UAVs for data collection – plugging the gap

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Abstract

Unmanned aerial vehicles (UAVs) have emerged as important and useful platforms for acquiring remotely sensed data, offering the ability to collect imagery and other data with increased spatial and temporal resolution. In the New Zealand and Australian forestry sectors, UAV applications include a range of tasks such as cutover mapping, forest health assessment, and silvicultural quality assessment. As a platform, UAVs remain constrained by weight, distance and regulatory considerations. These factors mean that UAVs have primarily found a niche collecting data for smaller areas of forest that are uneconomical to survey using satellite-based earth observation or aerial survey. UAV and sensor technologies are maturing rapidly and a range of potential applications highlighted by the forest industry are currently being investigated.

Introduction

Towards the end of 2015, the US Federal Aviation Administration predicted around one million drones would be under the Christmas tree (Popular Mechanics, 2015). While drones may be the latest 'must have' toy, the concept of miniaturised remotely piloted aircraft has been around since the middle 1800s. The first patented design for an unmanned aerial vehicle (UAV) was a balloon transporting a bomb in the US Civil War (Pebley, 1863). World War I and II saw the development of unmanned aircraft for explosives delivery and later radio controlled aircraft were manufactured for target practice by the navy and army. UAVs have since been regularly deployed by the armed forces on a variety of tasks including data collection during nuclear tests, operational reconnaissance, as decoys during combat and for weather observation (Darack, 2011).

The use of UAVs has also become more widespread by those with more peaceful intentions. UAVs provide a complementary addition to conventional remote sensing platforms because data capture using conventional airborne and satellite platforms can be expensive, operationally inflexible, and may not deliver data with the required spatial and temporal resolution (Nebikera et al, 2008). For remote sensing researchers and practitioners UAVs have become increasingly popular because they are affordable, portable and autonomous, they can operate in remote or difficult locations, and can acquire data under cloudy conditions (Whitehead, 2014).

Remote sensing data has a long history in supporting forest management and much of this data was collected by manned aircraft (Tosh & Jozkow, 2016). By the 1970s, public space-borne sensors such as Landsat and early private ventures such as IKONOS (launched in 1999) gradually replaced some imagery applications previously collected by manned aircraft. Since then, imagery from satellites has continued to decline in price while its spatial and temporal resolution has continued to improve (Dash et al, 2016). With the recent lifting of export restrictions on high-resolution imagery, US operators such as DigitalGlobe have been able to come to market with products such as WorldView 3, offering 8-band multispectral and short wave infrared at 0.3 m resolution.

This high-resolution imagery comes at significant expense, with prices starting at NZ$43 per km^2 and requiring a minimum order size of around 100 km^2. Other commercial platforms such as RapidEye offer coarser resolution imagery (5 m), but with prices starting at NZ$1.40 per km^2 and a minimum order size of 3,500 km^2. Publicly available imagery has also improved significantly; the latest US Landsat 8 provides 30 m multispectral imagery, while the European Space Agency's (ESA's) Copernicus programme will see six pairs of Sentinel satellites in orbit for global earth observation. The Sentinel-2 satellites (one deployed and one to be launched in 2017) will offer 10 m multispectral resolution imagery across much of the earth.

New Zealand is fortunate to be well covered by the acquisition path and the final revisit time will be five days (ESA Sentinel, 2016). A large proportion of remotely sensed data has been collected from conventional manned aeroplanes. These craft offer an attractive combination of high payload capability, and the capacity to survey large areas and flexible deployment, but they do have several drawbacks. The fixed costs and planning required limits the minimum feasible area to around 5 km^2, depending on various factors, and repeated revisits may become prohibitively expensive. Conventional aircraft also struggle with cloud cover and obtaining very high-resolution imagery can require expensive imaging equipment and the use of a helicopter.

Applications for the forest industry

UAVs may provide an effective means of addressing these shortcomings for forest monitoring, providing high spatial and temporal resolution data collection for smaller areas. Applications for the forest industry include:

- Post-planting assessment
- Disease detection
- Guidance and quality control for silvicultural operations
- Pre-harvest inventory
- Post-harvest cutover residue assessment.

Accurate digital surface models can be captured to guide site-specific work such as forest road construction and erosion management. Targeted control operations can be performed following weed detection and mapping, using a UAV, saving time and money and promoting sustainable practices. Controlled and wild fire management can benefit from an 'eye in the sky' to support ground crews with hotspot detection and monitoring fire front development. Whether an organisation is planning to purchase their own craft or engage a service provider, it is useful to have an understanding of the technology available and how it can add value.

In this article we summarise current UAV platforms, sensors and the associated costs relevant to forest management in New Zealand. We also evaluate the potential uses relevant to commercial forestry and describe the current state of research and commercial application. The unique challenges and current limitations of this emerging technology will also be addressed.

