Journal of Tropical Forest Research 3 (1) : 54-61 (2019)

Original article

A Comparative Evaluation of Unmanned Aerial Vehicles (UAVs) for Forest Survey

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Received: Feb 27, 2019 Revised : May 7, 2019 Accepted : Jun 19, 2019

ABSTRACT

Small unmanned aerial vehicles (UAVs), or drones, are being used increasingly in mapping, monitoring, and inventorying forests. However, there is a lack of guidelines which can help forest managers in selecting a suitable UAV, cameras, and survey settings for a specific forest area. The objective of this study was to develop an overview by comparing the circumstances under which multicopter and fixed-wing UAVs can be used in forest surveys.

The general relationships of ground sampling distance, image overlap, flight altitude, and speed, as well as the camera system were established and described. Based on these relations, the UAV systems were compared for their applicability and efficiency in surveying different forest areas.

The comparison of multicopter and fixed-wing UAV systems showed that surveys of large forest areas at a ground sampling distance (GSD) of more than 5 cm should be conducted using fixed-wing UAV to shorten flight times and improve survey efficiency. In contrast, surveys of tree seedlings would require a multicopter, whose low flight speed could ensure high image overlaps at a high ground resolution. Thus, the selection of a UAV system is mainly dictated by the required GSD and survey area.

Keywords: Fixed-wing UAV, Multicopter, Forest survey, Photogrammetry, Structure-from-motion

INTRODUCTION

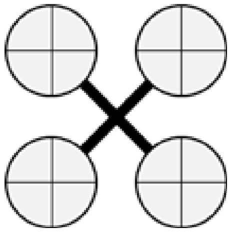
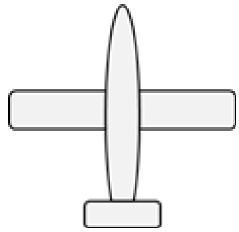
Small unmanned aerial vehicles (UAVs) or drones, are being increasingly used for mapping, monitoring, and management of forest resources. This is a direct result of a continuous decline of their purchase price and costs of operation in the last decade (Koh and Wich, 2012; Zhang *et al.*, 2016). UAVs have several advantages over other remote sensing platforms, which make them useful in natural resource management and research (Paneque-Galvez *et al.*, 2014). Firstly, the cameras installed on a UAVs capture images at an altitude between 50 and 300 m above the ground producing imagery of a very high spatial resolution (3-10 cm/pixel depending on the camera type). At this spatial resolution, individual trees and canopy gaps can be identified and monitored easily. This is possible only because UAVs can fly over areas which would be otherwise be difficult to access. Secondly, UAVs can also provide information at a high temporal resolution in addition to their high spatial resolution, as the low costs of operation allows the operators to conduct forest surveys much more frequently. The produced aerial imagery can be used to determine structural forest parameters such as tree height, crown area, and tree density.

Eventhough the market for and variety of the available UAV models has increased steadily in recent years, many forest managers remain unaware about the potentials and limitations of UAVs in forest inventories. The availability of UAV technology is steadily increasing, but despite its potential, the utilization in Thailand's forest industry is still limited. An important reason is the lack of skilled UAV technicians, operators, and pilots despite the fact that UAV-based forest surveys could provide accurate forest stand information more efficiently than conventional ground-based forest surveys. Moreover, knowledge regarding the efficient use of UAVs in forest surveys is limited.

UAV-based surveys using cameras, instead of laser-based sensors, rely on photogrammetric techniques, such as "Structure-from-motion", in which the images are aligned through an identification of the common points in order to determine the location of each camera (Niethammer *et al.*, 2010). During the processing of survey images, first, a two-dimensional orthorectified map, or orthomosaic, is created in which the camera distortions are geometrically corrected. Second, a three-dimensional point cloud of the surveyed area is produced, which is used to generate a digital surface model (DSM). In combination with an accurate digital terrain model (DTM), the DSM can be used to estimate tree heights as a difference between DSM and DTM (Kellner *et al.*, 2009).

