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NOTE

UAV LiDAR for below-canopy forest surveys

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Abstract: Remote sensing tools are increasingly being used to survey forest structure. Most current methods rely on GPS signals, which are available in above-canopy surveys or in below-canopy surveys of open forests, but may be absent in below-canopy environments of dense forests. We trialled a technology that facilitates mobile surveys in GPS-denied below-canopy forest environments. The platform consists of a battery-powered UAV mounted with a LiDAR. It lacks a GPS or any other localisation device. The vehicle is capable of an 8 min flight duration and autonomous operation but was remotely piloted in the present study. We flew the UAV around a 20 m × 20 m patch of roadside trees and developed postprocessing software to estimate the diameter-at-breast-height (DBH) of 12 trees that were detected by the LiDAR. The method detected 73% of trees greater than 200 mm DBH within 3 m of the flight path. Smaller and more distant trees could not be detected reliably. The UAV-based DBH estimates of detected trees were positively correlated with the human-based estimates (R^2 = 0.45, p = 0.017) with a median absolute error of 18.1%, a root-mean-square error of 25.1% and a bias of −1.2%. We summarise the main current limitations of this technology and outline potential solutions. The greatest gains in precision could be achieved through use of a localisation device. The long-term factor limiting the deployment of below-canopy UAV surveys is likely to be battery technology.

Key words: LiDAR, forest survey, tree, diameter measurement, unmanned aerial vehicle, biomass estimation.

Résumé : Les outils de télédétection sont de plus en plus utilisés pour analyser la structure forestière. La plupart des méthodes courantes se servent de signaux GPS qui sont perceptibles au-dessus du couvert forestier ou en dessous du couvert forestier dans les forêts ouvertes, mais qui ne sont pas captables en dessous du couvert forestier lorsque la forêt est dense. Nous avons mis à l'essai une technique qui facilite la recherche mobile en dessous du couvert forestier où les signaux GPS ne sont pas captables. Notre plateforme consiste en un véhicule aérien sans pilote (UAV), alimenté par piles et muni d'un LiDAR. Il n'est équipé ni de GPS ni d'autre dispositif de localisation. Le véhicule a une capacité de vol et d'opération autonome d'une durée de huit (8) minutes, bien qu'il ait été téléguidé aux fins de la présente étude. Nous avons fait voler l'UAV au-dessus d'un terrain de 20 m × 20 m doté d'arbres d'alignement et avons élaboré un logiciel post-traitement afin d'évaluer le diamètre à hauteur d'homme (DHH) de 12 arbres détectés par le LiDAR. Cette méthode nous a permis de détecter 73 % des arbres dont le DHH était plus grand que 200 mm dans un rayon de 3 m de la trajectoire de vol. Les arbres plus petits et plus éloignés n'ont pu être détectés efficacement. Les estimations du DHH des arbres détectés à partir du UAV ont été positivement corrélées avec les estimations effectuées par les humains (R^2 = 0.45, p = 0.017), prenant en

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compte une erreur médiane absolue de 18,1 %, une erreur quadratique moyenne de 25,1 % et une erreur de justesse de –1,2 %. Nous résumons les principales limitations de la présente technique et proposons des solutions possibles. Par exemple, l'utilisation d'un dispositif de localisation pourrait améliorer de beaucoup la précision de la recherche. Le facteur limitatif à long terme de ce type de recherche en dessous du couvert forestier à l'aide d'un UAV est vraisemblablement l'alimentation par piles.

Mots-clés : LiDAR, analyse de la structure forestière, arbre, mesure du diamètre, véhicule aérien sans pilote, estimation de la biomasse.