Review of the technology

A wide variety of craft are available and these are commonly divided into two categories: fixed wing and rotary wing. The choice of platform type may well depend on the data collection requirements and procedures required. Each system has a distinct set of performance properties that users should understand to decide which is most appropriate for their planned uses. The UAV Global website (2016) lists 49 manufacturing countries and at least 440 currently active UAV manufacturers. The US has the greatest number of providers but manufacturers in China, such as DJI, have had considerable success with ready to fly 'out of the box' models.

With increasing choice and rapid improvements in capacity and performance, choosing a method for data acquisition is commonly governed by the size and the nature of the task and the resolution and accuracy of the data required. Two key determinants in selecting an appropriate UAV are flight time/range and payload carrying capacity. For effective deployment a UAV needs to be able to lift itself, its power source and sensors into the air to carry out a survey. The total weight of items, excluding the craft itself, which can be supported during an operational flight are referred to as its payload. The length of time it can support its payload while deployed on an operational mission is its flight time. Flight time is defined by the size of the payload carried on a specific mission and the range is governed by the interaction between flight time and flight speed. Manufacturer websites are a good place to start for information on hardware, software and training.

Fixed-wing UAVs

A fixed-wing UAV consists of a rigid wing capable of flight due to the uplift generated by the aircraft's forward airspeed and the shape of the wing. The craft may be powered by an internal combustion engine or an electric motor. Like a conventional manned aeroplane, control surfaces built into the wing can include ailerons (roll along longitudinal axis), elevators (pitch – lateral axis) and rudder (yaw – vertical axis). Fixed-wing craft are useful for aerial surveying and surveillance and the platform has numerous positive and negative aspects (Table 1). Because of their simple structure fixed-wing UAVs are reasonably inexpensive to purchase and maintenance costs are low. They can fly for longer periods on considerably less power than a rotary-wing UAV, meaning that larger areas can be surveyed in a single flight. A reasonably wide, open area is usually required for take-off and landing, but recently several craft have been developed that can be launched by being thrown into the air. Hovering is not an option because the craft must continue in a forward motion to maintain lift.

Table 1: Fixed-wing aircraft – pro and cons

Advantages	Disadvantages
Simple structure Low maintenance Long flight times on less power Large survey areas Some craft can carry large payloads or twin sensors	Runway or launcher need for take-off and landing for some craft No hovering capability for close inspection Difficult landing in forested environments

The key advantage of fixed-wing craft is longer flight times. SenseFly, a Swiss-based UAV developer and a subsidiary of Parrot (www.parrot.com), has manufactured the eBee™, a 700 g fixed-wing UAV with an optical camera. The eBee ag™ (Figure 1) is equipped with several camera options such as optical, red-edge, thermal and multispectral. Contiguous images captured using a digital camera can be converted into an aerial mosaic of the entire area of interest or, with sufficient overlap, transformed with processing software into a coloured 3D point cloud using an approach called image-matching. Parrot's latest drone is the Disco, which weighs 690 g and can be launched, like the SenseFly eBee™, by simply being thrown into the air. A unique feature of the Disco is the ability to engage 'loiter mode' and orbit an area requiring closer scrutiny. US-based navigation and geo-spatial giant Trimble Navigation Ltd has also released fixed-wing UAV models that offer sector-leading flight times lasting from 40 to 50 minutes and they have a range of ~60 km.

Figure 1: SenseFly eBee (www.sensefly.com/drones/ebee.html)

Rotary-wing UAVs

For rotary-wing craft, lift is achieved by air flowing over a wing. Air movement is created by the wings (blades) revolving around a single mast called a rotor. There are numerous configurations available, including models with single or twin rotors on each arm. Craft may have as few as one rotor (helicopter) or as many as eight twin rotors (Octocopter). The key advantage of rotary-wing craft is that the vertical take-off and landing requires minimal space (Table 2). Because lift is created by blades revolving around the rotor, forward speed is not required to maintain lift, allowing for variation in speed and hovering capability. A range of different sensors can be carried beneath the craft, with or without gimbal mounting. A gimbal houses the sensor and reduces interference from engine vibrations or wind through enabling the sensor to pivot about a single axis with minimal friction. This means that the sensor remains stable, independent of the movements of the craft. Rotary-wing craft are more complex and with many more moving parts, requiring regular maintenance (Table 2).

Table 2: Rotary-wing UAVs – pros and cons

Advantages	Disadvantages
Vertical take-off and landing (VTOL) Hovering capability Can carry heavier payloads Improved stability in strong winds	Mechanical and electrical complexity Lower speeds on more power Short flight times constrained by batteries Specialised training required Low area coverage

The craft most commonly used by hobbyists and those planning to capture small areas belong to the DJI Phantom series. The Phantom 3 weighs less than 2 kg and can capture 4K (ultra high-definition) video and 12 megapixel (MP) photographs via its integrated optical camera. A brand new craft and backpack (Figure 2) can be purchased for under NZD$1,000 (Nixon, 2016).