UAVs are controlled through a ground control station and equipped with an autopilot to control the flight behavior, a GPS system for navigation, batteries, as well as an onboard camera. There are two types of UAV platforms commercially available: multicopter and fixed-wing (Table 1). Multicopter UAVs are equipped with at least four propellers and can take-off and land vertically due to their ability to hover and fly very slowly. In contrast, fixed-wing UAVs require larger landing areas similar to airplanes. However, fixed-wing UAVs can fly faster and are more energy-efficient and, thus, can have longer flight times. Under normal survey conditions, a multicopter can fly for a maximum time of around 30 min, whereas a fixed-wing UAV can fly for up to 60 min. Regardless of the platform type, UAVs carry their camera along the same grid-like flight pattern to ensure optimal image processing. The flight time a UAV can achieve with fully charged batteries greatly affects its operational costs. Longer flight time means that larger areas can be covered in a shorter time period without the need for landing, recharging, and flight preparations.

Table 1 Comparison of multicopter and fixed-wing UAV platforms (own elaboration)

	Multicopter	**Fixed-wing UAV**
Appearance		
Flight speed	3-6 m/s	12-20 m/s
Flight time	20-30 min	45-75 min
Landing space	Small (10 m × 10 m)	Large (20 m × 60 m)

In this study, the multicopter and fixed-wing UAVs are compared in terms of their applicability and efficiency in forest surveys. This was done by assessing the impact of their flight speed and endurance (flight time) on survey parameters, such as ground sampling distance (GSD), frontal overlap, and maximum survey area.

MATERIALS AND METHODS

In the following section, several equations are presented, which have been developed in order to plan the UAVs mapping flights, and are used in this study to compare the applicability of different UAVs platforms in forest surveys.

UAVs can be used to produce maps with very high ground resolution due to their low flight altitude. Resolution is generally determined by the ground sampling distance (GSD), which is the length on the ground corresponding to the side of one pixel in the image. A GSD of 1 cm means that each image pixel corresponds to a square of 1 cm side length on the ground. Three factors control the GSD:

$$GSD = \frac{(100 \times ALT \times p)}{fl}$$

where *ALT* is the altitude of the camera above the ground level (m). The size of each pixel *p* on the camera sensor (mm) is determined by the number of pixels on it and the size of the sensor (Leachtenauer and Driggers, 2001). The focal length of the camera *fl* (mm) determines its magnification. However, most UAVs operators plan survey missions with a required GSD and need to know at what altitude a camera-equipped UAV can fly. For instance, the monitoring of tree seedlings would require a GSD of less than 2 cm (Feduck *et al.*, 2018), whereas an 8 cm GSD would be sufficient to build an inventory of a mature forest plantation stand. The required flight altitude can be calculated as follows:

$$ALT = \frac{0.01 GSD \times fl}{p}$$

All UAVs follow a lawnmower flight pattern using predetermined GPS waypoints and altitude settings. In this pattern, the overlap between the images can be adjusted in two directions, forward and sideward (Figure 1)

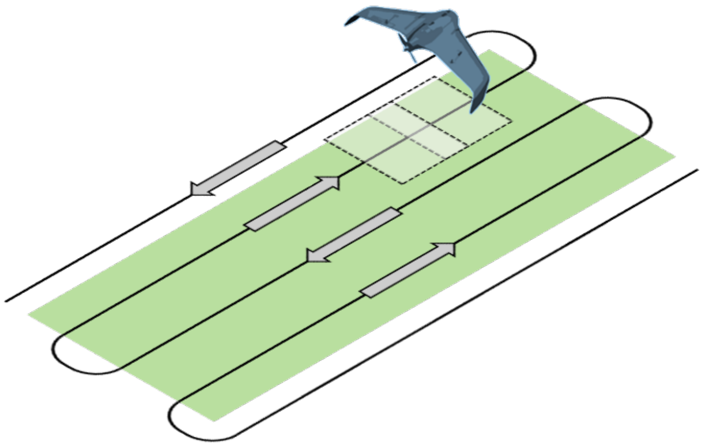


Figure 1 Typical lawnmower pattern of the UAV-based mapping surveys. The area of interest is colored in green.

