The DeLeaves: A UAV device for efficient tree canopy sampling

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Abstract:

Tree canopy sampling is critical in many forestry-related applications, including ecophysiology, foliar nutrient diagnostics, remote sensing model development, genetic analysis, and biodiversity monitoring and conservation. Many of these applications require foliage samples that have been exposed to full sunlight. Unfortunately, current sampling techniques are severely limited in cases where site topography (e.g., rivers, cliffs, canyons) or tree height (i.e., branches located above $10\ \mathrm{m}$) make it time-consuming, expensive, and possibly hazardous to collect samples. This paper reviews the recent developments related to UAV-based tree sampling and presents the DeLeaves tool, a new device that can be installed under a small UAV to efficiently sample small branches in the uppermost canopy (i.e., $< 25\ \mathrm{mm}$ stem diameter, $< 500\ \mathrm{g}$ total weight, any orientation). Four different sampling campaigns using the DeLeaves tool are presented to illustrate its real-life use in various environments. So far, the DeLeaves tool has been able to collect more than 250 samples from over 20 different species with an average sampling time of $6\ \mathrm{min}$. These results demonstrate UAV-based tree sampling's potential to greatly enhance key tasks in forestry, botany, and ecology.

Key words: canopy sampling, tree sampling, foliar analysis, UAV, tool.

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1. Introduction

Unmanned aerial vehicles (UAV) are poised to play a major role in plant biodiversity conservation and sustainable forest management. Indeed, their use is becoming ubiquitous due to decreasing purchase prices and increasing applications (*Wing et al.*, 2013; *Tang and Shao*, 2015). Equipped with the appropriate cameras, UAVs can now map land use (*Paneque-Gálvez et al.*, 2014) and canopy gaps (*Getzin et al.*, 2012, 2014) to detect standing deadwood (*Dunford et al.*, 2009), as well as to assess canopy structure (*Sharma et al.*, 2013) and species composition (*Gini et al.*, 2014). In some remote or hard-to-access areas, like cliffs, UAVs can also be used to identify the distribution of certain rare plant species (*Nyberg*, 2018).

Beyond imagery, UAVs are also being considered for other tasks like inspection, maintenance, and sampling. For many forestry and conservation applications, UAVs that could efficiently sample foliage from the tree canopy would be invaluable. For example, such a flight platform could be used to optimize the productivity of fast-growing tree species plantations (e.g., pine, eucalyptus, and hybrid poplars). Indeed, such plantations have high nutrient demand and are often fertilized to increase both productivity and profitability, e.g., in North America (*Stanton et al.*, 2002), in Scandinavia (*Christersson*, 2006), and in Europe (*González-García et al.*, 2014). In some cases, growth can increase by 200% following fertilization (*Coyle and Coleman*, 2005). Although other methods are available to plan fertilization treatments (i.e., soils analysis), foliar analysis is the most direct way to monitor trees' nutritional needs (*Weetman and Wells*, 1990). Tree canopy samples are also used to develop and calibrate models of leaf chemistry based on hyperspectral imagery, enabling large-scale ecosystem monitoring (*Clevers et al.*, 2010; *Inoue et al.*, 2016; *Schweiger et al.*, 2020). Foliar samples are particularly useful for accurately interpreting spectral data toward mapping nutrients like nitrogen and phosphorus (*Clevers and Kooistra*, 2011; *Sammons*, 2019).

Finally, horticulturists and botanists could use canopy-sampling UAVs to collect stem cuttings for vegetative propagation. For example, researchers at the University of British Columbia (UBC) Botanical Garden often travel to different regions around the world to document, discover and collect propagules from various tree species (*Justice*, 2017, 2018). Unfortunately, the ability to collect propagules is often severely limited in the field, as many of the samples of interest are located high up in tree canopies. Furthermore, the trees of interest are often inaccessible, being located on steep slopes or across rivers or canyons.

Fig. 1. UAV, equipped with the DeLeaves tool, after collecting a red spruce (*Picea rubens*) sample in Quebec.

Canopy sampling is useful for many applications, so several different approaches have been developed to accomplish it. The pole pruner technique is simple and low-cost. However, very few pole pruners extend past 10 m due to the difficulty of manipulating them. Furthermore, their repeated usage could result in neck and back injuries. Tree climbing facilitates access to higher branches, but it requires specialized skills, additional equipment, and takes some time to set up . Moreover, it is not always possible for a climber to reach the terminal branches. In some situations, the tree could be cut down, but obviously, destructive sampling is generally undesirable. Shooting down a branch with a shotgun was also a popular method, but is now prohibited in many forests for security reasons (*Portlock et al.*, 1996). This method is also inefficient for cutting flexible branches, and its repeated use can damage other parts of the tree. Another approach, known as the line launcher, consists of shooting a blank bullet from a gun to propel a weight and cable over the branches. Large slingshots can also be used to propel the weight. This approach becomes complex in the field due to the need for cable management, however, as well as a direct viewpoint and accurate shooting. Other techniques have been developed specially for cone collection, such as operating a large sampler by helicopter (*Jackaman*, 2016). To conclude the list of canopy sampling techniques, there is also the use of canopy cranes (*Stork*, 2007) and canopy rafts (*Basset et al.*, 2003). These massive and fixed infrastructures are typically only used for long-term experiments.

This article presents the DExtrous Leaf Extracting Aerial VEhicle from Sherbrooke (DeLeaves). This novel tree sampling tool, illustrated in Fig. 1, was initially developed to support the UBC Botanical Garden, and is now devoted to many sampling applications. Section 2 of this paper describes the general requirements for UAV-based tree sampling. Section 3 reviews recent UAV sampling developments. Section 4 discusses the system-level choices involved in the design of an aerial tree sampler, while Section 5 presents the prototypes that lead to the DeLeaves tool. Section 6 concludes by demonstrating the DeLeaves's use in four scenarios: propagule sampling in Vietnam with the UBC Botanical Garden, foliar analysis to monitor the effects of fertilization on trees, sun-lit tree foliage sampling to measure spectral-optical properties with the Canadian Airborne Biodiversity Observatory (CABO), and, finally, canopy sampling for long-term assessment of ecosystem changes with the National Ecological Observatory Network (NEON).

