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REVIEW ARTICLE

Drone remote sensing for forestry research and practices

Lina Tang[1] · Guofan Shao[2]

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Abstract Drones of various shapes, sizes, and functionalities have emerged over the past few decades, and their civilian applications are becoming increasingly appealing. Flexible, low-cost, and high-resolution remote sensing systems that use drones as platforms are important for filling data gaps and supplementing the capabilities of crewed/manned aircraft and satellite remote sensing systems. Here, we refer to this growing remote sensing initiative as *drone remote sensing* and explain its unique advantages in forestry research and practices. Furthermore, we summarize the various approaches of drone remote sensing to surveying forests, mapping canopy gaps, measuring forest canopy height, tracking forest wildfires, and supporting intensive forest management. The benefits of drone remote sensing include low material and operational costs, flexible control of spatial and temporal resolution, high-intensity data collection, and the absence of risk to crews. The current forestry applications of drone remote sensing are still at an experimental stage, but they are expected to expand rapidly. To better guide the development of drone remote sensing for sustainable forestry, it is important to systematically and continuously conduct comparative studies to determine the appropriate drone remote sensing technologies for various forest conditions and/or forestry applications.

Keywords Drone · Remote sensing · UAV · UAS · UA · RPA · Forest

Introduction

Accurate information about forest composition, structure, volume, growth, and extent is essential for sustainable forest management and can be extracted directly or indirectly from remotely sensed imagery (Shao 2012a). Over the past few decades, increasing attention has been focused on improving remote sensing applications in forestry. This is evidenced by the increase in publications in ISI-indexed journals: the results of an ISI-indexed publication search using "forest" and "remote sensing" as key words reveal one article published in the 1960s; four in the 1970s; 24 in the 1980s; 536 in the 1990s; 2519 in the 2000s; and 2930 from 2010 to 2014. The sharpest jump in the number of publications between the 1980s and 1990s reflects the rapid advances in civilian satellite remote sensing achieved during that period (Boyd and Danson 2005; Shao 2012b). The Landsat program is world's longest remote sensing program for observing Earth resources, and its imagery is most often used in forestry (Alberts 2012).

Along with the development of sensor and computation technologies, remote sensing applications in forestry have evolved from conventional aerial photography-based forest inventories (Lyons 1966) to satellite imagery-based forest resource monitoring (Asner et al. 2005; Tang et al. 2010; Pope et al. 2015), from multispectral data-based forest

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Corresponding editor: Chai Ruihai

✉ Guofan Shao
shao@purdue.edu

[1] Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, China

[2] Department of Forestry and Natural Resources, Purdue University, 715 West State Street, West Lafayette, IN 47907, USA

cover mapping (Zhu and Evans 1994; Shao et al. 1996) to hyperspectral data-based biophysical forest estimations (Martin and Aber 1997; Treitz and Howarth 1999), and from passive remote sensing-based forest leaf area index measurements (Turner et al. 1999; Thakur et al. 2014) to active remote sensing-based forest structure characterizations (Dubayah and Drake 2000; Lefsky et al. 2002). Through the integration of multiple data sources, it is possible to improve estimations of forest volume and biomass (Lu 2006; Koch 2010).

Although remote sensing is widely used in forestry, technical challenges still exist. One of the most critical barriers to remote sensing applications in forestry is the lack of timely data collection over target areas. For example, when one wants to assess pest outbreaks (Wulder et al. 2006) or wildfire spread (Arroyo et al. 2008) in a forested landscape, appropriate satellite imagery might be unavailable and aerial photography from crewed/manned aircrafts might be unaffordable. Moreover, stand-level information is critical for sustainable forestry (Zhang and Jim 2013) but cannot be extracted from medium- or coarse-resolution remote sensing approaches. Flexible and inexpensive remote sensing systems can help supplement existing remote sensing capabilities and explore new applications. Drones as remote sensing platforms have the potential to increase the efficiency of data acquisition, but their applications are still at an experimental stage (Ambrosia et al. 2011a; Wing et al. 2013; Shahbazi et al. 2014). Here, we briefly review the fundamental concepts and initial applications of drone-based remote sensing in forestry research and hope to guide forestry professionals and researchers to better apply this new geospatial technology.