Figure 2: DJI Phantom 3 carrying a 12 MP camera with 4K video capability. Source: DJI, 2016

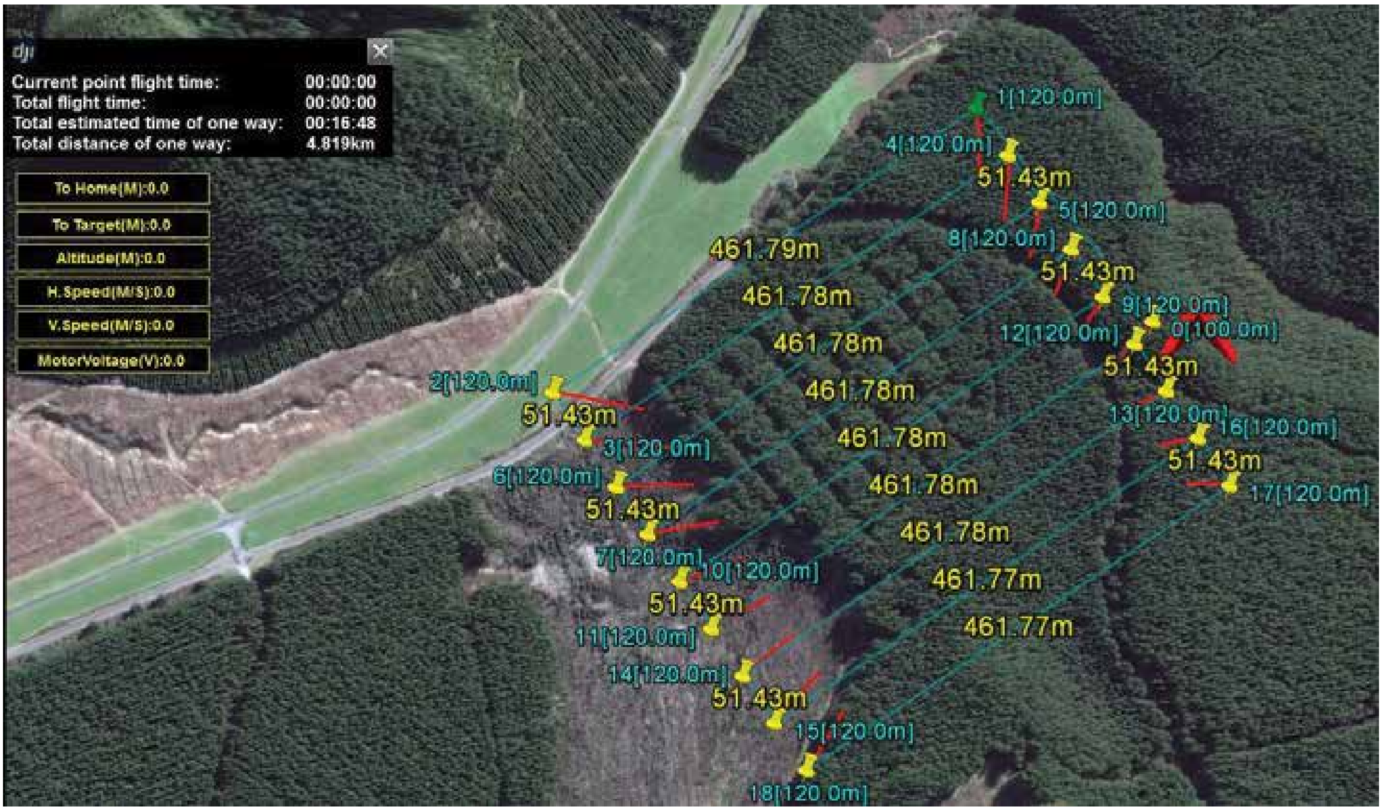

Figure 3: Flight plan covering approximately 16 ha or 5 km flight path drawn up on DJI ground station software

The Phantom can fly up to 5 km or around 20 minutes using only a single battery, depending on weather conditions and the speed of the craft. The flight plan drawn up on DJI ground station software outlined in Figure 3 shows an area of 16 ha of mature forest (4.8 km covered), which can be covered during a single flight.

DJI has a range of craft that are designed to undertake small to medium tasks and can accommodate a range of sensors. Larger craft in the Phantom series include the Inspire which costs just under NZD$3,000, weighs 3 kg, and has a visible spectrum camera producing 12 MP resolution in JPG or raw format. It has a vision positioning system, which uses a camera and sonar to analyse the terrain under the aircraft for improved stability and altitude adjustments as the terrain changes. Flight time is up to 18 minutes (Fisher, 2016). The DJI Matrice 100, known as the developer's UAV, has expansion bays to allow for a customised payload (under 2 kg). It has a flight time ranging from 22 to 40 minutes, depending on battery load, and retails for NZD$4,500. The Matrice 600 has a 5.5 kg payload, flies for around 18 minutes and retails for NZD$6,500. Within New Zealand there are a number of manufacturers providing small to large craft for the domestic and international market. Altus based in Hamilton and Aeronavics in Raglan each have small, medium and heavy lift craft for various field applications (Figure 4).