2. Requirements

This project was begun to support the UBC Botanical Garden's sampling efforts during expeditions in Southeast Asia. As this work matured through various field missions, our understanding of the major requirements for tree canopy sampling evolved. The main requirements we identified were the ability to collect samples: (1) located in the upper canopy, (2) that meet minimum size requirements, (3) from diverse tree species, (4) in variable weather conditions, (5) quickly as possible, (6) while operating at a range of up to 300 m from the launch point, and (7) operating within current UAV legislation.

Of crucial importance is the ability to locate samples on a tree. At first glance, there may seem to be plenty of branches to sample from. Samples could come from the lower, more accessible part of the canopy; from the side of the crown; from the very top; or they could even be picked up off the ground. Although different applications may require different branch locations, sampling protocols for many applications, such as foliar analysis and propagule collection, recommend sampling leaves exposed to direct sunlight (*Weintraub*, 2019). For most trees within natural forests, this exposed foliage is only found on the uppermost part of the tree crown. These leaves have the nutrient composition most representative of the last growing season. Older leaves exhibit strong variations in N, P, K, Mg, and Ca (*Weetman and Wells*, 1990). Similarly, the best samples for field identification, vegetative propagation, and herbarium specimens (e.g., seeds, flowers, fruits, stems, or leaves) are generally found in the youngest branches at the top of a tree.

The UAV should also be able to collect sufficiently large samples for analysis, identification, and/or propagation without negatively affecting the tree. According to the sampling protocol of the National

Fig. 2. Tree sampling techniques. Top row, from left to right: pole pruner, climber (*Walker*, 2016), shotgun (*Portlock et al.*, 1996), line launcher, slingshot (*WesSpur*, 2019). Bottom row: hydraulic lift (*Käslin et al.*, 2018), helicopter (*Portlock et al.*, 1996), canopy crane (*Canopy Crane Papua New Guinea*, 2019), canopy raft (*Reforest'Action*, 2017).

Ecological Observatory Network (NEON), 30-$40\mathrm{g}$ of fresh plant material is sufficient to perform chemical analyses and measure leaf mass per area and leaf water content (*Weintraub*, 2019). That means that a UAV must collect a sample ranging from $100\ \mathrm{g}$ to $400\ \mathrm{g}$, including foliage, stems, cones, fruit, and flowers. In many cases, the UAV must also carry the sample down to ensure that it will reach the ground. For certain applications, there should also be minimal exposure of the sample to the environment (such as the ground or other branches/trees), to avoid contamination. With these requirements in mind, it is possible to design the capability of the cutting and holding mechanisms, and select the appropriate UAV to carry such samples.

Moreover, the sampling tool must be able to sample a wide variety of species. Since canopy structure differs greatly from one tree species to another, the sampling tool must be able to collect small branches in any orientation, including the typically vertical-growing branches of deciduous trees, and the typically horizontal-growing branches of conifers. The sampling tool must also be able to access a sampling area without being encumbered by the branches' structure and their distribution within the canopy (involving factors such as the number and length of branches, stem diameter, wood hardness, and foliage density).

Weather conditions are also a concern for UAV sampling. Indeed, sampling with a UAV requires precision control. The UAV should be able to fly stably in moderate winds and light rain (drizzle). However, branches that move in the wind add complexity to UAV sampling. According to the Beaufort scale, small branches begin to move in wind between 20 and $28\,\mathrm{km/h}$ (i.e., *moderate breeze*)); as such, this is likely the upper limit for UAV sampling.

UAV sampling must be efficient enough to justify its use. Different sampling techniques vary greatly in terms of efficiency. NEON provides some estimates in its sampling protocols (*Weintraub*, 2019): for instance, the sampling time required in a tall-stature, closed-canopy forest using a line launcher can be up to $2\ \mathrm{h}$ per sample, with a crew of two to three people. Meanwhile, certain applications, such as genomic selection, can require as many as 1000 samples (*Grattapaglia and Resende*, 2011). Line launching is unlikely to be used for genomic selection sampling because of its inefficiency. To be competitive with other applicable sampling techniques and allowing extensive sampling campaigns, a sampling UAV should be faster than these estimates.

Remote operation of the sampler using a video stream allows the user to collect samples beyond visual line-of-sight (BVLOS), which is extremely valuable because it can enable significant savings in time and resources. In many field situations, forest density and topography simply does not allow for a suitable takeoff location near the tree of interest, nor even easy access to the targeted tree. For example, most managed forests have their own road infrastructures distributed evenly across the territory. These forest roads are ideal for setting up the ground station while generally granting sufficient canopy openings. However, when a sampler UAV is flying near the canopy, the radio signal used for control and video transmission has to travel through the forest. This greatly reduces the range of reliable radio control. Our discussions with practitioners revealed that an operating range of $300\ \mathrm{m}$ would be a good objective.

Finally, according to Canadian aviation regulations (part IX, section 901.43) and the Federal Aviation Administration (United States Department of Transportations, part 107 of FAA regulations), the DeLeaves device is allowed to be fixed to a UAV. Since all DeLeaves-compatible UAVs weigh less than 25 kg with the added payload mass, their operation is subject to the current regulations for small remotely piloted aircraft systems (*Transport Canada*, 2020). Among other requirements in Canada, the pilot must have a Basic Operations Pilot Certificate and the UAV must be registered. The pilot must also have a visual line-of-sight (VLOS) with the aircraft for the entire duration of the flight. However, a VLOS can also be maintained by having one or more trained visual observers in communication with the pilot. If it is not possible for the pilot to perform the flight with a VLOS, the number and the position of visual observers must be planned accordingly. Also, Government of Canada is currently consulting the UAV industry to allow BVLOS for low-risk operations in the near future, such as UAV below 25 kg in low population density areas. The reader is strongly advised to refer to the appropriate legislation in their region for proper use of the DeLeaves system.

