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Design and Testing of a Novel Unoccupied Aircraft System for the Collection of Forest Canopy Samples

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Abstract: Unoccupied Aircraft Systems (UAS) are beginning to replace conventional forest plot mensuration through their use as low-cost and powerful remote sensing tools for monitoring growth, estimating biomass, evaluating carbon stocks and detecting weeds; however, physical samples remain mostly collected through time-consuming, expensive and potentially dangerous conventional techniques. Such conventional techniques include the use of arborists to climb the trees to retrieve samples, shooting branches with firearms from the ground, canopy cranes or the use of pole-mounted saws to access lower branches. UAS hold much potential to improve the safety, efficiency, and reduce the cost of acquiring canopy samples. In this work, we describe and demonstrate four iterations of 3D printed canopy sampling UAS. This work includes detailed explanations of designs and how each iteration informed the design decisions in the subsequent iteration. The fourth iteration of the aircraft was tested for the collection of 30 canopy samples from three tree species: eucalyptus pulchella, eucalyptus globulus and acacia dealbata trees. The collection times ranged from 1 min and 23 s, up to 3 min and 41 s for more distant and challenging to capture samples. A vision for the next iteration of this design is also provided. Future work may explore the integration of advanced remote sensing techniques with UAS-based canopy sampling to progress towards a fully-automated and holistic forest information capture system.

Keywords: canopy; drone; leaf; leaves; foliar; samples; sampling; Aerial robotics; UAS; UAV

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1. Introduction

Climate change is having a complex variety of effects on our forests from increased atmospheric carbon dioxide levels [1,2], environmental changes such as increasing drought severity and frequency [3–5], and more frequent and severe bushfires [6]. In some cases, local environmental changes are becoming sufficiently persistent and significant enough to shift conditions beyond the tolerable limits of some species, causing the large scale loss of forests and even threatening some species with extinction without assisted migration [7,8]. Scalable and high-fidelity measurements are of considerable importance to furthering our understanding of these changing conditions and their associated impacts on our forests. Forest information will play an important role in enabling evidence-based policy decisions to be made regarding the mitigation of and adaptation to such climate impacts. The enhancement of the tools available for sampling and monitoring our forests will enable larger scale and lower cost collection of forest information.

Unoccupied Aircraft Systems (UAS), remote-sensing and deep-learning technologies have been revolutionising the way we can monitor the structure of forests and quantify carbon stores [9–18] for use in climate models; however, physical samples remain important for calibrating some remote sensing techniques [19,20], directly measuring foliar nutrients, collecting genetic samples, monitoring pests/diseases and studying physical plant traits. Canopy and sub-canopy physical samples can be used to answer questions related to plant, ecosystem, and environmental health. These samples can provide a valuable source of feedback to forest growers and researchers to further optimize and inform the management of our forest resources, but obtaining these samples remains a challenge.

Canopy samples are typically collected with considerable effort through the use of canopy cranes [21–23], arborists, shotguns, crossbows [24,25], line launchers and pole pruners [26]. These techniques can be time-consuming, expensive and in some cases dangerous. Aerial robots/UAS have the potential to help us obtain these samples more safely, cheaply, and rapidly, but to do so, they need to be able to physically interact with trees. Promising research is ongoing to develop platforms such as [27–31] to enable UAS to precisely interact with objects; however, further research is needed to bring this technology to forest sampling. Such robotic systems present an interesting opportunity to improve the way we collect samples and physically interact with forest canopies.

The canopy sampling or pruning designs in the literature fit into three main categories. The most common design category involves a sampling tool that hangs underneath the UAS on a long pole [32–38]. This approach is most suitable for sampling the tops of canopies and is unaffected by a closed canopy, provided that the local UAS regulations around line-of-sight operations and field conditions make this possible. The second most common design category includes those which are lateral reaching [39–42], i.e., the sampling tool protrudes in front of the aircraft rather than hanging beneath it. These systems approach trees from the side rather than from above, so they are able to access locations that the hanging designs cannot reach, such as those which are not at the very top of the tree or locations beneath a closed canopy. Such an approach ideally needs a counterweight to ensure the centre of gravity remains in line with the centre of thrust to avoid wasted performance, instability and other control related issues. Lastly, there is an example of a UAS which approaches from underneath branches, with the cutting tool above it [43]. The latter system is intended for pruning rather than sampling, however, it would still enable leaf sampling and is therefore relevant to this discussion. This design is unable to sample from the top or the side, requiring a vegetation-free section of the branch to fly underneath and hook onto. The tools used to cut the sample or branch by all previous studies identified included circular saws [32–34,41,43], electrically powered [39,42] or spring-loaded secateurs [35] or a simple razor blade [40].