Figure 4: Altus Delta LRX heavy lift craft carrying a RouteScene LiDAR pod

X-Craft based in Auckland specialise in custom-built quadcopters and fixed-wing craft. Heavy lift craft are needed to carry larger sensors such as laser scanners or a reservoir for spraying operations. Within New Zealand there are currently no medium-sized heavy lift craft that can fly for longer than 30 minutes, as the need for more batteries increases the craft weight and limits flight time. For many operations, a small to medium craft is adequate to carry a range of lightweight sensors.

Sensors and software

Digital SLR cameras

Many 'out of the box' craft have an inbuilt visible spectrum camera. To gather useful metrics for forestry, or identify individual trees across a small spatial extent (smaller area), a higher-resolution camera may be required to provide additional detail. Specific tree properties can be measured if the imaged trees are larger than the image pixel size (Nixon, 2016). Pixel size is a unit of resolution so, in general, the smaller the pixel size the better the resolution. The Sony NEX 7, Sony A6000 and Lumix 4K (high-definition) are all capable of capturing imagery with high-resolution and range in price from NZD$700 to NZD$2,000. Processing of visible spectrum images can produce geo-referenced 2D maps, 3D spatial data and digital surface models with relative ease. Two commonly used software products for UAV image processing are Pix4D™ (USD$8,700 one-time charge or rent options available) and PhotoScan™ (USD$3,499 stand-alone licence).

UAV photogrammetry

Photogrammetry is the science of making measurements from photographs. 3D point clouds can be generated by using a UAV as a platform for photogrammetric data acquisition. Deriving metrics from photogrammetric point clouds can provide a low-cost alternative to a limited number of forest biophysical metrics usually requiring aerial laser scanning (ALS or LiDAR). Puliti et al. (2015) tested UAS-SFM (UAS combined with a structure from motion algorithms and photogrammetric principles) by surveying a predominantly mixed-aged boreal forest in Norway. Aerial LiDAR data were gathered using a manned aircraft. UAV data were collected using a SenseFly eBee fixed-wing craft carrying a Canon S110 near infra-red (NIR) camera, producing 12.1 MP images in the green, red and NIR wavelengths.

When compared with ALS, and ground truthing, UAS-SFM results indicated that relatively accurate forest inventory information could be obtained at a local scale (Puliti et al., 2015). Wallace et al. (2016) found that the photogrammetric technique under-performed compared to LiDAR in a dense canopy eucalyptus forest. Recent research by Scion shows photogrammetric data from a UAV to be useful for deriving *Pinus radiata* canopy metrics prior to canopy closure. Early research findings suggest that generating 3D point clouds from imagery based on current methods is challenging following canopy closure in *Pinus radiata* stands.

Multispectral and hyperspectral cameras

Multispectral and hyperspectral imagery offers the capacity to view the world outside of visible wavelengths that can be observed by the human eye. The main difference between multispectral and hyperspectral imagery is the number and width of bands or descriptive regions in the electromagnetic spectrum. Multispectral imagery typically offers around five wide bands and can be used to determine a range of vegetation properties. The most popular UAV compatible camera currently being used in New Zealand is the MicaSense RedEdge™ (Figure 5).

Figure 5: The RedEdge™ multispectral camera. Source: MicaSense, 2016

This RedEdge has five discrete spectral bands (red, blue, green, red edge and NIR), providing band reflectance and allowing calculation of a range of vegetation indices. The RedEdge is easy to use and has its own global positioning system (GPS) and WiFi, allowing access to the data via computer or a mobile device. Image mosaicing can be carried out by using commercial software, such as Pix4D™ or PhotoScan™ image processing software, although separate methods are required for image calibration. The camera manufacturer also offers a processing package that charges a 'per area' rate (NZD$0.80 per ha) or a flat rate of NZD$70 to NZD$350 per month for calibration and processing through to commonly used outputs. The outputted geo-rectified mosaic covering the study area and digital surface model (DSM) are provided in GeoTiff format. These data can easily be visualised and manipulated within a geographic information system (GIS). In Figure 6, these images show some of the results that are available through the Atlas MicaSense processing site, showing visible spectrum imagery, a vegetation index image and a visualisation of the NIR, green and red wavelengths displayed through the red green and blue channels.

Numerous vegetation indices have been proposed and used in the scientific literature. Several of these quantify the amount of infrared light reflected from vegetation, which is strongly correlated with photosynthetic activity (Rouse et al., 1973). The normalised difference vegetation index (NDVI) is amongst the most popular and well-known vegetation indices (Figure 6). Multispectral imagery can be used to determine a range of vegetation properties. The colour changes associated with a stressed or diseased plant can be detected in the NIR wavelength long before these changes are observed in the visible spectrum.

Hyperspectral sensors can detect hundreds of continuous narrow bands of the electromagnetic spectrum from ultraviolet to infrared. Potentially this provides increased information about the vegetation captured in the image, although complex processing after collection is required. The resulting data have been used to detect health changes or nutrient content in vegetation and for landscape mapping to determine soil properties. With a price tag close to NZD$500,000 for a manned aerial survey sensor, manufacturers have sought to develop an alternative that can be mounted on a UAV. Several companies have made significant research efforts in recent years to develop sensors that are lighter and more affordable. The Headwall Nano weighs around 1 kg and collects data in the spectral range of 400–1000 nm (Headwall, 2016). The COSI-cam weighs 500 g and has a spectral range of 600–900 nm (Vito, 2016). Prices start at around NZD$65,000, with variation between models in the capacity for on-board processing and image quality. Data analysis is a complex process requiring specialist image analysis software for calibration and spectral classification.