3. Existing tree sampling UAVs

As shown in Fig. 3, several research groups around the world have developed UAV devices for tree sampling. Since these samplers have only been developed recently, the information available on them is still fairly limited. Some of these projects were developed with different applications in mind (e.g., for arborists), which lead to different design choices.

In 2015, UC Berkeley introduced its tree sampling UAV (*UC Berkeley Forest Pathology and Mycology Lab*, 2015). It consists of a laterally-reaching lightweight rod with a razor blade at the end. The razor blade forms a hook that can cut leaves. This passive solution requires the pilot to fly the hook into a tree and catch a twig with the hook on the way out, which is a complex operation. Since the mechanism is attached rigidly on the UAV, the end effector's vertical positioning is coupled with the pitch motion required to approach the sample. This complicates the alignment of the sampler with a specific leaf.

Jamie Hyneman, from the *Mythbusters* TV show, developed two different designs to create an arborist UAV (*Hyneman*, 2015, 2017). The first design used a rotating saw suspended at the end of a rod under a UAV. However, without any mechanism to hold it on the branch, the saw constantly slipped around the branch without cutting it. The second design used a laterally-reaching configuration with shears actuated by a powerful electric motor connected to a heavy gearbox. The prototype was able to cut one branch before crashing. The UAV had the same end-effector positioning challenges as the Berkeley design, due to the horizontal arm being rigidly attached to the UAV.

Fig. 3. Tree sampling UAVs from around the world. From left to right, top to bottom: UC Berkeley (*UC Berkeley Forest Pathology and Mycology Lab*, 2015), Arborist II from Jamie Hyneman (*Hyneman*, 2017), FTTS from ETH Zurich (*Käslin et al.*, 2018), Lucanus from Slovenian Forestry Institute (*Finžgar et al.*, 2016), Arborist I from Jamie Hyneman (*Hyneman*, 2015), UC Santa Barbara (*Bailey et al.*, 2018).

A third project, called Lucanus, was developed by the Slovenian Forestry Institute (*Finžgar et al.*, 2016). It uses a vertically suspended tool design with shears oriented to cut small horizontal branches by approaching them from the side. These shears are manually spring-loaded before each attempt, and are automatically activated by a proximity sensor. A camera installed on the mechanism helps with remote operation and alignment. Finally, a safety release mechanism allows the operator to detach the sampler from the UAV in an emergency.

More recently, the Flying Tree Top Sampler (FTTS) was introduced by the Institute of Agricultural Sciences of ETH Zurich (*Käslin et al.*, 2018). Their design is vertically suspended under a UAV and uses a small circular saw to cut vertical branches. A proximity sensor detects when a branch is close enough and triggers the grippers, which automatically close to grab it. There is also a camera, so the pilot can operate the mechanism remotely, and a safety release mechanism for emergency.

The latest project from the University of California in Santa Barbara (UCSB) uses a vertically suspended design to sample horizontal branches (*Bailey et al.*, 2018). The design was implemented on a 3DR X8+ UAV. It consists of a rotating saw capable of cutting small branches. The saw is protected by a spring-loaded guard and an embedded system controls their automated cutting sequence. A summary of all the UAV sampling systems, including DeLeaves, is presented in Table 1.

Given the relatively recent development of the majority of these various tree sampling concepts, many of the design choices made by each team are still not well documented. The following section compares the most important designs for a tree sampling drone: the choice of cutting device and the sampler position with respect to the drone. Furthermore, the field performance of most of these systems is still fairly unclear. In most cases, the performance can only be assessed from edited videos. This paper provides details about the DeLeaves sampler and its field performance and limitations, so that efficient sampling campaigns can be planned accordingly.

Table 1. Summary of various tree sampler features.

Project	Cutting Device	Sampler Configuration	Sample Orientation	Safety Release	Assisted Sampling Sequence	Sample Holding Mechanism	Tool Weight	UAV Platform
UC Berkeley	Blade	Lateral	Horizontal				N/A	DJI Phantom
Hyneman 1	Saw	Down	Vertical				N/A	DJI Inspire
Hyneman 2	Shears	Lateral	Vertical				N/A	DJI Inspire
UCSB	Saw	Down	Horizontal		√	√	0.9 kg	3DR X8+
Lucanus	Shears	Down	Horizontal	√	√	√	N/A	Sky Hero X8
FTTS	Saw	Down	Vertical	√	√	√	1.25 kg	Tarot X6
DeLeaves	Saw	Down	Any	√	√	√	1.1 kg	Tarot 680 or similar

4. System design

As pointed out in the literature review, a number of strategies have been used to collect small branches with a UAV. This section discusses the trade-offs of the main strategies, including the choice of the cutting mechanism, the lateral-reaching vs. downward-reaching configurations, and the length of the rod used to suspend a tool in the downward-reaching configuration.

4.1. Cutting mechanism

Previous designs tended to use either shears or a circular saw. Shears are used in many gardening tools. However, when operated on a UAV, their geometry is such that the stem tends to be pushed away from the mechanism. The shear force required to cut branches is also proportional to the square of the stem diameter, and alignment between the two blades is critical. To achieve the forces and alignment needed, stiff and heavy parts are typically used. A long lever arm is also used to provide sufficient force. Creating the required force on a UAV requires a strong motor with a heavy gearbox, as implemented by *Hyneman* (2017). A spring could also be used to provide the required cutting force, as done by *Finžgar et al.* (2016). However, given the limited payload capacity of UAVs, shears tend to be too heavy for aerial tree sampling.