1. Introduction

A range of remote-sensing technologies is currently available for assessing the structure of forest ecosystems (Gibbs et al. 2007). Specific applications include the estimation of carbon stocks (Mascaro et al. 2011; Asner et al. 2012*a*) and the identification of tree species (Dinuls et al. 2012; Feret and Asner, 2012). Technologies include above-canopy unmanned aerial vehicle (UAV)-based multispectral and LiDAR technology (Asner et al. 2007, 2012*b*; Goetz and Dubayah 2011; Turner et al. 2011; Stephens et al. 2012; Montaghi et al. 2013), ground-based stationary LiDAR (Forsman and Halme 2005; Watt and Donoghue 2005; McDaniel et al. 2012) and below-canopy UAV-based LiDAR in GPS-available environments (Jaakkola et al. 2010; Wallace et al. 2012). Ground-based robotic vehicle-mounted LiDAR may eventually automate below-canopy forest surveys (McDaniel et al. 2012), but this technology will face the challenges of steep terrain, thick understorey vegetation, and abundant debris characteristic of many forests. Below-canopy UAV-based surveys offer greater flexibility of movement but can be hampered by their reliance on GPS signals, which may not be available in dense forests. Current autonomous navigation systems for GPS-denied environments can operate successfully in indoor and urban environments (e.g., Bachrach et al. 2011), but have not been demonstrated in complex natural environments, such as forests.

Here we conduct a trial of UAV-mounted LiDAR for mobile below-canopy forest surveys in GPS-denied environments. The specific application we focus on is the mapping of tree stems and the measurement of tree diameter at breast height (DBH). Stem mapping and DBH measurement are core components of forest surveys (Condit 1998). Data from such surveys can be used to estimate stand basal area, successional status, crowding, and other forest structure parameters. Combined with allometric relationships, DBH measurements and stem maps can also be used to estimate tree biomass and its variation across a forest. This is of primary interest for studying ecosystem function, estimating forest carbon storage, and estimating timber yields. A current limiting factor in forest surveying is the need for labour-intensive manual measurement of stem locations and diameters: for example, it takes about 12 person-years to map and measure the hundreds of thousands of stems in a 50 ha long-term research plot (R. Condit, pers. comm., 2012). Here we provide a first glimpse into how UAV technology could be used to automate such surveys. We identify current limitations and chart some of the major technological challenges that will have to be overcome before this technology is feasible on scales relevant to science and forest management.

2. Methods

2.1. Platform

The UAV platform consists of a custom-built quadrocopter with integrated electronic system, Hokuyo UTM-30LX LiDAR, battery, inertial measurement unit (IMU), and foam protection scheme (which protects the UAV from impacts in horizontal directions). The LiDAR operates at 10 Hz with 1081 beams per scan, a scanning range of 30 m, and a scanning angle of 270°. The LiDAR is mounted at the centre of the UAV and scans only the horizontal plane (i.e., there is no vertical field of view). The central line of scan points forward, which aligns with the forward direction of the UAV. The UAV is capable of roughly 8 min flight duration. The UAV lacks a GPS or any other localisation device. Although the UAV hardware is capable of autonomous flight, autonomous navigation software is still in development and so the UAV was remotely operated in this trial.

2.2. Software

We developed postprocessing software in R, version 2.15.1 (http://www.r-project.org/), to reconstruct a map of a horizontal cross section of the forest from the laser scans and thereby estimate the DBHs of trees. The software uses pattern-matching algorithms to collate data from the laser scans and build a map of a horizontal cross section of the forest. This typically involves millions of data points: for each flight, the UAV produces $N = 10\ \text{Hz} \times T$ frames, where T is the flight duration in seconds, and each frame contains $n_B = 1081$ data points (one for each beam angle). Each raw data point consists of a reading that indicates the distance (d) from the UAV at which the LiDAR recorded an object. We culled any data points with $d < d_{\min} = 100$ mm or $d > d_{\max} = 6000$ mm because we considered these to be unreliable (the UAV never came within 100 mm of an object and slight changes to the pitch of the UAV can cause large errors in distant readings).

The map-reconstruction algorithm is described in detail in the supplementary material[1]. Briefly, the algorithm uses an iterative procedure to pattern-match each scan to the previous scans and thereby estimate the UAV location and orientation. The previous scans are stored not as raw points but as a set of merged points to facilitate faster computation. The pattern-matching algorithm uses a two-step least-squares procedure and makes the simplifying assumption that altitude, pitch, and roll are constant. The justification for this simplification is that in our field trial we maintained approximately constant height and zero pitch and roll. A more complete characterisation of the UAV position and orientation would allow six degrees of freedom (three Cartesian coordinates and pitch, roll, and yaw), and could utilise data from the onboard IMU. We address this further in the discussion (Sect. 4).

Having reconstructed the map of the forest, we wrote a clustering algorithm and applied it to the global point map. The algorithm works by setting a threshold (100 mm) within which points are assumed to belong to the same tree and then fitting circles to the resulting clusters. Circles are accepted as trees if goodness-of-fit criteria are satisfied (see supplementary material for details).