LiDAR

LiDAR systems measure distance by illuminating a target with a laser and analysing the back-scattered radiation. Large amounts of high-resolution surface and feature data can be captured for terrain with or without vegetation cover. Processed LiDAR can be converted into locally normalised 3D point clouds and used to create accurate digital surface models, and to characterise vegetation structure using helpful metrics such as tree height and volume. Monitoring of silvicultural processes using LiDAR from a UAV-mounted system has been shown to assist in ensuring best practice operations for pruning with a high degree of accuracy (Wallace, 2014).

LiDAR sensors range in price from around USD$8,000 for those used on UAVs to over USD$500,000 for the highly sophisticated systems commonly used on manned aircraft by professional surveying companies. Scion has been developing operational procedures to apply a RouteScene LiDAR pod (NZD$180,000) for use in New Zealand forestry conditions. This system

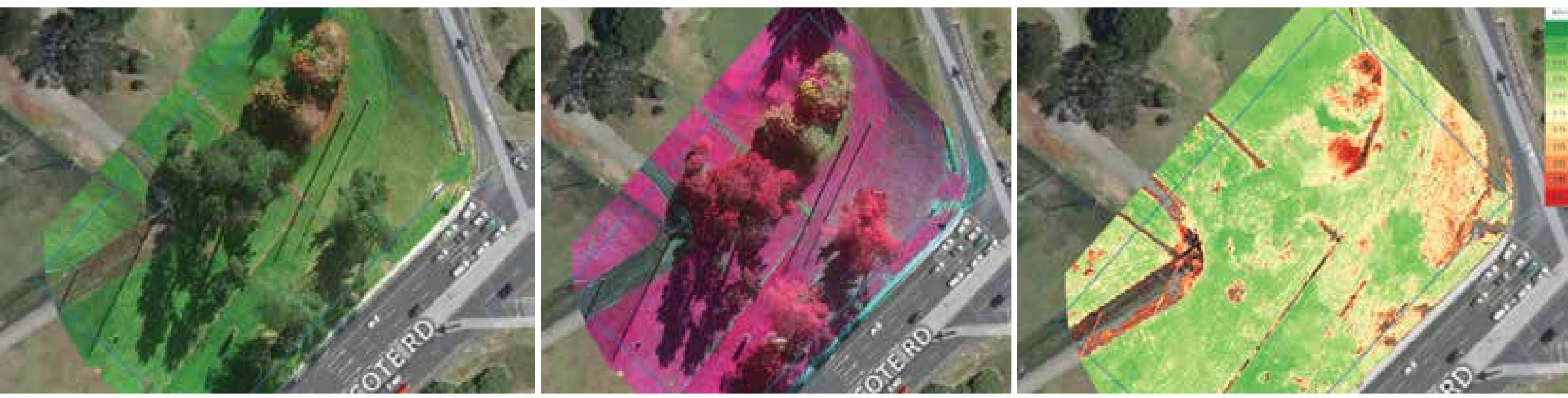

Figure 6: A Ministry of Primary Industries (MPI) high-risk site surveillance (HRSS) transect. Left: red, green, blue (RGB) imagery; middle: near infrared, red, green (NRG); right: normalised difference vegetation index (NDVI)

includes a Velodyne HDL32E scanner with 32 laser sensors capable of emitting 700,000 pulses per second and recording up to two returns per pulse. The system has an integrated global navigation satellite system (GNSS) and inertial navigation system (INS) to deliver accurate and reliable navigation and orientation. Figure 7 shows a LiDAR image of mature forest in the North Island. Scion's trials have shown that this system is capable of delivering exceptionally detailed data over forested environments.

Table 3: Civil Aviation Part 101 and Part 102 rules for operating a UAV. Certificates for operations outside Part 101 rules are granted on a case-by-case basis. Risk identification and mitigations plans are required to support applications

Part 101	Part 102
Airspace height limit 120 m (400 ft) above ground level (AGL)	Airspace height not limited to 120 m AGL
Fly in daylight hours	Night flying permitted
Give way to crewed craft	Give way to crewed craft unless operating in a UAV classified restricted area
Aircraft weighs less than 25 kg	Aircraft above 25 kg
Permission required to fly within 4 km of aerodrome	Permission required to fly within 4 km of aerodrome
Consent from landowner of area to be flown and from people who will be flown over	Consent to fly over land and people not required but recommended as best practice
Aircraft must remain within visual line of sight at all times (VLOS)	Beyond line of sight possible (BLOS)

Training and Civil Aviation regulations

There are two sets of rules for pilots of UAVs within New Zealand, which are referred to as Civil Aviation Part 101 and Part 102. Part 101 rules apply to hobbyists or operators performing low-risk tasks. As Part 102 rules have fewer restrictions, and allow beyond line of sight operations (BLOS), commercial operators generally aim to operate under these conditions. The two sets of rules are outlined in Table 3.