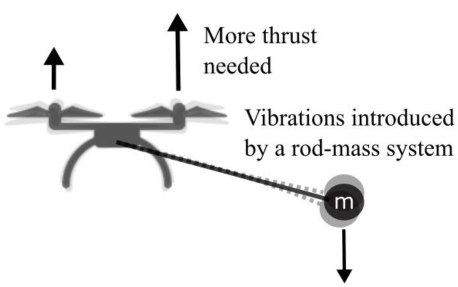
In contrast, circular saws provide much more flexibility. The cutting strategy can rely on a large number of small teeth, high rotation speed, and slow feed rate to minimize the torque needed to cut a branch. These parameters can be varied to match the motor with the saw to accommodate the desired stem diameter. Both DC or brushless DC (BLDC) motors can be used. DC motors typically have a faster rotation speed at lower torque, which might necessitate a gearbox. BLDC motors commonly rotate at slower speeds with higher torque, which often eliminates the need for a gearbox. However, without added sensors to measure the rotor position at slow speeds, the BLDC's stall torque is limited by its drive. Also, in a configuration where the saw is mounted directly on the motor axis, the maximum stem diameter that can be cut is limited by the saw's clearance over the motor. Finally, we note that the rotating components associated with the saw also create gyroscopic effects, although this was not a concern in the various prototypes built to date.

4.2. Lateral-reaching vs. downward-reaching sampler configuration

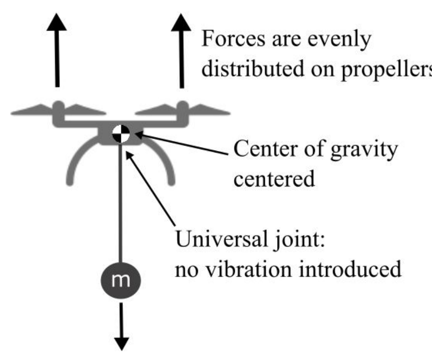
Two different sampler configurations have been explored in the literature: lateral-reaching and downward-reaching. The lateral-reaching design is advantageous when samples need to be collected on the side of the tree. However, a counterweight must be used to balance the system, otherwise some propellers will reach their maximum thrust prematurely to compensate for the offset center of mass. This impacts the system by reducing the UAV's maximum payload capacity and maneuverability. When rigidly connected to the UAV, this extra mass modifies the inertia of the whole system, which can make the UAV's control system unstable. Vibrations can also be caused by the sampler mass added at the end of the pole—which, given its finite stiffness, creates a mass-spring system. These vibrations could require additional signal filtering. When a collision occurs with a branch, the contact force at the far end of the sampling mechanism will also create destabilizing moments of force on the UAV. Finally, a UAV has to change its attitude in order to move in the horizontal plane. These rotations affect the end effector's positioning while trying to reach a target, which makes the pilot's job of operating the device more complex.

A downward-reaching design has the advantage of keeping the center of mass centered under the propellers. When connected to the UAV with a universal joint (no rotation allowed in the yaw axis), the system acts as a pendulum under the UAV so that no additional inertia is perceived by the UAV system. Fig. 4 illustrates these basic concepts. This design also eliminates destabilizing moments created by interaction forces, while trading the high-frequency oscillations of a mass-spring system for slow pendulum oscillations. This enables use of a commercial UAV controller without any adjustments. The pendulum motion could reduce the sampler's positioning precision, but slow UAV displacements can limit these effects. Finally, the main advantage of a suspended mechanism is to allow for sampling of canopy branches while the UAV safely hovers above the trees. This reduces the pilot's cognitive load when operating such a system.

Fig. 4. Lateral-reaching vs. downward-reaching sampler positioning strategies, and their effect on thrust, inertia, and vibrations.



(a) Lateral



(b) Downward

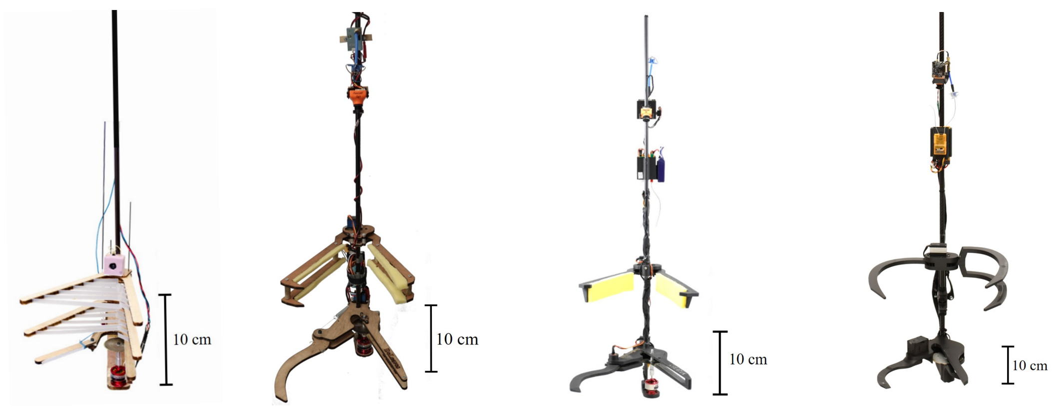
4.3. Rod length

In a downward-reaching sampler configuration, rod length directly controls three main effects: branch motion resulting from the UAV's prop wash; pendulum oscillation frequency; and the cutting tool's downward reach while the UAV is kept above obstacles (e.g., treetops). For every one of these considerations, longer rod length is desirable, up to the limits of the UAV's maximum payload and the rod's mechanical limits (e.g., stiffness, buckling, strength). Although it is difficult to model or establish general relations, the prop wash effect diminishes with the distance from the UAV. A reasonable objective is to maintain the prop wash velocity below the *moderate breeze* level according to the Beaufort scale to limit the motion of small branches.

