wing UAS component adds the ability to reach places which a full scale craft would never be able to, for example when inspecting trees for damage. In this situation, the UAS proved to be a highly adaptable replacement for the requirement to use off-the-ground climbing teams, provided the canopy is not too thick. In the example used in this study, the resulting images provided the grounds maintenance team with the information required to assess the need for maintenance.

'Yes the photo shows there is also substantial bird damage to the main fork of an upper scaffold limb to the right- I did not know about it because I could not see from the ground and it is of the most concern. I will be scheduling some selective weight reduction to affected branches and might even look into installing some mesh over a couple of the bad forks to prevent further bird damage plus to give the branches a chance to heal /compartmentalise. I might even have to look at Cobra bracing this tree as a precaution in the future.
I am glad you did the RAW images - they show up really well.' - Melinda Walker, ANU Arborist, email 21st May 2015

UAS-based photography is an excellent addition to standard land-based photography in surveying fixed points. The ability to rise above the canopy level and see the structure of the surrounding areas was highly approved when surveying Peniup. For the measurement of canopy cover, it has been proven that it is possible to conduct line analysis on UAS sourced photography. Any use of other methods, such as supervised classification, is pursuant on the use of a camera which is capable of true vertical. Without true vertical the parallax will eventually distort the ratios, though this can be managed by limiting the amount of the image which is used. Further research would be required to examine the boundaries of limitation, but as many modern gimbals provide a greater freedom of movement that the one utilised, it is unlikely to be a major issue when using modern UASs.

The following overview of the value of the UAS at Peniup, WA was provided by David Freudenberger, who has been closely involved in the monitoring of Greening Australia's revegetation project since its inception.

'1) Speed: The UAV was able to capture 7-8 images and mulitple altitudes rapidly and efficiently across a large area (250 ha) far faster than the ground-based plot measurements.

2) Perspective: The oblique angle may have made quantitative analysis difficult, but it provided fine qualitative insights. As humans we are use to viewing landscapes from oblique angles (e.g. from a hilltop), such views are part of our evolution. Aerial images looking straight down are a recent invention and only readily available now thanks to Google Earth launched about 10 years ago. I find is takes a while for many viewers to work out what a straight down view is showing, where we instinctively and instantly recognise an oblique angle. Google Earth now can be rotated to provide an oblique angle, but not the quality of the UAV images.

3) Multiple Scales: Images from the three heights provide insightful perspectives on the patchiness of the Peniup Restoration at multiple scales. What one sees at 10m is often very different to what one sees at 50m.

4) Wide angle: These images benefited from the wide angle (fish eye) - that lens 'sucks in' the greatest amount of information at a given height, but image correction is needed and greatly appreciated.

5) Repeatability: I am confident that some one in 5 or 10 years time can repeat the sequence of images.

6) Forest from the trees: I have been taking ground based photo points for the past 7 years. Over the first 5 years all photos were highly informative showing the rapid increase in woody plant structure and the nature of the ground cover. However, over the past couple of years many photopoints are providing little additional information/perspective, as all one sees is a mass of greenery. The UAV images get me up and above these increasing walls of vegetation. Wish I had year 1 or year 2 post planting UAV images!

7) Science Communication: In conclusion, the UAV images help communicate to a diversity of stakeholders (interested people) the remarkable ecological restoration occuring at Peniup. Yes I have stem density data, biomass calculations, means and variation... (and published papers), but the cliche, "A picture is worth a 1000 words' still holds true. The UAV images sweep across this transformed landscape showing what the largest single restoration planting in Australia (at the time) looks like in all its patchy glory.' - Extracts from David Freudenberger, Senior Lecturer at ANU, email, 1st November 2015

6.5.3 Site size

The Phantom, and other similar UASs, are not in a position to replace full scale aerial surveys. The limitations imposed on flight time by the fuel, as well as legal restrictions on line of sight, restrict them to small-scale plots. This does not, however, mean that they are without purpose; though they might not replace one facet, they provide a significant capacity to augment management. The ability for a surveyor to carry around a piece of equipment that can let them see the canopy from above is a significant leap forward in capability by itself. That the equipment is low-cost and easy to learn and use is an added bonus.