Drones as platforms

The Merriam-Webster Dictionary defines a drone as "an unmanned aircraft or ship guided by remote control or onboard computers". Drones are also referred to as unmanned aerial vehicles (UAV), unmanned aerial systems (UAS), unmanned aircrafts (UA), or remotely piloted aircrafts (RPA). Sometimes the term UAV is purposely changed to UAS to reflect the complex systems that are involved in drone operations. The term RPA is typically used by the military (Ambrosia et al. 2011a). Initial forms of drones were developed in the early 20th century (Zaloga 2008). Since the 1950s, drones' major mission has been aerial reconnaissance. As of 2005, the development of drones for military purposes still dominated the drone industry (Colomina and Molina 2014). Over the past few decades, drones of various shapes, sizes, and capabilities have been developed so rapidly that their potentials for civilian applications are overwhelming (Colomina and Molina 2014).

There are different classifications of drones. For example, Watts et al. (2012) classified drones into seven categories: MAV (Micro or Miniature) or NAV (Nano Air Vehicles), VTOL (Vertical Take-Off & Landing), LASE (Low Altitude, Short Endurance), LASE Close, LALE (Low Altitude, Long Endurance), MALE (Medium Altitude, Long Endurance), and HALE (High Altitude, Long Endurance). Anderson and Gaston (2013) classified drones into four size classes: large, medium, small and mini, and micro and nano. Furthermore, others have classified drones into five usage types: target and decoy, reconnaissance, combat, research and development, and civil and commercial (www.theuav.com).

There are two major types of drones based on takeoff and landing techniques: horizontal takeoff and landing and vertical takeoff and landing. Horizontal takeoff and landing are typical characteristics of fixed-wing drones (airplanes), whereas rotorcrafts or rotary-wing drones (helicopters and autogyros), ships, and balloons perform vertical takeoff and landing. For the purpose of remote sensing applications, stability and flight range are critical considerations in drone development. Fixed- and rotary-wing drones perform differently in terms of stability and range. When field coverage is large, fixed-wing drones may be preferable, whereas rotary-wing drones may be more suitable for achieving high spatial resolution measurements. A notable advantage of fixed-wing drones is that minimal experience is required to operate them. However, as more rotor blades are added, the risk of system crashes is reduced for rotary-wing drones (Anderson and Gaston 2013). Large fixed-wing drones need a runway to take off and land, whereas smaller ones can be launched manually or by using ground stands or vehicles.

Power source directly affects flight endurance (Dudek et al. 2013), and is thus, one of the most important elements of drone equipment. Although internal combustion engines are common for state-of-the-art drones, electrical motors are better choices for smaller drones. Because electrical motors are more economical and vibrate less, they are more suitable for remote sensing applications. Various batteries and fuel cells are available to power electrical motors on drones. In the future, solar energy will be able to help increase flight endurance from hours to days and even years.

Maximum payload weight determines how heavy a suitable sensor on a drone should be. Heavier sensors generally require larger drones. The weight of drone payload ranges from dozens of grams to hundreds of kilograms.

Drones fly autonomously or through remote control/piloting. Autonomous flights are preprogrammed each time with computers and are suitable for systematic landscape mapping. Remotely piloted drones are effective for providing photographs and videos at a local level.

Drone remote sensing

The earliest aerial photographs were taken in the 1860s using balloons as platforms. During World Wars II and I, airplanes were used as aerial photographic platforms. The first generation of Earth-orbiting satellites was launched into space around 1960, and they were exclusively made for reconnaissance. Previously, all the data collected from the Earth's atmosphere or space was in analog form (i.e., film). Since the 1970s, digital sensors have been employed, satellites have been launched for civil applications, and the term remote sensing has become formal. In addition, airborne remote sensing and spaceborne/satellite remote sensing have gradually become well-known terms. Drones had been used for reconnaissance for decades before they were employed for civilian purposes, but their recent application to remote sensing was exceptionally fast. Currently, drones are found in the fields of meteorology, precision agriculture, wildlife research, forestry, land management, infrastructure inspection, traffic monitoring, epidemic emergencies, natural disaster management, and wilderness search and rescue (Shahbazi et al. 2014). We recommend calling this large-scale remote sensing initiative *drone remote sensing* to distinguish it from crewed aircraft remote sensing and make it comparable to satellite remote sensing (Fig. 1).