According to our tests on a number of tree species with UAVs between $1.2\ \mathrm{kg}$ and $4.5\ \mathrm{kg}$ (e.g., DJI F450, DJI M210), a $2.5\ \mathrm{m}$ distance between the propellers and branches is sufficient to limit canopy motion. Lastly, rod length also affects the mechanism's oscillation frequency, which is proportional to $\sqrt{1/L}$. A longer rod reduces the oscillation frequency, making it easier for the operator to align the grasping mechanism with a target. A longer rod may seem like it would be more difficult to manage during takeoff and landing, but these maneuvers are actually quite easy to perform with a forward/backward motion (Fig. 5). Finally, a longer rod requires a bigger takeoff and landing area.

Fig. 5. Takeoff sequence timelapse.

Fig. 6. Prototype timeline: (a) passive holding mechanism, actuated by light muscle wire, (b) servo-actuated holding mechanism, grasping mechanism semi-actuated with return-spring, (c) "Expedition Edition," servo-actuated grasping with memory foam for additional grip, and (d) "Forestry Edition," a scaled-up version for forestry applications with direct gripper actuation.



(a) 2016 (b) 2017 (c) 2018 (d) 2019

5. Prototype review

The DeLeaves tool evolved through a number of prototypes that were refined through field trials. Fig. 6 shows some of these iterations. The evolution and refinement of these prototypes led to two functional devices of different sizes. The "Expedition Edition," shown in Fig. 6(c), is optimized to be carried by backpack for expeditions in remote areas, and is installed under a DJI F450 drone. The "Forestry Edition," shown in Fig. 6(d), is designed to collect larger samples and for installation on drones like the DJI M200 or M600. Table 2 compares both editions' main specifications. Although the weight difference between both tools is only $565\ \mathrm{g}$, this difference is enough to allow the Expedition Edition to be installed on much smaller drones that use lighter batteries, resulting in significant size/weight savings during field operations. This section describes the heavier-weight Forestry Edition, which is the latest version of the DeLeaves sampling tool. For updated information on commercial availability and pricing, readers are referred to www.deleaves-drone.com.

5.1. Components and technical specifications

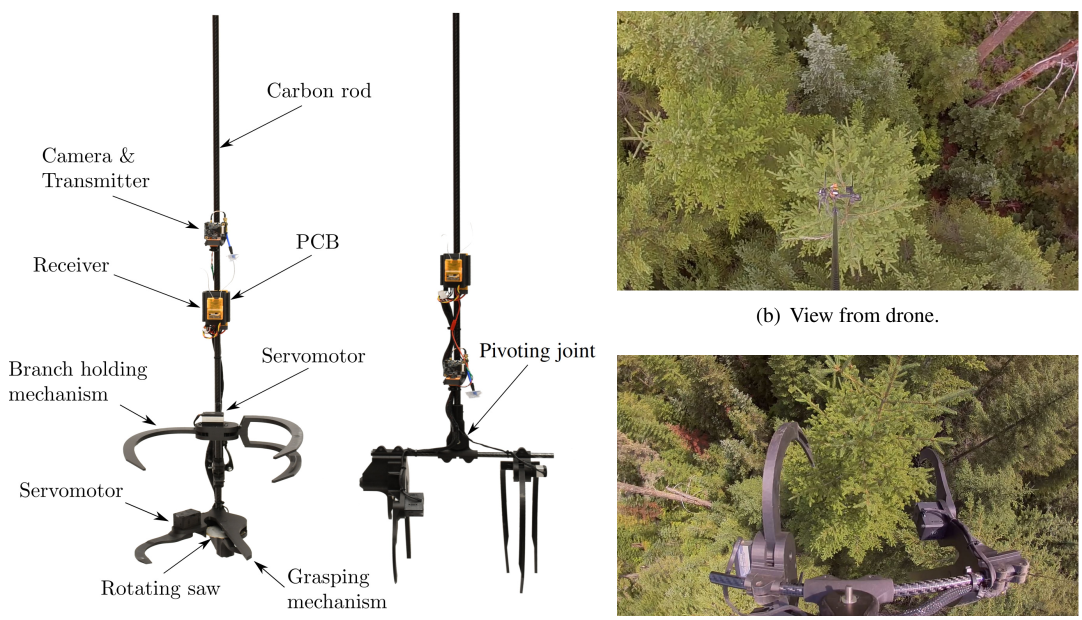
The DeLeaves Forestry Edition is illustrated in Fig. 7(a). It consists of a grasping mechanism, rotating saw, branch-holding mechanism, and camera. This hardware is installed at the end of a 2.6-m carbon-fiber rod fixed to the drone through a universal joint in series with a custom remote-activated

Table 2. Technical specifications.

Specifications	Expedition Edition	Forestry Edition
Operating range	up to 150 m	up to 150 m
Max. cutting diameter	12 mm	25 m
Max. sample weigth	150 g	500 g
Tool weight	535 g	1100 g
Tool length	2.6 m	2.6 m

quick-release mechanism. DeLeaves is mostly built from 3D printed parts that use embedded continuous fiber for a high stiffness-to-weight ratio. The grasping mechanism is actuated by a Dynamixel Xl430-W250, which allows for position control of the grasping mechanism during the approach, as well as control of the feed rate during the cutting phase to prevent the saw from stalling. The geometry of the lower gripper/cutter is carefully designed to rapidly capture a branch and guide it toward the rotating saw. A fixed stopper guide lets stem be stabilized while it is cut, and orients the cutting forces. The rotating saw is a carbide grit blade of 77 mm mounted on a 335-W BLDC motor. The upper branch holding mechanism is actuated by a servomotor. It corrects the branch's orientation to ensure an efficient cutting process, and holds the branch sample during the flight back to the ground station. Both grippers can be opened at any time, either to release a branch that was too hard to cut, or to drop a collected sample onto the ground for quicker collection. To collect branches with different orientations, we added a pivoting joint that moves in $10°$ increments, to allow for manual adjustments to the end effector's orientation before takeoff.

Fig. 7. (a) DeLeaves prototype overview. (b) Perspective from the UAV-mounted camera. (c) Perspective from DeLeaves.



(a) System overview.

(b) View from drone.

(c) View from DeLeaves.