The algorithms described herein use various thresholds and step sizes (e.g., for the minimum angle over which points on an object had to be detected before it could be accepted as a putative tree stem; see supplementary material for details). These were tuned to produce a plausible UAV trajectory and to include as trees objects that appeared visually close to circular in the resulting map. Importantly, the entire software development and tuning process was carried out using only the laser scans from the field trial and in the absence of any knowledge about the absolute locations of trees or their DBHs (these data were collected afterwards in a ground-truthing survey: see Sect. 2.3).

2.3. Field site

Our trial site was a roadside on Old Holland Rd., Singapore (1°19′50″ N, 103°47′05 ″E). The site is flat, with vegetation comprising a planted grove of *Casuarina equisetifolia* (a species native to Singapore), occasional lianas and shrubs, and an understorey of mown grass. We flew the UAV for $T = 222$ s at 1.5 m above the ground (rather than the standard survey height of 1.3 m because the data were originally collected for a different purpose). The flight consisted of two laps of a loop approximately 15 m in diameter (Fig. 1) within a 20 m × 20 m area. Two laps allowed us to confirm that our map reconstruction algorithm could effectively "close the loop", that is, to recognise when it had returned to a previously visited location.

After running the postprocessing software on the UAV flight data, we returned to the site to ground-truth the UAV method by measuring and mapping all trees within 6 m of the UAV's flight path.

3. Results

From the Old Holland Rd. UAV data, the software reconstructed an accurate map of a horizontal plane of the forest (Fig. 1) comprising 2432 final points (merged from 4 990 977 scanned points). The software detected 12 objects in this map that suitably approximated circles and estimated their DBHs. The postprocessing of the data took several hours on a desktop machine. The UAV-measured and human-measured DBHs were positively correlated ($R^2 = 0.45$, $p = 0.017$; Fig. 2*a*). The median absolute error in the UAV-based estimates was 18.1% and the root-mean-square error was 25.1%. The bias was −1.2%. All of the detected trees were within 3 m of the UAV's path and had true (human-measured) DBHs of greater than 200 mm, with the exception of one tree that had a true DBH of 139 mm. The UAV-based method failed to detect four trees that met these criteria (Fig. 2*b*), so the effective detection rate for trees greater than 200 mm DBH within 3 m of the UAV's path was 73%. Failure to resolve stems was in some cases attributable to lianas and shrubs obstructing the LiDAR's view (Fig. 1*a*–*b*). Failure to resolve stems more than 3 m away (there were 11 such stems greater than 200 mm DBH at the site) was attributable to insufficient scanned points. Failure to resolve stems below 200 mm DBH was attributable to noise in the data that confounded the circle-fitting algorithm.

[1]Supplementary data are available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/juvs-2013-0017.

Fig. 1. Main panel: Reconstructed map of the Old Holland Rd. site based on laser scans from the UAV. The red "X" and "O" indicate the start and end of the UAV's trajectory. Grey points indicate points from the final global map, with darker colours indicating greater weights (i.e., points formed from larger numbers of raw scanned points). The blue circles with labels in millimetres indicate estimated tree DBHs from the UAV data. Inset panels show enlargements of scans of two trees. Lower panels A and B show enlargements of the "A" and "B" clusters from the upper panel, which were found in subsequent ground truthing to be trees obscured by a liana and a shrub, respectively (photos).