This places the UAS as a tool for comparatively small-scale sites or small plots within sites (Fig. 28), though with a very wide angle lens it can provide a general overview of medium-sized plots. As an example of use, a UAS would be extremely valuable in tracking the progression of a disease. Once the current boundary of extent has been established, the UAS can be sent up to examine the boundary and any changes on a regular basis, with the launch point moving as required. This enables high fidelity tracking and monitoring of disease progression at an extremely low-cost, enabling high temporal frequency. The cost of performing daily, or even weekly, full-scale aerial flights for the same goal is extremely prohibitive. Using the UAS in such a spot-monitoring manner circumvents the limitations imposed by the fuel.

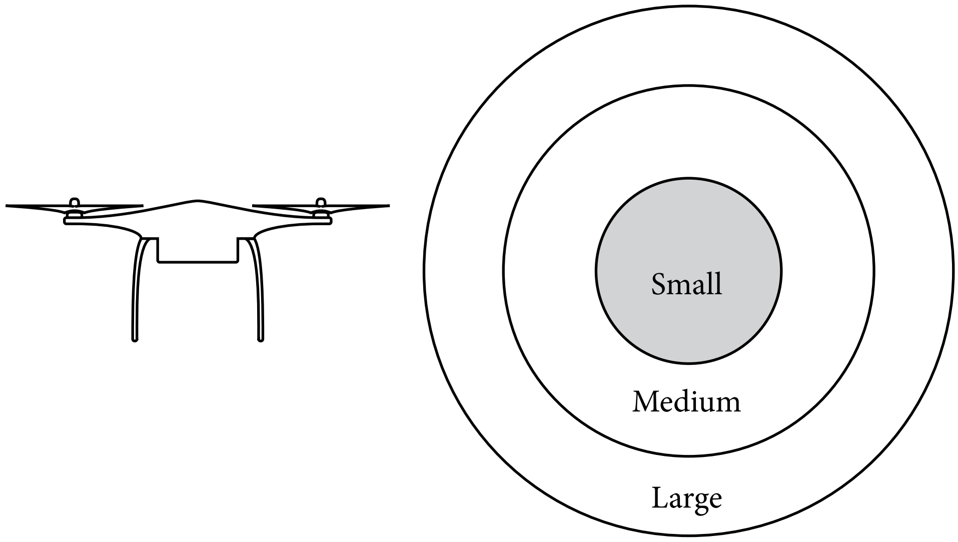

Fig. 28a. The suggested relative coverage of UAS surveying

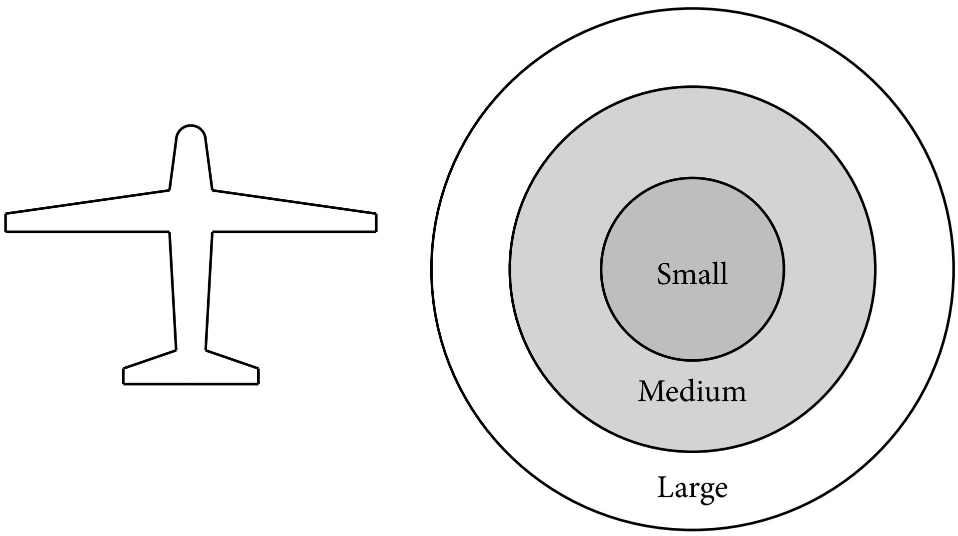

Fig. 28b. The suggested relative coverage of aerial surveying

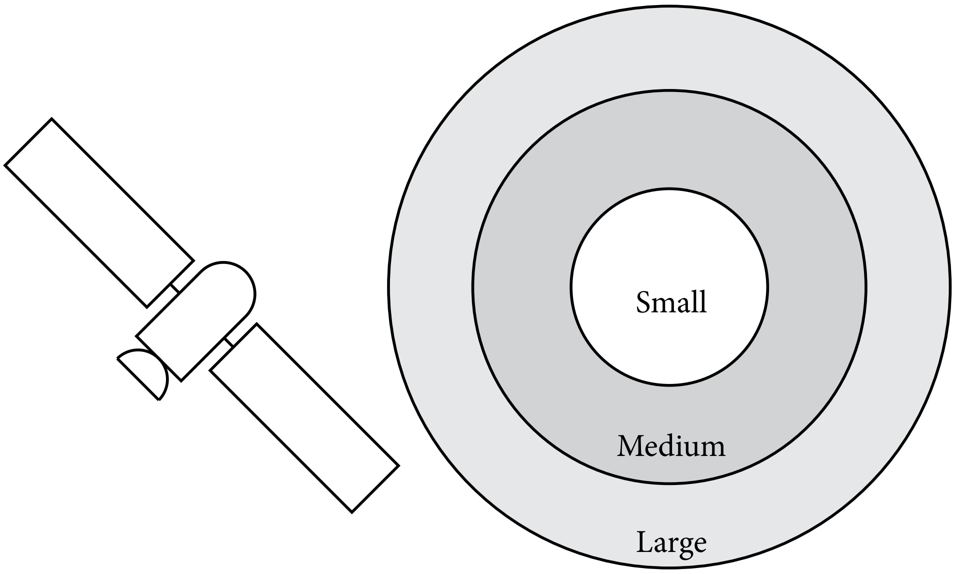

Fig. 28c. The suggested relative coverage of satellite surveying

7. Conclusion

This thesis has demonstrated that commercial, low-cost unmanned aerial systems possess the ability to augment arboreal natural resource assessment.

The flight technology, both in hardware and software, is ready for general usage, though some areas would still benefit from improvements. The particular defects identified were the short battery life and the lack of usable autopilot for the chosen UAS. Battery life is an ongoing research area, though the structural integrity of new battery types must also be considered in order to maintain safety standards.

The open source community is far ahead of the offerings from DJI, though currently this open source technology cannot be used with the DJI hardware/firmware. The use of open source technology brings its own issues, as although the system can be applied to almost any UAS, the technological challenges of doing so place this in the realm of the specialist engineer. 3DRobotics has addressed this issue very recently with the introduction of a ready-to-fly model as a rival to the new DJI model. Having a stated design goal of use in surveying, it will be interesting to see what this new UAS from 3DRobotics is capable of.

Other facets of the UAS platform have made significant advances, such as the improvements to mobile GPS accuracy. The Phantom 2 camera is far outshone by its modern counterparts, which is of particular relevance to point cloud construction. A more sensitive camera will reduce the requirement of raising the ISO in order to compensate for light conditions. This in turn reduces the amount of artificial noise on images, aiding match reconstruction.