To allow DeLeaves to be used on many different commercial UAVs, the sampling device is completely independent of the UAV platform. A $1000\ \mathrm{mA\,h}$, 3S ($11.1\ \mathrm{V}$) battery is included to power the sampler's electronics, grippers, and saw. This battery was chosen to match the autonomy of most UAVs (e.g., $18\text{-}30\ \mathrm{min}$). DeLeaves is controlled through a separate RC remote operated by a second operator. Although full control of each actuator is possible, an onboard computer can also perform a fully automated grasping and cutting sequence. At least three channels are required to respectively start and stop the saw rotation, activate the automated cutting sequence, and activate the quick-release system. Finally, a downward-facing camera was installed above the sampler to clearly identify the targets, position the sampler, and observe the operations. This close view is also complemented by the camera on the UAV, which provides an overview of the situation to the pilot (helpful for avoiding surrounding obstacles). Fig. 7 illustrates the camera perspectives, both of which are available to the drone pilot and DeLeaves operator.

Considering the total mass of the system, including the tool ($1100\ \mathrm{g}$) and the added mass from the sample (i.e., less than $500\ \mathrm{g}$), the UAV needs a minimum payload allowance of $1500\ \mathrm{g}$. The Tarot 680 pro hexacopter with a PixHawk flight controller was used during most of the prototyping and field trials due to the versatility offered by this affordable and open-source platform. However, the DeLeaves tool is now mostly used with the DJI M200 series and M600, which are both off-the-shelf commercially available UAVs.

As described before, operations BVLOS can considerably speed up the operations, but presents a challenge because flying close to the trees significantly reduces the radio range. The current $5.8\ \mathrm{GHz}$, $600\,\mathrm{mW}$ analog video transmission system with mushroom-type antennas was tested up to $150\,\mathrm{m}$. This was evaluated for a base station located on a forestry road, with the drone flying 3 to $5\,\mathrm{m}$ above a maple forest containing $20\ \mathrm{m}$ high trees with fully grown leaves. Beyond this distance, the camera's signal was lost. Work is in progress to extend this range.

5.2. Operation sequence

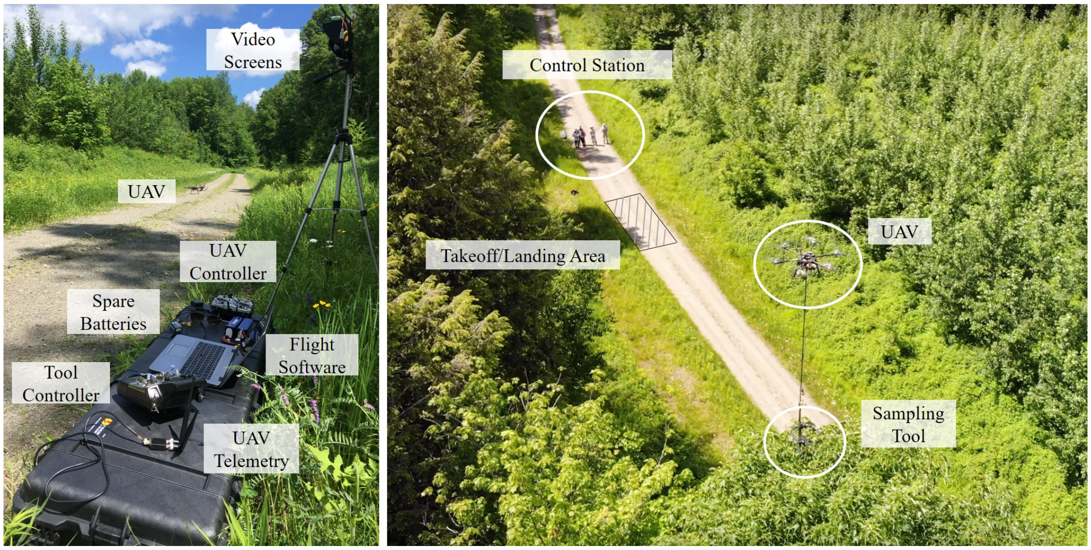
For more efficient tree sampling, common automated flight features are used to help the operators. After manual takeoff, automated guidance with GPS coordinates is used to bring the drone just above the targeted tree. After sampling a tree through manual flight, the drone's return-to-home function is activated to automatically return to the base station. To support the pilot and sample operator during manual flight, a control station is set up as shown in Fig. 8. For safe operations, visual observers are located near the targeted tree and along the flight path to ensure a direct line-of-sight with the UAV at all times. Observers can also help by confirming that the right tree is being sampled, and by informing the pilot about surrounding obstacles using radio communication as needed.

6. Results

As of January 2020, the DeLeaves tool has successfully sampled more than 250 individual trees from more than 20 different species, including maples (e.g., *Acer saccharum*, *Acer rubrum*, *Acer saccharinum*), poplars (e.g., *Populus balsamifera*, *Populus deltoides*, *Populus tremuloides*), pines (e.g., *Pinus strobus*, *Pinus resinosa*, *Pseudotsuga menziesii*), spruces (e.g., *Picea abies*, *Picea glauca*), and others (e.g., *Juniperus virginiana*, *Larix laricina*, *Tsuga canadensis*). During that time, DeLeaves was involved in four sampling campaigns for different projects: propagule sampling during the UBC Botanical Garden's yearly expeditions, assessment of tree fertilization effects through foliar sampling and nutrient analysis, sampling of sun-lit foliage for measurement of spectral-optical properties with the Canadian Airborne Biodiversity Observatory (CABO), and canopy sampling to support the assessment of ecosystem changes with the National Ecological Observatory Network (NEON). Footage from these sampling campaigns has been made available online to complement the following descriptions.[4]

[4] Youtube channel: www.bit.ly/deleaves

Fig. 8. The control station setup (left), and an overview of a typical sampling operation (right).



Credits: Etienne Laliberté, 2019 (Right).