Two studies were particularly noteworthy for their use of computer vision to simplify the task of choosing a branch and making the cut. One demonstration uses machine learning and computer vision to identify stems and branches in real-time and robotically cut them with a secateur style pruning tool [42,44]. Another more recent study used computer vision techniques on a depth image to select a target branch and actively assist the pilot in collecting the sample [37].

With the exception of [42], which had a small propeller guard at the front of the aircraft, and [40], which used off-the-shelf propeller guards, collision tolerance was not present in the existing designs. While this is not a problem for hanging designs, lateral reaching designs are frequently in close proximity to the canopy when cutting/collecting a sample, which puts the aircraft at risk of colliding propellers with branches/leaves and crashing. The two above-mentioned systems with propeller guards may have had some protection from stems and other solid vertical surfaces; however, these systems would not have protection from branches and leaves, which tend to move and do not provide much resistance when flying into them. Collision tolerance which can stop such a lateral reaching UAS from flying too deeply into the canopy would be useful in preventing crashes and would reduce the stress of the sampling operation on the pilot; however, a large surface area is needed to provide sufficient resistance to prevent flying deep into the canopy. Providing such a large surface area for collision presents challenges with regard to aircraft weight and aerodynamics.

In this article, we describe our approach to rapidly prototype a purpose-built UAS for the collection of canopy samples, which was collision tolerant and able to collect samples from the side of trees. Four novel design iterations are presented, with design decisions and justifications described throughout. The designs we present are not intended to replace hanging sampler designs, which are a very logical approach for capturing samples from the top of the canopy. Instead, the goal was to provide the capability of capturing samples from locations from which a hanging design cannot reach, such as from underneath a canopy, from the side of a canopy, inside a forest with a closed canopy or from the side of vertical or overhanging cliff faces.

2. Materials and Methods

The structure of the methodology is as follows: first, the common system components and ideas used in all iterations of the canopy sampling UAS are described. The design process in this study was highly iterative and made extensive use of 3D printing in order to rapidly prototype and test new ideas as different challenges were identified through field testing. In this article, each iteration is presented in order of creation, with lessons learnt from the first design informing the design decisions made for the subsequent design iterations. Lastly, the details of the field testing to evaluate the utility of the approach are described, along with a discussion of relevant safety considerations within the context of existing sampling techniques.

2.1. Overall System Design Considerations and Components

As hanging designs are generally limited to sampling the very tops of trees, and as there are already successful designs for this task such as DeLeaves [32], our design was intended to access samples that would not be accessible with a hanging design, so the first major design goal was to develop a lateral reaching design which was capable of tolerating collisions with the canopy. Further, by having the propellers in line with the sampling tool, the considerable prop-wash does not blow directly into the sample to be captured. If the sample was beneath this aircraft, it would always be a moving target, though a sufficiently long pole can reduce this effect, as demonstrated in other designs.

Lateral reaching designs result in a relatively heavy sampling tool being extended far in front of the centre of gravity, so it is necessary to counterbalance this offset mass to maintain alignment of the centre of gravity with the centre of thrust. It was noted in [32] that there was a need for a counterweight in a lateral reaching design, and this is generally correct; however, it is important to note that the counterweight does not need to be dead weight and does not necessarily reduce the flight time due to weight. Most UAS are already carrying a relatively heavy battery, so it makes sense to use this and/or other components already required by the aircraft as the counterweight for the lateral payload. While this avoids unnecessary weight, it must be acknowledged that a lateral design also means an increase in the moment of inertia about the pitch axis, which does require more energy for a given attitude change. An example of how this counterweight is employed is depicted in Figure 1. Any collisions between the vegetation and the propellers can quickly result in a crash, so a design goal was to keep the sampling tool as far forward as practicable, and therefore keep the vegetation away from the propellers.