The data resulting from the surveys conducted has many uses; still images are very useful as augmentations to fixed points and provide a new perspective on the structural composition of the subject area. Additionally, the images have proven useful in inspecting trees for damage, increasing the safety of the task whilst decreasing the cost.

For three-dimensional images, structure from motion techniques worked far better than expected in producing a point cloud from a series of UAS images, particularly when random noise textures were involved. This was impaired by the model generation sequence, as the algorithm attempts to create a smooth surface as opposed to the series of crown points present in the test subject. However, this sequence has potential for improvement, as an algorithm to identify crown points could then be used to generate the model, including a sub-canopy overview based on heuristic modelling.

The legal restrictions around small UAS flight are still being revised according to CASA, though this has been the case for many years. Countries other than Australia are starting to relax their laws on UAS flight as the advantages of the technology become apparent. Private operators are also taking an interest in the regulatory area, with at least one insurance provider offering to insure UAS operators against public liability. This is currently conditional on the operator completing a mandatory course of training and abiding by a set of rules.

It is highly likely that Australia will follow this course, as the Australian outback is an ideal environment for non-line of sight use, due to the low population density and sheer size of the areas which need monitoring. In all, it is almost certain that the use of UASs in arboreal natural resource management and monitoring will become widespread.

The widespread use of small UASs does not currently have the potential to replace full-size aircraft for monitoring, due to flight time and legal restrictions. Their current role is as small-scale data collection devices, ideal for sites or plots within sites of around 1 hectare or smaller where it would be impractical to hire a full-size aircraft. It is still currently necessary for the operator to visit the site, due to both legal requirements and to set up the reference markers required to enable photogrammetry. The information that the UAS gathers differs from that which full-size craft can obtain, mainly due to the height at which it operates. This enables the UAS to acquire much higher resolution information on the canopy and upper stem.