Forward overlap OL_f is controlled by the time elapsed between two simultaneous triggerings of the onboard camera:

$$OL_f = \frac{t_{cam} \times v_{ground}}{h_{sensor} \times 0.01 GSD_{(cm)}} - 1$$

in which t_{cam} is the time (in s) for an image to be taken, processed, and written to memory. This is partially influenced by the camera's shutter speed, but more strongly determined by the camera's memory card speed and the image size. Thus, a memory card, which ensures fast writing of image data, is an important component of an efficient UAV mapping system. The UAV's relative ground speed v_{ground} (m/s) is determined by its nominal speed and the speed and direction of wind. The vertical size of the camera's image sensor (h_{sensor}) is determined by the number of individual pixels which can be recorded.

Most photogrammetric processing software packages require an image overlap of at least 60% to create an accurate map and DSM. However, forest canopies have a lesser number of distinctive features compared to urban areas, which can result in a poor image alignment, if the image overlap is too low. Thus, it is generally recommended to plan forest surveys with an image overlap of more than 80% to achieve satisfactory results (Dandois *et al.*, 2015). Thus, UAVs operators have to determine whether a UAVs system, with a pre-determined flight speed, can ensure sufficient overlap, while providing images at the required GSD, as follows:

$$GSD_{min} = \frac{v_{ground} \times t_{cam}}{h_{sensor}\,(\text{-OL}_f\text{+1})}$$

Side overlap, OL_s, and the horizontal number of pixels on the image sensor, w_{sensor}, determine the distance between the flight lines, d_{line}, so that the higher the side image overlap the closer the flight lines are planned. The distance between flight lines or d_{line} is calculated through the equation

$$d_{line} = w_{sensor} \times 0.01 GSD \times (1\text{-}OL_s)$$

Unlike multicopter, fixed-wing UAVs are unable to make sudden flight changes but follow a lawnmower pattern with intermittent banked turns. The flight distance during these turns depends on the distance between flight lines:

$$d_{turn} = \pi\, d_{line}.$$

Subsequently, the maximum areal coverage of a UAV survey flight, *A*, can be estimated as

$$A = (d_{max} - d_{line}\,(n-2)) \times d_{line},$$

where d_{max} is the maximum flight distance, n is the number of flight lines, from which the most outer ones have to be excluded, as they do not provide sufficient overlap.

Consumer-grade cameras are often used in a UAV due to their small size and low weight as an alternative to the more expensive survey-grade sensors. In this study, a 12 megapixels (3024 × 4032 pixels) with a sensor width of 6.25 mm, a resulting pixel size of 0.00155 mm, and a focal length of 3.37 mm is used for illustrative purposes. Cameras, such as Gopro's Hero or Mapir's Survey 3 are typical examples.

RESULTS AND DISCUSSION

Figure 2 indicates that a UAV's flight speed can significantly limit the desired GSD as a sufficient frontal overlap of more than 80% cannot be guaranteed at high speeds. Using a fast flying fixed-wing UAV, it becomes especially difficult to ensure sufficient overlap if GSD falls below 5 cm. In such cases, only multicopter platforms can be used as they can fly at a slower speed which is enough to provide sufficient resolution for image acquisition while flying over the survey area. A second option would be to use a camera with faster processing speed. However, cameras with low processing speed (> 2s) can only be employed in slow UAVs (multicopter) or at higher altitudes.