Drones can carry a variety of sensing instruments, including visible light, near infrared (NIR), shortwave infrared (SWIR), thermal infrared (TIR), Radar, and Lidar sensors. Drone-borne optical sensors, including visible, NIR, and SWIR, also record data as multispectral or hyperspectral bands (Berni et al. 2009; Saari et al. 2011; Shao 2015). Owing to advances in sensor technology, increasingly smaller, lighter, and cheaper sensors have become available for drone remote sensing applications. Anderson and Gaston (2013) and Colomina and Molina (2014) provide detailed introductions to various drone remote sensing systems.

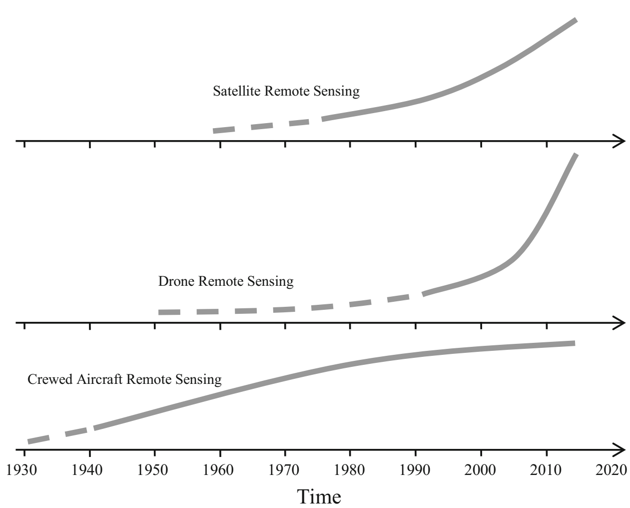

Fig. 1 A conceptual comparison of relative development trends among three remote sensing disciplines. *Dashed lines* represent reconnaissance-dominated applications, and *solid lines* indicate mainly civilian applications. Slopes of the temporal curves reflect the pace of advancement in platform diversity, sensor functionality, and data richness

Application examples

The benefits of drone remote sensing include low material and operational costs, flexible control of spatial and temporal resolution, high-intensity data collection, and absence of risk to crews. The following pioneer studies demonstrate the unique advantages of drone remote sensing for forestry research and practices.

Surveying forests

Koh and Wich (2012) experimented with using drone remote sensing to survey and map tropical forests in Indonesia because of the high costs of high-resolution satellite remote sensing data, frequent cloud cover, and difficult/expensive ground surveys. The experiment involved an inexpensive (<\$100) and lightweight (~650 g) fixed-wing drone powered by a 2200 mAh battery and a still/video camera. This drone could fly for ~25 min per mission and cover a total distance of ~15 km. The researchers assembled the drone images to develop land use/cover maps at a spatial resolution of 5.1 cm, used the video footage to detect human activities (e.g., burning and logging), and combined the photographic and video information to survey wildlife species and identify flora. They suggested that using drone remote sensing could lead to significant savings in terms of time, manpower, and financial resources for local conservation workers and researchers in the developing tropics. Such applications especially make sense for community-based forest monitoring and forestry programs, such as REDD (Reducing Emissions from Deforestation and forest Degradation), in developing countries (Paneque-Galvez et al. 2014). Many forest surveyors have started to enhance forest measurements with drone remote sensing (Fig. 2).

Mapping canopy gaps

Forest canopy gaps reflect disturbance and affect forest diversity and productivity, but small forest gaps cannot be measured accurately with satellite remote sensing (Frolking

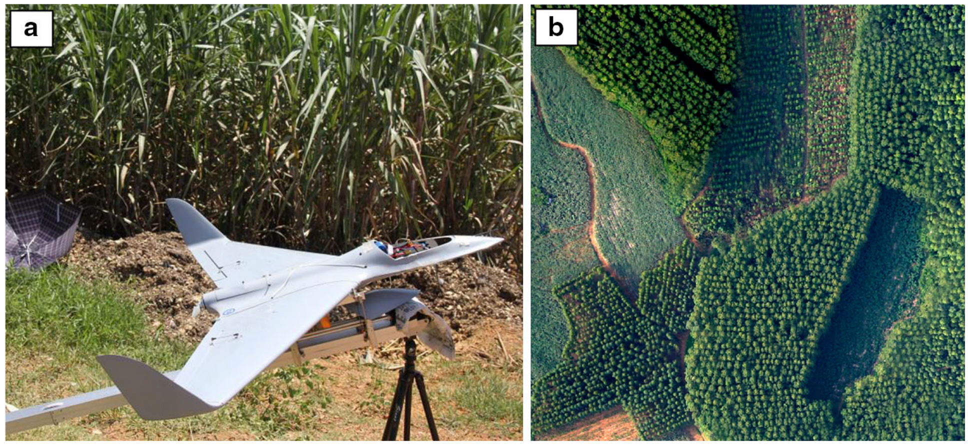

Fig. 2 A picture of a fixed-wing drone **a** owned by China's Guangxi Forest Inventory and Planning Institute and a 20-cm resolution image **b** obtained with the drone flying at 400-m altitude. The image covers an area of 9 ha, and the forest stands shown in the image are *Eucalyptus* plantations of ages ranging from 1 to 6 years. Both the picture and image are credited to Dr. Chungan Li