The UAS also enables ground surveyors to send a camera through the canopy at points of interest in order to view details in real-time, ranging from the immediate structure to the overall composition of the area, as demonstrated in Western Australia. This allows not only a better understanding of the context setting, but also much better acquisition and understanding of canopy measurements and dynamics, which may enable much more powerful allometry to be used. The future holds much in store for the expansion of this technology, including larger UASs which provide greater range, and the relaxation of legal restrictions to allow the UAS to operate further from the operator. Until such time, small UASs are best used to enhance *in situ* monitoring by providing accurate, detailed and real-time information.

8. Bibliography

Aerial Surveys n.d., “LIDAR Systems For Sale”, Viewed 5th August 2015, <http://www.aerialsurvey.com/services/LIDAR-systems-for-hire/LIDAR-systems-for-sale/>

Aerometrix, 2012 “High Resolution Digital Aerial Imagery vs High Resolution Satellite Imagery – Part 1”, viewed 15th August 2015, <http://aerometrex.com.au/blog/?p=217>

APM DroneCode 2015, “Mission Planner”, Viewed 6th August 2015 <http://planner.ardupilot.com/>

Asner, G.P. 2009, “Tropical forest carbon assessment: integrating satellite and airborne mapping approaches”, *Environmental Research Letters*, vol 4, no 3

Austbrokers 2015, “UAV Insurance”, Viewed 5th August 2015, <http://www.absaviation.com.au/html/uav_insurance.cfm>

Autodesk 2015, “123D Catch”, Viewed 6th August 2015, <http://www.123dapp.com/catch>

CASA, 2014, “Notice of Proposed Rule Making: Remotely Piloted Aircraft Systems”, Viewed 15th August 2015, <https://www.casa.gov.au/sites/g/files/net351/f/_assets/main/newrules/ops/nprm/nprm1309os.pdf>

Chiabrando, F., Marenchino, D., Nex, F., Piatti, D., Rinaudo, F. 2009, “UAV systems for photogrammetric recording in archaeological areas: problems, suggestions, and products”, *Remote Sensing for Environmental Monitoring, GIS Applications, and Geology IX,* vol 7478

CSIRO 2015, “Zebedee”, Viewed 5th August 2015, <https://wiki.csiro.au/display/ASL/Zebedee>

Dandois, J.P., Ellis, E.C. 2013 “High spatial resolution three-dimensional mapping of vegetation spectral dynamics using computer vision”, *Remote Sensing of Environment*, vol 136, pp 259-276

Department of Agriculture and Water Resources 2015, “The Montreal Process”, Viewed 7th August 2015
< http://www.agriculture.gov.au/forestry/international/forums/montreal>

Ecosynth 2015, “3D Tools for Ecology”, Viewed 23rd May 2015, <http://ecosynth.org/>

Erdody, T.L., Moskal, M.L. 2009, “Fusion of LIDAR and imagery for estimating forest canopy fuels”, Remote Sensing of Environment, vol 114, no 4, pp 725-737

First Flight Centennial n.d., “The First Commercial Flight”, Viewed 5th August 2015, <http://www.firstflightcentennial.org/the-first-commercial-flight/>

Forestry Commission 2015, “History”, Viewed 5th August 2015, <http://www.forestry.gov.uk/forestry/cmon-4uum6r>
ITTO 2015, “International Tropical Timber Organisation”, Viewed 7th August 2015, < http://www.itto.int/ >

Kruse, P.W., Skatrud, D.D. 1997, “Uncooled infrared imaging arrays and systems”, Academic Press, San Diego

Law360, 2015 “Amazon Tells Reps. Drone Tech Is Outpacing FAA Regs” Viewed 8th August 2015,
<http://www.law360.com/articles/668646/amazon-tells-reps-drone-tech-is-outpacing-faa-regs>

Ling, L. 2013 “Dense Real-time 3D Reconstruction from Multiple Images”, *PhD Dissertation for the School of Electrical and Computer Engineering, College of Science, Engineering and Health, RMIT University*

Lingua, A., Marenchino, D., Nex, F. 2009, “Performance Analysis of the SIFT Operator for Automatic Feature Extraction and Matching in Photogrammetric Applications”, *sensors*, vol 9, pp 3745-3766