Challenges and opportunities

There are many challenges involved with UAV operations and battery duration is amongst the most limiting at the present time. Heavy lift rotary-wing UAVs allow targeted spray operations and the use of large sophisticated sensors. However, the power required for these procedures means that the craft must carry the additional weight of more batteries and, as a result, operational flight time is reduced. The development of diesel-powered craft is being explored by manufacturers as a solution to short flight times. Fixed-wing UAVs carrying smaller sensors are not so time constrained and many models can fly for over an hour, covering larger areas. However, as outlined in Table 3, Part 102 certification is required for BLOS operations.

UAV and sensor technology is developing at an exceptionally rapid pace. To avoid over-capitalisation when starting out it is useful for operators to carefully consider their objectives, understand the limitations of the available craft and comply with the regulatory environment. Talking to other operators and attending demonstrations held by manufacturers can help inform

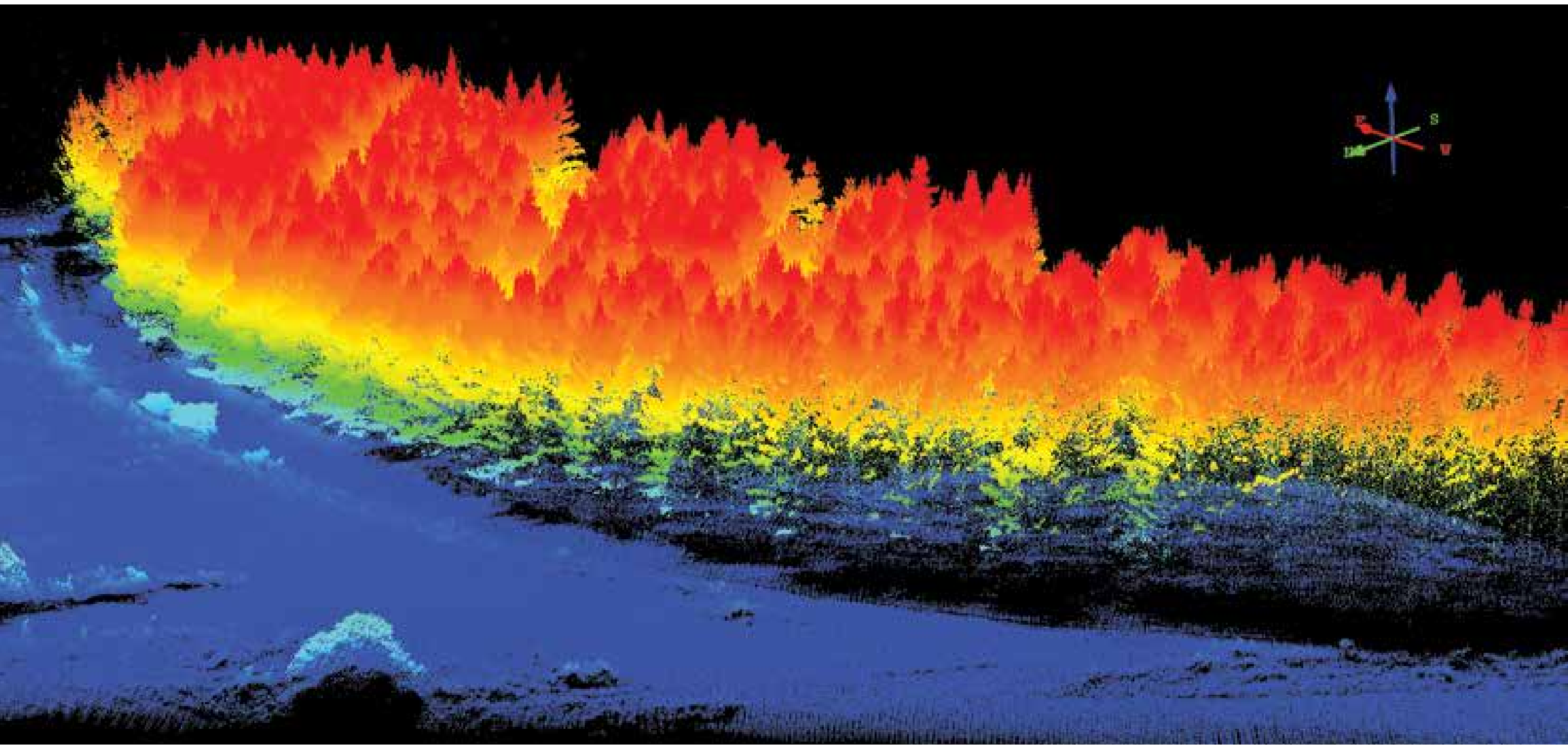

Figure 7: A mature *Pinus radiata* plantation captured using LiDAR from Scion's RouteScene LiDAR pod mounted on a UAV

decisions about hardware purchase. For some operations, it may be less expensive to hire a contractor to carry out work that involves more elaborate or expensive sensors.