et al. 2009). Getzin et al. (2012) obtained 7-cm-resolution, natural-color images for beech-dominated deciduous and deciduous-coniferous mixed forests in Germany, as such resolution permits the accurate identification of gap objects as small as 1 m^2. With a wing span of 2 m and a weight of 6 kg, the drone could fly up to 250 m in altitude for up to 60 min. The flight lines were preprogrammed, and all images were orthorectified based on the internal drone orientation, GPS position, and a digital terrain model. The researchers found strong correlations between the biodiversity measurements and forest gap metrics obtained from drone remote sensing. This study suggests that drone remote sensing is capable of acquiring very high-resolution images suitable for characterizing forest gaps as reliable indicators of biodiversity. The key to the successful high-resolution image acquisition in this study was that the drone could fly at low altitudes. An important imaging product is the digital surface model, which is also useful for measuring forest canopy height, as described below.

Measuring forest canopy height

Forest canopy height is a critical parameter of forest quantification, and it is traditionally estimated with analog photogrammetric methods and ground surveys. Lidar technologies have become a new means for estimating canopy height (Lefsky et al. 2002), and traditional photogrammetry has almost been abandoned in forestry. This is particularly the case as drone-borne Lidar technologies are becoming more affordable (Tulldahl and Larsson 2014; Wallace et al. 2014). In addition, high-resolution, low-oblique drone-borne optical imagery promotes forest canopy height measurements through the integration of digital photogrammetry and structure-from-motion techniques (Siebert and Teizer 2014).

Lisein et al. (2013) demonstrated a similar approach for a forest in Belgium. They used a small fixed-wing drone with a wingspan of 1 m, a weight of 2 kg, a cruise speed of 80 km/h, a flight height of 100–750 m, and maximum flight duration of 40 min to obtain NIR images with a spatial resolution of ~7.6 cm. The measurements of forest canopy height derived from the inexpensive photogrammetric method were in strong agreement with Lidar data obtained from an expensive crewed aircraft.

Zarco-Tejada et al. (2014) quantified the tree height in 158 ha of forestland in Spain using a low-cost camera mounted on a fixed-wing drone with a 2-m wingspan and a flight speed of 63 km/h. A low-cost camera was modified to obtain color infrared images at a spatial resolution of 5 cm. The tree height values obtained from the images were accurate when they were compared with ground-measured values.

A study by Dandois and Ellis (2013) was conducted with a similar photogrammetric approach in the U.S. They acquired overlapping aerial photographs with a consumer-grade camera mounted on a small rotary-wing drone that flew at low altitude (<130 m). The study site covered three 625-ha deciduous forests in the state of Maryland. They were satisfied with the ability of this approach to observe 3D canopy phenology at high temporal resolutions. Such inexpensive but effective technologies for the multispectral 3D scanning of vegetation provide foresters with another good reason to apply drone remote sensing to their research.

The three experiments described above suggest that this inexpensive optical approach has a similar accuracy to more complex and costly Lidar systems.

Tracking forest wildfires

The use of remote sensing to support real-time fire-control tactics is in its infancy (Wing et al. 2014). The MODIS satellite imagery has a high temporal resolution (1–2 days revisiting time) and is commonly applied in forest wildfire monitoring and management. However, the low spatial resolution of MODIS is insufficient for this task at local scales. Crewed aircraft deployments for the real-time monitoring of the spread of forest wildfires are potentially unsafe to crews.

Between 2006 and 2010, NASA and the US Forest Service demonstrated the employment of a large, long-duration (24 h), fixed-wing drone for assisting forest wildfire management (Ambrosia et al. 2011b; Hinkley and Zajkowski 2011). The drone weighed nearly five tons and could carry instruments weighing up to one ton. The researchers mounted a multispectral scanner to autonomously collect image data with 16 bands, ranging from visible to TIR. The TIR-band information provided enhanced wildfire images. The drone remote sensing missions provided near real-time (5–10 min) intelligence to support forest wildfire management.