6.1. Vietnam Expeditions with the UBC Botanical Garden

During the springs of 2017 and 2018, the Sherbrooke team was invited to test the DeLeaves sampler for the UBC Botanical Garden's yearly Vietnam expedition. The goal of these expeditions was to document, study, and collect rare species from this part of the world. During these expeditions, interesting specimens are often out of reach, either on dangerous terrain (e.g., slopes, cliffs), high up in a tree, or across a river. A UAV's reach is thus invaluable in many of these situations. Takeoffs are particularly challenging as the terrain in Northern Vietnam is often steep, with few flat spots large enough for a UAV equipped with a sampler to takeoff or land. Despite that difficulty, the team was able to collect three native species (i.e., *Aesculus assamica*, *Azadirachta indica*, *Aesculus wangii*) with the 2017 version of DeLeaves (Fig. 6 (b)). Field operations realized during the 2018 expedition are illustrated in Fig. 9. Further information about this expedition is available online.[5]

6.2. Assessing fertilization effects on trees

During the summer of 2018, a sampling campaign was performed in sugar maple (*Acer saccharum*) stands of southern Quebec. The purpose of this project was to assess the fertilization effects of five stands by sampling paired fertilized and unfertilized (control) plots. In each plot, two canopy samples were collected using the DeLeaves tool on two mature maple trees, thus totalling 40 samples. This sampling campaign required 53 flights with an Expedition Edition prototype (Fig. 6 (c)). The 40 samples collected are shown in Fig. 10. Overall, the operations required a total flight time of $4.5\,\mathrm{h}$ performed on four days distributed over two weeks, to allow for travel between the various sites, inclement weather, and the team's availability. For the 13 flights that did not bring back a sample on that early version of the DeLeaves tool, the main reasons were: (1) operator did not locate an accessible sample in time (this early version had a shorter maximum flight duration of about $10\,\mathrm{min}$); (2) operator targeted an oversize sample; and (3) poor signal reception for the camera.

[5] www.botanicalgarden.ubc.ca/trekking-in-the-mountains-of-northern-vietnam/

Fig. 9. Vietnam expedition in 2018. Top (left to right): Vietnam's steep terrain to access remote areas; Robichaud-Courteau holding a freshly collected *Azadirachta indica* sample. Bottom: An improvised takeoff area in the dense vegetation; Collecting a flower of *Aesculus wangii*, as seen from DeLeaves's camera.

Each flight's GPS coordinates were recorded to quantify the DeLeaves's performance. On average, it took $5\,\mathrm{min}$ to collect a sample. The average distance of sampled trees from the base station was $80\,\mathrm{m}$, and the trees had an average height of 20 m. More than 70% of the mission time was used to confirm the target tree with a ground observer, identify a suitable branch that DeLeaves could sample, and align the tool so as to grab the desired branch. We successfully measured the macronutrient (N, P, K, Ca and Mg) concentrations of all the collected samples, and will publish the results in the near future.

6.3. Quantifying intra-individual foliar spectral and functional trait variation with CABO

The Canadian Airborne Biodiversity Observatory (CABO) (https://www.caboscience.org/) has the overall objective to study and understand changes in plant biodiversity across Canada using spectranomics, and more particularly to improve our ability to forecast biosystems' response to environmental changes (*Asner and Martin*, 2016). To do so, they map plant species and functional traits using imaging spectroscopy. The purpose of the sampling campaign performed with the DeLeaves tool was to quantify intra-individual trait variation of an important regional tree. The chemical and structural leaf traits, as well as spectra, were measured between paired leaf samples from the canopy of 10 mature sugar maples (*Acer saccharum*). One set of leaves was collected with the DeLeaves tool in the upper and mid-tier canopy, whereas the other set was collected from the crown periphery using a pole pruner (Fig. 11). Both sets of leaves were exposed to sunlight. This research project took place in June 2019 in southern Quebec. The results showed significant differences in many leaf traits resulting from the sampling location within the canopy. More details are available in *Schweiger et al.* (2020).

Fig. 10. The 40 maple foliage samples collected in early August 2018. The samples have an average diameter of 5.1 mm (min: 2.1 mm, max: 7.9 mm), an average length of 24 cm (min: 8 cm, max: 50 cm) and an average weight of 24 g (min: 8 g, max: 70 g).

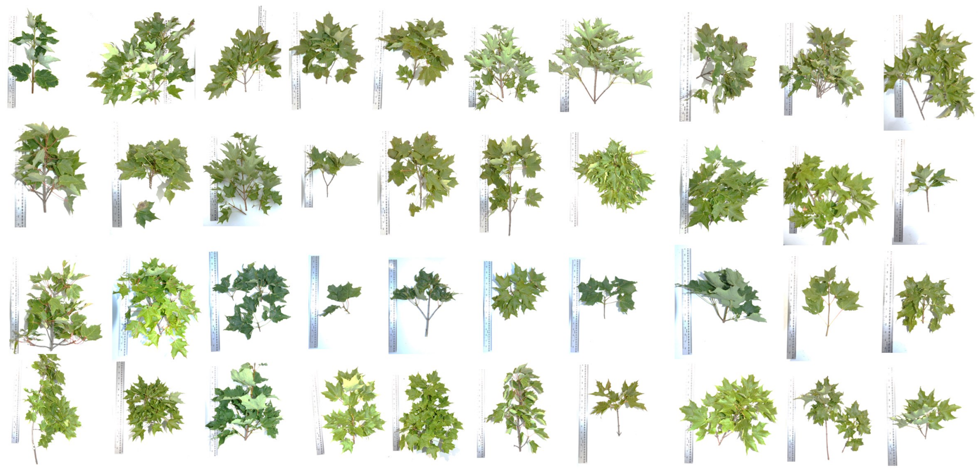


Fig. 11. Comparison of representative sampling locations used with CABO on sugar maple stands in Quebec. Left: pole pruner. Right: DeLeaves tool.