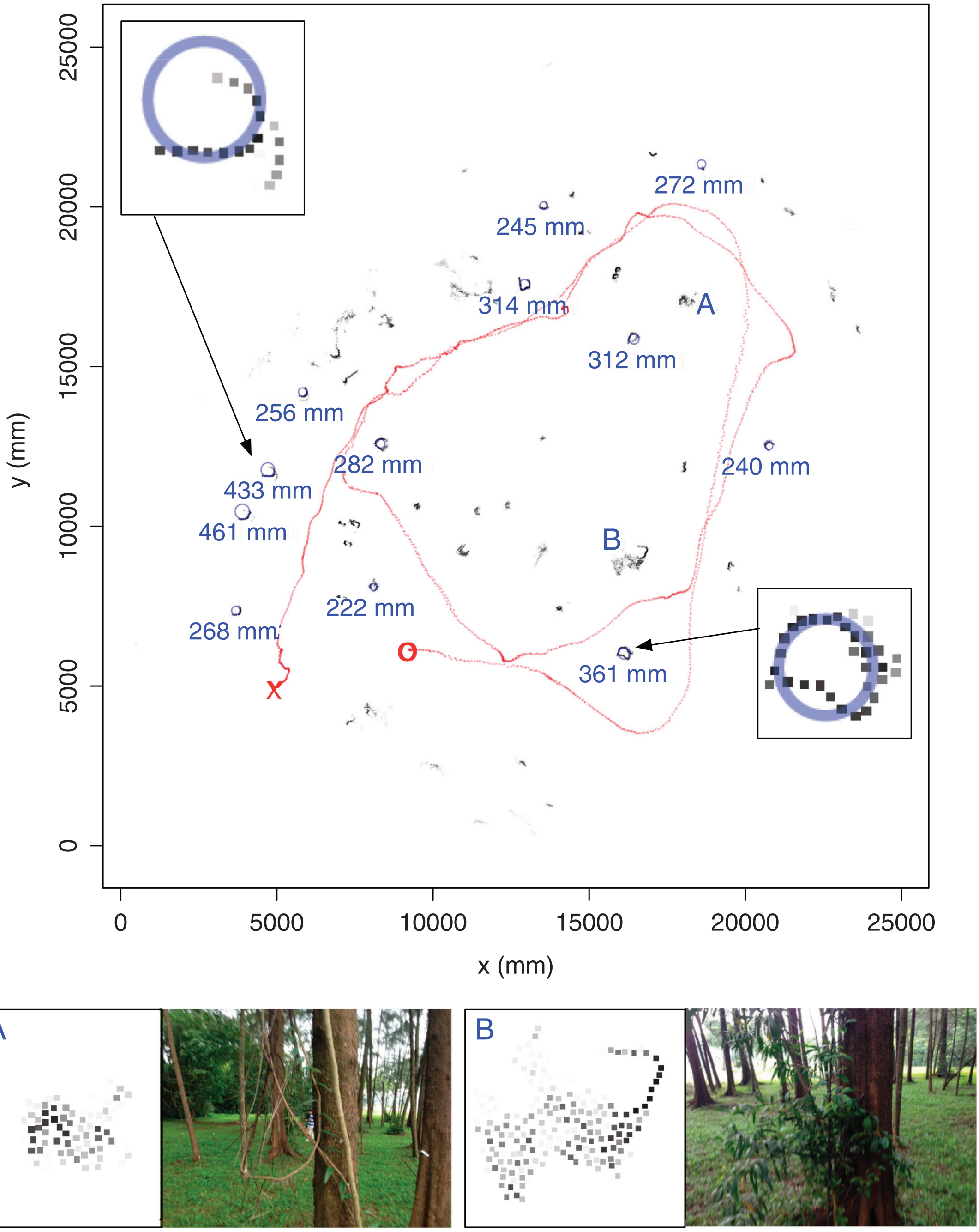
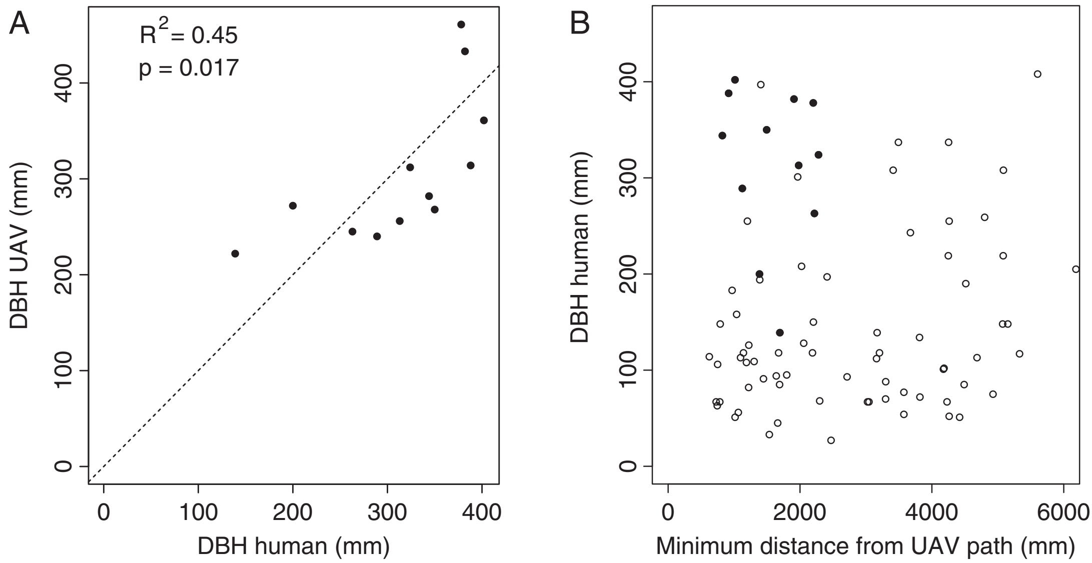