The ability of rotary-wing drones to detect forest wildfires was also tested in Portugal and Spain (Martinez-de Dios et al. 2011; Merino et al. 2012). A series of experiments indicated that rotary-wing drones could effectively collect real-time data of forest wildfires. Specifically, the simultaneous use of multiple drones, either autonomous or remotely controlled, allowed larger areas to be measured and obtained complementary views of wildfires. Medium- and high-altitude drones are more suitable for flying over wildfire areas.

Supporting intensive forest management

Intensive forest management is an effective approach to promoting forest productivity and meeting the increasing demand for timber (Arano and Munn 2006; Bai et al. 2015). The management of fast-growing forest plantations is similar to the practice of precision agriculture and can be promoted with drone remote sensing (Wang et al. 2014). A typical exercise is applying fertilizer at the right time and in the right place. Felderhof and Gillieson (2011) acquired NIR imagery with drone remote sensing to map tree canopy health in a macadamia plantation. They found a significant correlation between spectral radiometry and leaf nitrogen levels determined by field sampling. This approach exploited drones to help cut the cost of intensive forest management and increase economic returns.

Forest density control is a traditional forestry practice that is critical for maximizing forest productivity. With drone remote sensing, it is possible to obtain wall-to-wall forest density information at a landscape level (Fig. 2b).

The pruning of forest plantations is important for increasing timber quality and value. Wallace et al. (2014) conducted an experiment to obtain three-return Lidar data of a 4-year-old *Eucalyptus* stand located in Tasmania, Australia. The scanner platform was a rotary-wing drone, which could fly at a low altitude (40 m) and at low speed. This way they obtained high-density point clouds (145 and 220 pulses/m^2). The Lidar data were collected before and after pruning. Individual tree crowns were automatically segmented from the data and both crown volume and base height were determined using the geometry of the point cloud. The results showed significant differences in canopy properties between unpruned and pruned stems, indicating that the drone-based Lidar system could effectively distinguish pruning treatments. At the individual tree-level, there were moderate correlations between Lidar-derived and field-measured crown base heights. As laser scanners continuously become lighter, they can be mounted on smaller drones (Tulldahl and Larsson 2014), making their forestry applications more efficient and affordable.

Concluding remarks

The five types of applications discussed above demonstrate the advantages drone remote sensing has over established remote-sensing methods. Continuous developments of new drones and sensors are making remote sensing applications more appealing. Some of the applications that can be accomplished inexpensively with drone remote sensing are difficult to conduct using crewed aircraft remote sensing or satellite remote sensing. Without crews, drones can be extremely small, and their flight endurance can be increased as a result of greater fuel economy (Wing et al. 2014). Some drones are so small that they can fly near forest canopies; some drones are big enough to fly at medium or high altitudes and can fly repeatedly to record the extent of an ongoing wildfire without jeopardizing crews' safety.

In the field of modern forestry, rational forest management requires detailed forest information in digital format (Tang et al. 2009). Forestry has a history of employing aerial photography to obtain forest information. During the past a half century, satellite imagery has become an important data source for forestry research. The present form of drone remote sensing applications in forestry is still at an initial stage, but it is reasonable to anticipate that the role of drone remote sensing will surpass crewed aircraft remote sensing in the near future. The flexibility and low cost of drone remote sensing is beneficial to transforming conventional forestry data into digital formats, enabling forestry practices to become more precise and efficient (Zhao et al. 2005).

Nevertheless, there are challenges for conducting regulated, safe, and comprehensive applications of drone remote sensing. Specifically, platforms, sensors, operations, and environments all have constraints (Anderson and Gaston 2013). Wing et al. (2013) explained that smaller drones are more susceptible to weather and human-related accidents, and therefore, may incur potentially large expenses due to damage from hitting the ground. The high diversity of platforms and sensors enables broad applications of drone remote sensing, however, inconsistencies in these technologies present barriers to standardized and up-scaled applications of drone remote sensing. Unfortunately, there are no multidisciplinary collaborations to promote the standardization of drone remote sensing development (Shahbazi et al. 2014). It is important to systematically and continuously conduct comparative studies to determine the appropriate drone remote sensing technologies for various forest conditions and/or forestry purposes.

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