Mathews, J. n.d., “1800 Ship Construction”, Viewed 5th August 2015, <http://www.navyandmarine.org/ondeck/1800shipconstruction.htm>

Middleton, C., Call, J., Holdsworth, A., Selwyn, G.A. 1786, “The first report of the Commissioners Appointed to Enquire into the State and Condition of the Woods, Forests, and Land Revenues of the Crown and to Sell or Alienate Fee Farm and Other

Unimproveable Rents", National Library of Australia

Miettinen, M., Ohman, M., Visala, A., Forsman, P. 2007, "Simultaneous Localization and Mapping for Forest Harvesters", *2007 IEEE International Conference on Robotics and Automation*, pp517-522

Montagu, K.D., Düttmer, K., Barton, C.V.M., Cowie, A.L. 2005, "Developing general allometric relationships for regional estimates of carbon sequestration—an example using Eucalyptus pilularis from seven contrasting sites", *Forest Ecology and Management*, vol 204, pp 115-129

Moore, G. 1965, "Cramming More Components onto Integrated Circuits", *Electronics*, pp 114-117

Moore, J. 1994, "Barriers to Technology Adoption", *Environmental Science Technology*, vol 28, pp 193A-195A

Ogrin, Scott, 2015 "Lithium Polymer vs Lithium-Ion Batteries", viewed 15th August 2015,
<http://scottiestech.info/2015/06/21/lithium-polymer-vs-lithium-ion-batteries-whats-the-deal/>

Öhman, M., Miettinen, M., Kannas, K., Jutila, J., Visala, A., Forsman, P. 2008, "Tree Measurement and Simultaneous Localization and Mapping System for Forest Harvesters", *6th International Conference on Field and Service Robotics*

Phys.org 2015, "New centimeter-accurate GPS system could transform virtual reality and mobile devices", Viewed 5th August 2015,
<http://phys.org/news/2015-05-centimeter-accurate-gps-virtual-reality-mobile.html>

Pix4D 2015 "Pix4D", Viewed 6th August 2015, <https://pix4d.com/>

Poso, S., Wang, G., Tuominen, S. 1999, "Weighting Alternative Estimates when Using Multi-Source Auxiliary Data for Forest Inventory", *Silva Fennica*, vol 33, pp 41-50

Pyysalo, U., Hyyppä, H. 2002, "Reconstructing tree crowns from laser scanner data for feature extraction", In *ISPRS Commission III, Symposium 2002 September 9 - 13, 2002, Graz, Austria* , page 218-222

Sala, O.E., Jackson, R.B., Mooney, H.A., Howarth, R.W. 2000, "Methods in Ecosystem Science", p12, Springer Science + Business Media New York, 2000
Sondhaus, L. 2001, "Naval Warfare, 1815-1914", Routledge

Stehman, S.V. 1997, "Estimating standard errors of accuracy assessment statistics under cluster sampling", *Remote Sensing of Environment*, vol 60, pp 258-269

The National Archives 2009, "Domesday - Landscape", Viewed 5th August 2015, <http://www.nationalarchives.gov.uk/domesday/world-of-domesday/landscape.htm>

Tsubouchi, T., Asano, A., Mochizuki, T., Kondou, S., Shiowaza, K., Matsumoto, M., Tomimura, S., Nakanishi, S., Mochizuki, A., Chiba, Y., Sasaki, K., Hayami, T., 2014, "Forest 3D Mapping and Tree Sizes Measurement for Forest Management Based on Sensing Technology for Mobile Robots", *Field and Service Robotics: Results of the 8th International Conference*

United Nations 2015, "REDD Plus", Viewed 5th August 2015, <http://unfccc.int/land_use_and_climate_change/redd/items/7377.php>

UN Partnerships 2015, "Asia Forest Partnership (AFP)", Viewed 7th August 2015, <https://sustainabledevelopment.un.org/partnership/?p=1483>

Walford, A., 2007, "What Is Photogrammetry?", viewed 15th August 2015, <http://www.photogrammetry.com/>

Wall Street Journal, 2015, "Amazon Says FAA Approval to Test Delivery Drones Already Obsolete", Viewed 8th August 2015, <http://www.wsj.com/articles/amazon-says-its-approval-to-test-delivery-drones-already-obsolete-1427219327>

Wallace, L.O., Lucieer, A., Watson, C.S. 2012, "Assessing the feasibility of UAV-based LIDAR for high resolution forest change detection", *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol 39

9. Glossary

Base Station
The master computer which communicates to a UAS and can direct or override the autopilot, along with associated communications equipment such as radios and directional antennae.