Fig. 2. (A) Comparison of UAV-measured and human-measured DBHs for the 12 UAV-detected trees at the Old Holland Rd. site. Each point represents a tree. The dashed line is the 1:1 line. (B) Human-measured DBH versus minimum distance from UAV path for all trees within 6 m of the UAV path (Fig. 1). Solid points represent the 12 UAV-detected trees from A. Open points represent trees that were not detected.



We observed that the map reconstruction algorithm was able to effectively "close the loop" on the second lap of the UAV's flight path by using landmarks to realise that it had drifted slightly and then snap back to the correct trajectory (e.g., the 433 mm tree shown enlarged in Fig. 1 shows a series of faint points representing the initial scans on the second lap before the map reconstruction algorithm corrected the UAV location and orientation to match the scans from the first lap (darker points)).

The point density (ρ) achieved by the system on each scan can be calculated from the formula $\rho = 1081/(3\pi r/2) \approx 230/r$. The furthest resolvable trees from the UAV were at a distance of about $r = 2.5$ m, which translates to a point density of 92 points/m. Our map reconstruction algorithm merges points from subsequent scans as it works, and each final point cluster (corresponding to a single stem; Fig. 1) typically contains between 10 and 30 merged points, representing a few thousand raw scanned points.

4. Discussion

The use of UAV-mounted LiDAR for below-canopy GPS-denied forest surveys has several current limitations, but appears to be a promising technology. The method was able to detect and measure most trees above 200 mm DBH and within 3 m of the UAV's path (Fig. 2*b*). Trees below 200 mm DBH or further than 3 m away could not be detected and measured reliably (Fig. 2*b*). The UAV-measured DBH estimates were strongly positively correlated with the human-based ones (Fig. 2*a*), although the root-mean-square and median errors of 25.1% and 18.1% are much larger than the corresponding errors of 8.0% and 0.9% in human-measured DBHs at Barro Colorado Island in Panama (based on raw data from Rüger et al. 2011). The DBH errors were comparable to those from a previous study using a fixed ground-based LiDAR of the same model (McDaniel et al. 2012), but larger than those from studies using bulkier ground-based LiDAR (e.g., Henning and Radtke 2006). The greater precision of bulkier LiDAR is to be expected, but such instruments are unsuitable for carrying on small below-canopy UAVs.

4.1. Current limitations and future improvements

The main limitations of the technology trialled here, and potential solutions, are summarised in Table 1. It is clear from the table that the greatest improvements could be achieved by adding a localisation device to the UAV. As noted, GPS devices are unreliable under the forest canopy, so the localisation device would have to communicate with ground-based transmitters. The UAV we used has no such localisation device, because it was originally built for the development of simultaneous localisation and mapping software for large-scale autonomous navigation through the forest (for a different

Table 1. Current limitations of the below-canopy UAV LiDAR technology and future research directions.