Keeping the sampling tool as far in front of the centre of gravity as possible is the first step for avoiding propeller–branch collisions; however, it has limited efficacy on its own. Intelligent sensing of the surrounding environment in order to avoid propeller-branch collisions would be a solution; however, reliable and precise detection and avoidance of small, dynamic obstacles (such as leaves and branches) remains a particularly challenging robotics problem at this time. Consequently, the system was designed to passively tolerate minor collisions with branches rather than attempt to avoid them entirely. The primary risk of these low-speed and minor collisions to the aircraft is the propellers striking branches and being slowed or stopped as a result. This can lead to a loss of thrust/control of that motor, often causing the aircraft to propel itself further into the branch and resulting in the loss of the aircraft. While the UAS designs presented in this work were able to descend safely in the event of losing a single motor, performance is considerably degraded if this occurs.

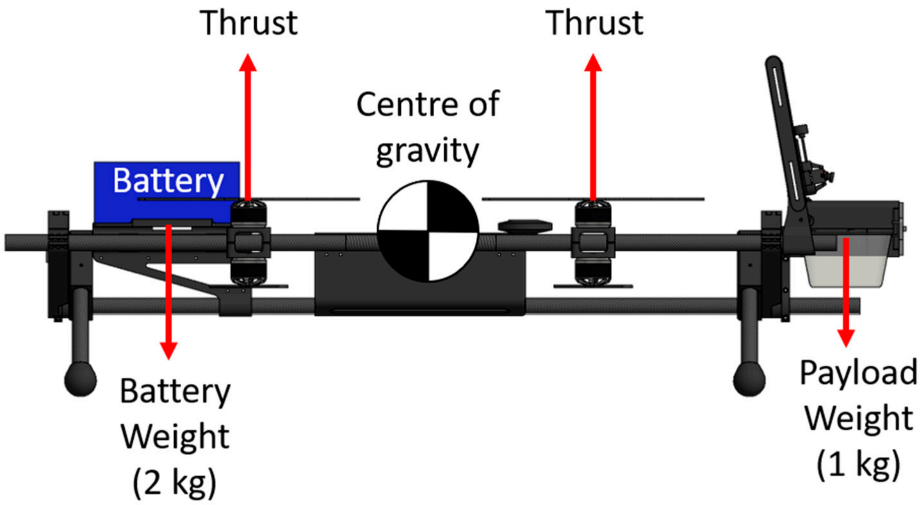

Figure 1. Our designs compensate for the offset payload mass by using the battery as a counterweight. With the battery weighing approximately 2 kg and the payload weighing approximately 1 kg, the payload can be further from the centre of mass than the battery, keeping the sampling operation as far in front of the propellers as practicable.

All iterations of the aircraft used the same base components as described in Table 1, and all used the battery as a counterweight to the sampling payload to ensure that the center of gravity was aligned with the center of thrust. The power components such as the battery, motors and propellers were not our first component choices, as the COVID-19 pandemic had impacted supply chains and greatly limited part availability for this project. A smaller aircraft was preferable, but smaller, suitable combinations of motors, propellers and batteries were unable to be acquired during the project. The resulting airframe was a coaxial octocopter to keep the footprint of the aircraft as small as possible while providing enough thrust to carry the cutting tool payloads.

Table 1. Common UAS components used for all iterations of this system.