Collection of data from a UAV provides many opportunities for the forest industry. Table 4 outlines forestry operations that may benefit from the application of UAVs and summarises their current position on the continuum between research and operational reality. Although most applications are in the research phase, early adoption of harvest detection and hotspot detection has taken place and resource assessment from UAVs is well developed. As many of the listed applications use data from multispectral or digital cameras, the use of UAVs is affordable in most cases.

Future uptake will largely depend on the cost efficacy of using a UAV in comparison to other forms of remote sensing or more traditional methods of data collection. Table 5 provides indicative costs for satellite, aerial and UAV platforms. These costs vary widely according to the requirements of the data, desired spatial resolution and area to be surveyed. Satellite products such as RapidEye clearly offer cost-effective coverage for larger areas where lower resolution is acceptable. Satellite data are, however, strongly limited by cloud cover over the region of interest. Aircraft offer the advantage of both higher resolution and the ability to capture LiDAR data over areas ranging from the level of the estate right up to nationwide scales. However, larger campaigns increase the amount of planning required, and smaller areas become prohibitively expensive when not included as part of a larger campaign or regional work programme.

Multirotor UAVs are most effective in collecting data at the stand level (<50 ha) and for tasks requiring very high-resolution data (2.5 to 9.0 cm can be achieved). These craft have no effective minimum area, with travel costs contributing the most to determining the economic viability of flying an area. Fixed-wing craft can cover much larger areas, with newer models offering 100 to 200 ha per day with swappable battery refreshes. For these craft, regulatory considerations and the cost efficacy of daily operations versus aircraft are the only practical limits on the size of the surveyed area.

Data for many of the applications listed in Table 4 could be collected from a wide variety of platforms and the forest manager needs to carefully match the operational requirements with the data provided by each platform. For example, mid to late rotation resource inventories are being increasingly undertaken using LiDAR from a manned aircraft, which can be collected at a relatively low cost per hectare, at an estate level (Table 5). However, at a stand level resource assessment from a UAV is likely to be more cost effective and more accurate. Similarly, harvest detection can be assessed quite effectively from satellite imagery. However, UAVs are able to provide more regular, accurate data collection and have greater flexibility as they can be used under cloudy conditions.

There are many operations that are well suited for UAV data collection. Applications where the fine spatial resolution provided by UAVs is an advantage include nursery tree counts, assessment of planting mortality and spacing and weed detection at the stand level. Depending on the extent of the affected area, assessment of damage from disease, wind or fire could be a potentially useful application as damage from these factors is often localised. Hotspot detection is well suited to UAVs as real-time information over a relatively small area at a fine spatial resolution is required. Measurement of genetics trials and inventory of difficult to reach plots could be important future applications of UAVs as these are small-scale operations where detailed information, such as accurate measurement of tree height, is a major advantage. Although still in the research phase, precision weed management using targeted spraying operations could reduce costs and prevent unnecessary chemical run-off, which in turn supports certification.

Table 4: Forestry operations that may be supported by remote sensing using a UAV

Application	Status	Sensors
Nursery		
Nursery tree count	Research	Multispectral
Site quality		
Soil fertility measure	Research	Multi/hyperspectral
Phenotyping	Research	Multi/hyperspectral, LiDAR
Post-establishment		
Disease detection	Research	Multi/ hyperspectral
Planting mortality/ spacing	Research	Multispectral
Weed detection	Research	Multispectral
Early to mid-rotation		
Selection of trees to prune	Research	LiDAR
Selection of trees to thin	Research	LiDAR, RGB
Thinning quality control	Research	LiDAR, RGB
Pre/post-harvest		
Use of digital terrain model for harvest plan	Research	LiDAR
Harvest detection	Operational	RGB
Waste assessment	Research	LIDAR, Multispectral, RGB
Inventory		
Stand-level inventory	Operational	LiDAR
Trial measurement	Research	RGB, LiDAR
Measurement of difficult to reach plots	Research	RGB, LiDAR
Forest health/fire, wind damage		
Wind/fire damage assessment	Research	LiDAR
Disease detection	Research	Multi/hyperspectral
Hotspot detection	Operational	Thermal

Table 5: Comparison of typical costs and area covered by different remote sensing platforms. Costs are indicative and may vary widely by task or site. Forestry-specific surveys include activities with higher post-processing such as post-planting assessment, tree counts and health assessment

Platform	Typical area	Indicative cost
Satellite (resolution)		(NZ$/100 ha)
RapidEye (5 m)	>350,000 ha	$1.40–1.70
WorldView (30 cm)	>100,000 ha	$43–$57
Aircraft		(NZ$/ha)
Imagery	>250–500 ha	$10–$20
LiDAR	>500–700 ha	$15–$20
UAV		(NZ$/ha)
Imagery	<200 ha/day	$8–$10
Specialised survey	<200 ha/day	$10–$20

Conclusions

UAVs are fast becoming a useful and multifaceted tool in the forest manager's toolbox. For discrete areas or repeat affordable data capture, a UAV can fulfil a requirement that may not yet be met by satellite and manned aircraft data capture. Throughout the entire forest rotation, captured imagery can support inventory, health monitoring, silviculture and harvesting operations. For UAV owner operators, certified training and robust health and safety plans or standard operating procedures will ensure that operations comply with Civil Aviation rules and avoid harm or expensive court cases should an incident occur.