	Research directions	
Current limitation	Software	Hardware
Reliance on remote control for UAV navigation	Develop autonomous navigation software. Incorporate data from the inertial measurement unit.	Add localisation device to UAV and ground-based receivers to facilitate autonomous navigation software.
Map reconstruction algorithm unable to resolve complex objects	Relax assumption by map reconstruction algorithm that all scans are in the same horizontal plane.	Add localisation device to UAV to improve accuracy in estimated relative locations of scans.
Map reconstruction algorithm unable to resolve trees below 200 mm DBH reliably	As above.	Use higher-resolution LiDAR. Localisation device will also help.
Assumption of circular tree cross sections	More flexible curve-fitting algorithms.	NA
Required intensive postprocessing of data for map reconstruction	Optimise code. In particular, many operations may be parallelised.	Localisation device will eliminate the need for complex pattern-matching algorithms.
Short battery life (≈ 8 min)	NA	In the short to medium term, seek to minimise payload. In the longer term, wait for improved battery technology.
Environmental hazards (e.g., moving branches)	Improved map reconstruction algorithms will allow autonomous navigation software to detect and avoid large branches and other major stationary obstacles.	Higher-resolution LiDAR will allow the detection of smaller obstacles. Protective foam casing may need to be upgraded to a cage to prevent small or moving branches from obstructing the rotors.
No vertical field of view	When developing autonomous navigation software, allow changes of UAV pitch and altitude in order to scan 3D objects with the existing 2D LiDAR.	Use 3D LiDAR. Current 3D LiDARs are too heavy for the UAV, but future models may be lighter.

research project), and the use of a localisation device with ground-based transmitters would have defeated this purpose. For the purpose of mapping a smaller area of forest, however, the use of ground-based transmitters would be acceptable.

The original motivation for this study was the mapping and measurement of tree stems in forests. Many forest surveys map and measure trees above 100 mm DBH. Athough we were unable to resolve trees less than 200 mm DBH reliably in this study, we expect that with the addition of a localisation device and software enhancements, our current platform could eventually be used to conduct surveys of trees down to the 100 mm DBH threshold, at least in fairly open forests. More challenging would be conducting forest surveys down to the 10 mm DBH threshold characteristic of more intensive ecological surveys (e.g., Condit 1998). The point density achieved on each LiDAR scan (about one point per centimetre on trees 2.5 m away) is currently too low for reliable detection or measurement of trees near the 10 mm DBH threshold. UAV-based surveys of these small trees must await improvements in LiDAR technology (Table 1).

Improved versions of the map reconstruction software would also incorporate roll, pitch, and yaw data from the IMU that are currently ignored (e.g., Bosse et al. 2012), and would take advantage of the parallel nature of the pattern-matching algorithms (the code currently runs in serial). The current map reconstruction software makes the simplifying assumption that roll and pitch are zero and that UAV height is constant. In the field trial, we attempted to fly a flat horizontal path, but nevertheless violations of these assumptions (i.e., movement of the LiDAR beam outside a single horizontal plane) are probably responsible for a proportion of the error in DBH measurements (Fig. 2). A complete six-dimensional characterisation of the UAV position and orientation would mitigate this problem. Considering these potential improvements (see also Table 1) and ongoing computer hardware advances, we anticipate that it will soon be feasible to develop map reconstruction software that runs in real time and facilitates autonomous navigation. It should be noted that autonomous UAV navigation systems are already able to navigate GPS-denied indoor and urban environments successfully in real time (Bachrach et al. 2011), but the much greater structural complexity of a forest presents greater navigation challenges.

The long-term limitation to the technology trialled here is likely to be battery life. Flight durations are currently limited to about 8 min, and battery technology is advancing less rapidly than other hardware. In principle, we could use a fuel-based engine to power the UAV, although the air pollution and noise associated with this may be unacceptable in the research areas and conservation sites where the technology would be most applicable.

4.2. Future applications

The UAV-based LiDAR technology can potentially provide estimates of tree biomass by applying allometric relationships to DBHs. In the longer term, the UAV technology can potentially be used to overcome the need for allometric equations by constructing 3D models of trees and estimating biomass directly. Direct estimates of tree biomass can in turn benefit above-canopy LiDAR, which relies on calibration to ground-based data (Asner et al. 2012*b*). Another long-term possible application of 3D UAV LiDAR in forests is the estimation of fuel loads over larger areas than is feasible with manual surveys. Estimating forest fuel loads is essential for developing accurate fire models and implementing fire-management strategies.

In coming years, the below-canopy UAV technology will likely be most feasible in forests on flat terrain with an open understorey and large regular-shaped trees. In the longer term, with the eventual development of autonomous navigation, improved battery technology, and advances in DNA barcoding (Kress et al. 2009; Steele and Pires 2011), we foresee a broader range of applications for below-canopy UAV-based forest surveying, in conjunction with traditional field surveys, above-canopy remote sensing and ground-based LiDAR.

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