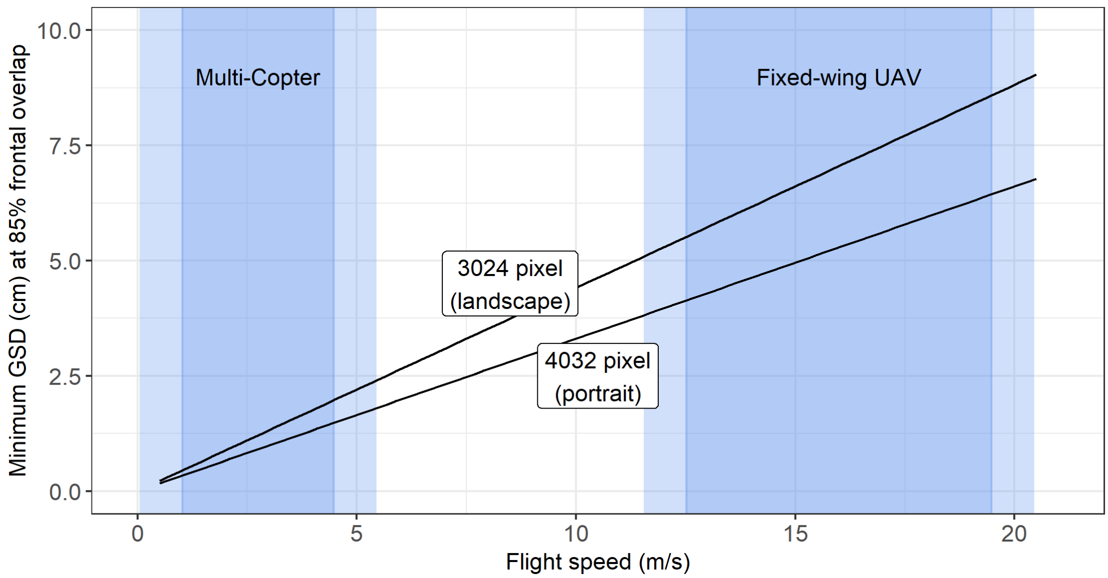


Figure 2 Relationship between the flight speed relative to the ground and minimum possible GSD at which a frontal overlap of 85% can still be guaranteed using a commercial sensor with a size of 3024 × 4032 pixels. Typical flight speed of multicopter and fixed-wing UAVs platforms are highlighted, respectively.

The advantage of faster and more enduring fixed-wing UAVs are more pronounced as GSD increases. A forest survey with a required ground resolution of 8 cm may be limited to an area smaller than 42 ha, if a multicopter UAV with a battery time of 30 min is used (Figure 3). In contrast, a fixed-wing UAV could survey over 200 ha within one flight mission without the need for landing and a battery replacement. Thus, UAV-based surveys of forest areas larger than 50 ha could be conducted more efficiently through the use of a fixed-wing instead of a multicopter UAV. However, at a high spatial resolution and a very low GSD, coverage does not differ sufficiently to justify the use of fixed-wing UAV. For instance, at a ground resolution of 2 cm, a multicopter can cover 0.4 ha/min, whereas a fixed-wing UAV would cover 1.1 ha/min.