6.4. Monitoring ecosystems with NEON

The latest sampling campaign was performed in partnership with NEON during the summer of 2019. NEON is a large-scale ecological initiative that collects environmental data to characterize 81 field sites strategically located in various ecosystems across the U.S. (www.neonscience.org/). According to their canopy foliage sampling protocol (*Weintraub*, 2019), canopy measurements are collected at each field site once every five years. Leaves must be collected at peak greenness from sun-lit canopy positions, with 20-60 samples collected per site covering the range of canopy species and environmental gradients present. Coincident with the sampling campaign, airborne remote sensing data is collected with their Airborne Observation Platform (AOP). All foliar trait and remote sensing data are publicly available on the NEON data portal (data.neonscience.org/home).

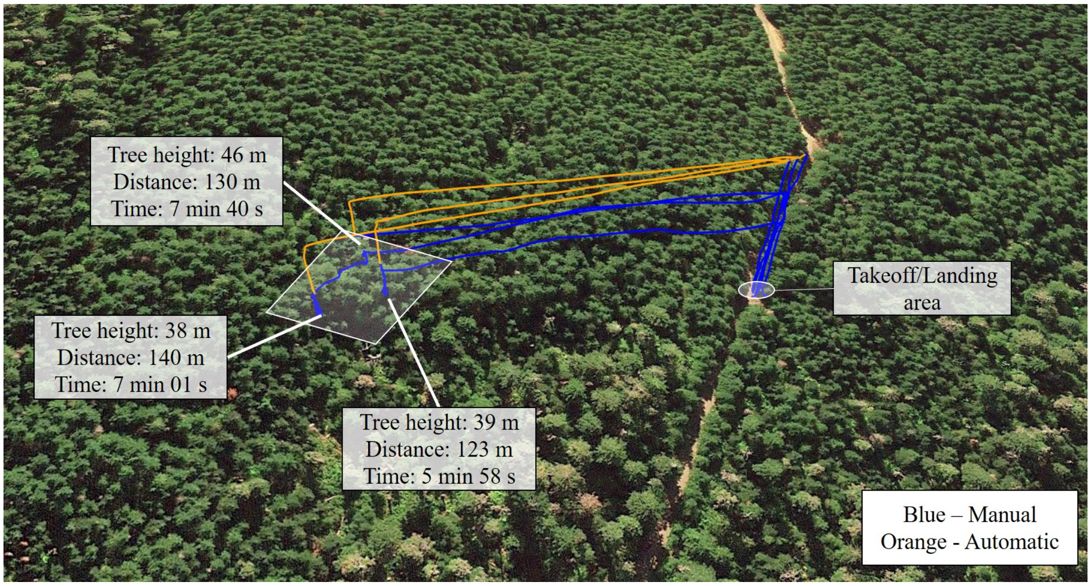
Fig. 12. View from DeLeaves's camera before collecting a branch from a $40\ \mathrm{meter}$ Douglas Fir.

A total of 12 trees were sampled with the DeLeaves tool at the Wind River Experimental Forest in Washington State. Three different species were collected: Douglas fir (Pseudotsuga menziesii), western hemlock (Tsuga heterophylla), and silver fir (Abies amabilis). Fig. 12 shows the DeLeaves tool while collecting from a $40\ \mathrm{meter}$ tall Douglas Fir. Sampling flights took an average of $7\ \mathrm{min}$ on trees as far as $130\ \mathrm{m}$. Fig. 13 shows the flight trajectories of three sampling flights as recorded by the on-board GPS. Since the GPS coordinates are recorded for each tree sample obtained by the UAV, it will be easy to return to the same trees in the next sampling campaign. Takeoff and landing were achieved from a small forest road with narrow canopy openings—too narrow to perform automatic takeoff. Further complicating matters, at ground level the GPS signals were obstructed by dense vegetation surrounding the road. Automatic operation with the GPS could only be resumed once the UAV cleared the canopy line. During this sampling campaign, one of NEON's UAV pilots was trained to use the DeLeaves tool. He was able, after less than half a day of training, to consecutively collect samples from three different Douglas fir trees. Because the trees at Wind River are extremely tall, DeLeaves yielded major improvements over traditional canopy sampling tools.

7. Conclusion and future work

Using UAVs to interact with the environment and collect samples is becoming possible with the latest technological advances. This paper explores the viability of tree sampling with UAVs, including forestry application requirements. These requirements include the ability to collect appropriate samples for foliar analysis, to be effective on a large variety of species, to comply with environmental and legal factors, and to go beyond visual line-of-sight operations to be efficient over large areas. To analyze the viability of UAV sampling, we first described traditional sampling techniques currently used in the industry. All these techniques involve drawbacks ranging from dangerous to difficult to deploy, while

Fig. 13. Recorded trajectories and statistics for three sampling flights at Wind River Experimental Forest, Washington State.



also often being expensive, which highlights the potential benefits of UAV-based tree canopy sampling.

We presented recent developments in tree sampling UAVs with the information available on these systems. The DeLeaves tool combines the best practices found and was described in detail. DeLeaves uses a downward-reaching tool suspended under a UAV to avoid added inertia or vibration modes that could perturb the flight controller. This has the added benefit of keeping the center of mass centered under the UAV even after collecting heavy samples, maximizing the available flight time. A rotating saw is used to ensure a lightweight system that requires minimal cutting forces. Cameras are employed to guide the pilot toward the desired sample. We also presented the results of four sampling campaigns conducted in different environments. Overall, the DeLeaves tool has sampled more than 20 species and demonstrated that it can reliably collect sub-500 g samples located $100+$ m away from launch point in about 6 min from takeoff to landing.

To meet all the initial requirements, future work includes integrating a video transmission system with a range of more than 300 m. Ongoing work also focuses on reducing the sampling time and improving the ease of use of such a system to increase its acceptance among forestry organizations and research groups. The DeLeaves tool is already being introduced in sampling protocols, and we expect that many other designs will also be explored successfully in the years to come.

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