Alternatively forest owners may instead choose to contract a UAV service provider to complete aerial surveys, thus avoiding the expense of hardware purchase, insurances and training. However, technology change in this space is rapid and the hardware and software will become increasingly affordable and the operations more routine. There are many potential applications for forestry, but very few UAV applications are as yet fully operationalised. There are of course many situations where an aircraft or satellite will be more efficient, but there are many opportunities where UAV data will 'plug the gap' in our current forest information systems.

References

Darack, E. 2011. *A Brief History of Unmanned Aircraft, Air and Space*. Accessed 22 January 2016 at www.airspacemag.com/photos/a-brief-history-of-unmanned-aircraft-174072843/?no-ist.

Dash, J.P., Pont, D., Brownlie, R.K., Dunningham, A., Watt, M.S. and Pearse, G.D. 2016. Remote Sensing for Precision Forestry. *New Zealand Journal of Forestry*, 60(4): 15–24.

DJI. 2016. *Phantom 3 Pro*. Accessed 1 June 2016 at www.dji.com/phantom-3-pro.

ESA Sentinel. 2016. *ESA Sentinel Online*. Accessed 1 September 2016 at https://sentinel.esa.int/web/sentinel/home.

Fisher, J. 2016. *PCMag*. Accessed 28 June 2016 at http://au.pcmag.com/dji-inspire-1/36627/review/dji-inspire-1.

Headwall. 2016. *Headwall Nano Hyperspectral Camera*. Accessed 1 September 2016 at www.headwallphotonics.com/spectral-imaging/hyperspectral/nano-hyperspec.

MicaSense. 2016. *RedEdge™ by MicaSense*. Accessed 30 May 2016 at www.micasense.com/rededge/.

Nebikera, S., Annena, A., Scherrerb, M. and Oeschc, D. 2008. A Light-Weight Multispectral Sensor for Micro UAV – Opportunities for Very High Resolution Airborne Remote Sensing. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. XXXVII, Part B1, Beijing 2008. Accessed on Google Scholar on 3 May 2016 at www.isprs.org/proceedings/XXXVII/congress/1_pdf/204.pdf.

Nixon. 2016. *How to Select an Agriculture Drone: An In-Depth Buyer's Guide*. Accessed 2 February 2016 at http://bestdroneforthejob.com/drones-for-work/agriculture-drone-buyers-guide/.

Pebley, C.I. 1863. *US37771A, N. Peters*. Photouthograp United States Patent.

Popular Mechanics. 2015. 1 *Million Drones Will be Sold this Christmas and the FAA is Terrified*. Accessed 11 February 2016 at www.popularmechanics.com/flight/drones/news/a17535/the-faa-is-terrified-that-1-million-drones-will-be-sold-this-christmas/.

Puliti, S., Ole Ørka, H., Gobakken, T. and Næsset, E. 2015. Inventory of Small Forest Areas Using an Unmanned Aerial System. *Remote Sensing*, 7: 9632-9654. Accessed 28 June 2016 at www.mdpi.com/journal/remotesensing.

Rouse, J.W., Haas, R.H., Schell, J.A. and Deering, D.W. 1973. Monitoring Vegetation Systems in the Great Plains with ERTS. *Proceedings of the Third ERTS Symposium*. NASA, Washington DC, US, 10–14 December. NASA SP-351: 309–317.

Sensefly eBee. 2016. eBee, *Professional Mapping Drone*. Accessed April 2016 at www.sensefly.com/drones/ebee.html.

Tosh, C. and Jozkow, G. 2016. Remote Sensing Platforms and Sensors: A Survey. *PSPRS Journal of Photogrammetry and Remote Sensing*, 115: 22–36.

UAV Global. 2016. *Global Market for Commercial UAV's*. Accessed 15 March 2016 at www.uavglobal.com/commercial-uav-manufacturers/.

Vito. 2016. *COSI-cam Hyperspectral Imaging*. Accessed 1 September 2016 at http://hyperspectral.vgt.vito.be/sites/default/files/Vito_COSI_Fiche_WEB.pdf.

Wallace, L., Watson, C. and Lucieer, A. 2014. Detecting Pruning of Individual Stems Using Airborne Laser Scanning Data Captured From An Unmanned Aerial Vehicle. *International Journal of Applied Earth Observation and Geoinformation*, 30: 76–85.

Whitehead, K. and Hugenholtz, C.H. 2014. *Remote Sensing of the Environment with Small Unmanned Aircraft Systems (UAVs). Part 1: A Review of Progress and Challenges*. NRC Research Press.

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