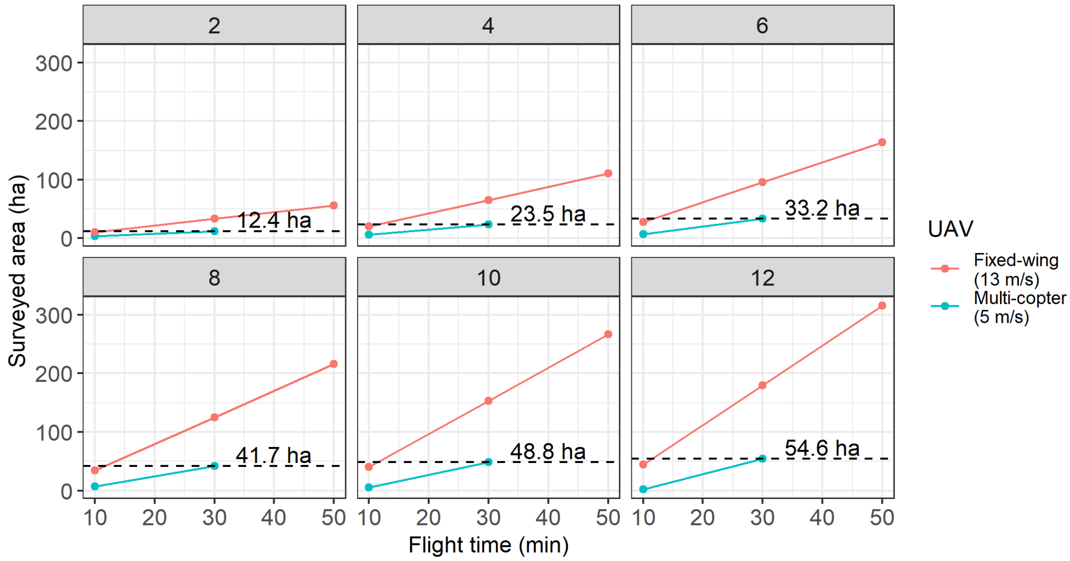


Figure 3 Relationship between UAV flight time and maximum area coverage given the two different UAV platforms with GSDs of 2, 4, 8, 10, and 12 cm. Maximum area surveyed with a multicopter UAV is indicated by a dashed line for each GSD.

Figure 4 highlights that the relationship between GSD and survey coverage is not positively linear but decreases as GSD increases. Coverage increases at a higher rate at lower values of GSD compared to higher GSD. The areal coverage of the multicopter increased at a lower rate as GSD increased. This was less pronounced in the fixed-wing UAVs. This observation underlines the superior efficiency of fixed-wing UAVs over multicopters at a higher GSD.

(A)

(B)

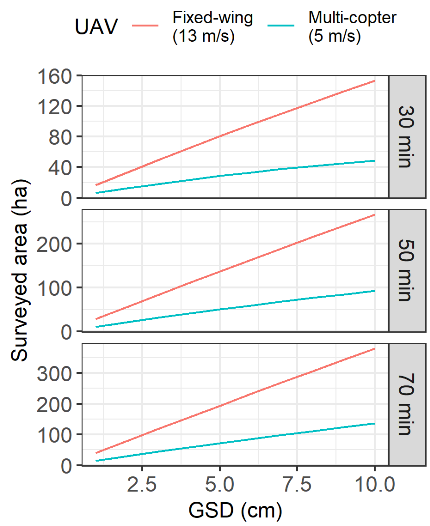


Figure 4 Relationship between GSD and survey coverage of fixed-wing and multicopter UAVs at three different flight times (30, 50, and 70 min)

The results showed that at a GSD of 8cm, which is sufficient for identifying trees and measuring crown areas, forest areas of less than a 100 ha can be surveyed within one flight using a multicopter UAV. With a fixed-wing UAV, forests of approximately 200 ha in size can be surveyed within one flight mission. However, larger forest areas still remain more difficult to survey and require a combination of multiple, consecutive survey flights. For instance, the survey of an FIO estate, with an average area of 2500 ha would require 13 flights. Overcoming the technical limitations of the batteries currently available and increasing the UAV's maximum flight time could reduce the operational costs dramatically by reducing the total number of flights required.

CONCLUSION

In this study, multicopter and fixed-wing UAV systems were compared for their abilities in the mapping of forest areas. The comparison showed that surveys of large forest areas at a GSD of more than 5 cm should be conducted using fixed-wing UAV to shorten flight times and improve survey efficiency. This would include stand inventories. In contrast, surveys of tree seedlings would require a multicopter, whose low flight speed could ensure high image overlaps at a high ground resolution. Thus, the choice of UAV system is mainly dictated by the required GSD and survey area.

ACKNOWLEDGMENTS

The manuscript was written during the research stay of Aor Pranchai at TU Dresden, which was supported by the Faculty of Forestry (Kasetsart University). We are thankful for the comments and suggestions of the anonymous reviewers.

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