CASA - Civil Aviation Safety Authority
The regulatory body for all non-military aviation, their primary involvement in this study is in their construction of the rules which govern the use of UASs. For more information, visit their website:
https://www.casa.gov.au/

Commandline
A method of interacting with a computer program by pure text. Commands are written, submitted and the output returned, all as text. This method of interaction is used in modern times primarily for programs which do not have a great deal of user input during processing, or where writing a Graphical User Interface (GUI) would take too much time. Commandline interfaces often tend to expose more of the program to modification by the user, as the software engineer does not have to make a new GUI for each possible combination of elements. This level of customisation makes them awkward to navigate at first, though with proficiency they can be faster to use that GUIs. Current examples are the DOS and Unix terminals, found on Windows and OSX/Linux builds respectively.

CPU - Central Processing Unit
A component of the computer, traditionally the part which does the 'thinking'. In modern computers, this task is split between the CPU and GPU with each specialising in a different type of task. The CPU is optimised for executing random instructions, e.g. launching and finding the information for different programs where the information is spread throughout the memory.

EXIF - EXchangeable Information File
A semi-standardised method of transferring metadata on any subject. Rather than set out what data must be transferred, it sets out the format in which data must be transferred. This allows the format to be used by a number of applications, of which its use in images is of particular interest to this study. Images tend to have embedded EXIF tags which contain data such as the camera parameters at the time the image was taken, and the position of the camera.

Fixed Wing
An aircraft which has fixed wings, the typical airplane.

FPV Flight - First Person View Flight
A method of flying remote control aircraft in which the operator views and controls the craft from the view of an on-board camera. This method is often used in conjunction with virtual reality devices, such as the Oculus Rift.

Gimbal
The device which determines which connects a camera to a fixed surface whilst allowing the camera to rotate. The number of axes it can rotate in depends upon the type of gimbal.

GPU - Graphical Processing Unit
A component of the computer, originally optimised for displaying graphical elements. In modern computing that has been extended to optimisation for repetitive tasks. They are less able to execute random instructions than the CPU, and so perform best when given variations on one task, e.g. comparing two numbers, due to the emphasis it places on parallel computing.

GUI - Graphical User Interface
A method of interacting with a computer program by the use of visual elements such as buttons. Most computers use this form of interface, e.g. Windows, OSX, Word.

ISO
A measurement of the sensitivity of the sensor in a camera. The higher the number, the less light it takes for the camera to register the 'colour'. In the pre-digital age, this represented how fast the film would react to light. A higher ISO has the benefit of allowing photography in lower light conditions, but the downside of introducing random noise to the image.

LIDAR
Also known as lidar, LiDaR, or even LADAR, this system relies on measuring the emission and subsequent reflection of pulses of light to determine the distance of surfaces from the point of origin.

Oculus Rift
A virtual reality device which can be used to display the feed from a camera to a person wearing the headset. Notably it supports the ability to feed two different image streams,

one to each eye, allowing for the user to experience depth perception. In FPV flight this can be exploited by mounting two cameras on a UAS, with a gap between them to mimic the spacing of human eyes. This setup allows the FPV operator to experience true depth perception from their UAS. However, motion sickness may become a problem.

RAW
An image file format which aims to preserve every bit of information possible about an image. This leads to large file sizes when compared to other formats such as compressed JPG, but far better quality. A key feature is the retention of information on either side of the brightness scale (very dark or very light). This retention allows postprocessing methods to recover and adjust this information, as opposed to compressed JPG which would replace the information with an approximation.

Remote Sensing
A set of techniques for obtaining data from far away. The two current mainstream techniques are the use of aircraft and satellites.

Rotary Wing
An aircraft where the life is generated by rotating wings e.g. a helicopter

Wrapper
A layer of code added around a software package to transform it from one type to another. In this study the wrapping refers to turning a commandline program into a GUI one, though other wrappers focus on operating system translations. A GUI wrapper is typically of low functionality compared to the underlying commandline, and often incomplete. They are made to provide novice users a more 'comforting' view when they start a program and often end up being bypassed once the operator is familiar with the system. The slimmer the wrapper, the less functionality has been transferred.