Component Type	Model
Flight Controller	Holybro Pixhawk 4—PX4 Firmware
Motors	T-Motor MN4014-11, 330 KV
Propellers	Carbon fibre 431.8 mm diameter, 140 mm pitch
Battery	Turnigy 16 Ah, 6S (Lithium Polymer)
Airframe	Custom 3D printed designs with carbon fibre tubing. Printed using Polylactic Acid (PLA) filament for all components except the motor mounts, which were printed in Polyethylene terephthalate glycol (PETG) for the higher glass transition temperature underneath the motors. Past experience has found that PLA motor mounts can soften and fail catastrophically from motor heat loads.
Companion Computer	Nvidia Jetson Tegra X2 (Nvidia, Santa Clara, California, United States of America) with Auvidea J120 development board (Auvidea, Denklingen, Germany). Note: used from version 3.0 onwards.
Visual Inertial Odometry Sensor	Intel Realsense T265 (Intel, Santa Clara, California, United States of America). Note: used from version 3.0 onwards.

Many prior works made use of entirely custom tooling for the sampling operation; however, our approach was to purchase existing, low-cost power tools and modify them for the task. The penalty of this approach was the additional weight when compared to a custom tool, but the advantages included the ability to rapidly change the approach while also saving considerable engineering effort, time and manufacturing costs during the development of a suitable approach.

2.2. Version 1—Full Collision Box with Electric Secateurs

The first design iteration involved a cage-like structure that was integrated into the airframe, with the intent to cover this in tough plastic meshing. The sampling tool consisted of an electrically powered secateur tool (Ryobi 18 Volt One+ Lopper, https://www.ryobitools.com/outdoor/products/details/18v-one-plus-lopper, last accessed on 10 March 2021) which consisted of sharp jaws driven by a linear actuator and was capable of cutting branches of up to 30 mm in diameter. To adapt the tool for this application, a Pulse Width Modulation (PWM) controlled relay was wired in parallel with the tool's trigger switch, allowing the tool to be controlled using the radio control (RC) transmitter. This version was successful in trimming off sample branches; however, it was difficult to aim due to the small cutting area of the tool. While it was possible to guide the tool into place with rods protruding from the front of the tool [35,39], it was decided that the retrieval of the sample would be greatly preferable to dropping the sample, as it may be challenging to find the trimmed branch, or it may not even fall all the way to the ground. This first version is shown in Figure 2.

Figure 2. Version 1 was most similar to [39]. The first sampling approach used powered secateurs to drop branches of up to 30 mm in diameter to the ground for retrieval. This required precise aiming and flight control during cutting, and while it was functional, a more practical approach that required less precise flight control was sought.

In addition to being challenging to aim, this design was limited to branches with sufficient space for the UAS to fly alongside it with the tool perpendicular to the branch to make the cut. In practice, meeting this requirement was found to be more difficult than initially expected. Further, triggering the cutting mechanism while a branch was in the jaws required both good timing and strong pilot skills; both undesirable traits for a system that needs to be simple to use. Figure 3 show this version trimming a branch sample, though this can be more clearly seen in the provided video in the results section.

Figure 3. Version 1 of the canopy sampling drone trimming off a sample branch. This design was functional but difficult to aim, and it dropped the sample; resulting in the pursuit of a different approach.

While the secateur-based approach did work, and there are other examples of a similar approach being used [35,39,42], it was decided that an alternative approach that required less precise flight control was desirable; especially one with the means to retrieve samples instead of dropping them to the ground (where they may be difficult to identify). To reduce the difficulty of the sample capture process, a simpler approach was sought.

2.3. Version 2—Full Collision Box with Electric Hedge Trimmer

A number of tools were considered, such as small chainsaws and circular saws; however, reacting to the forces required to operate these tools effectively was of concern. Further, it was preferable to avoid the risks associated with getting a saw or secateur-based tool stuck in a branch. While hanging designs such as DeLeaves [32] are able to be released in an emergency, a lateral reaching design does not easily allow for this capability. A single-handed electric hedge trimmer was considered instead, which uses a shearing method of cutting which reacts with its own cutting forces. Further, the blades are designed to limit the size of the branches that can enter the cutting region to a size that should be safely cuttable by the tool: minimising the risks of a stuck tool while sampling. A hedge trimmer also forces the samples to be accumulated slowly and gently into the sample container, minimising the risk of a sample being too heavy (potentially catching the operator by surprise) and shifting the centre of gravity too far from the centre of thrust or overcoming the maximum weight limit of the aircraft.

A low-cost, cordless hedge trimmer (Ryobi 18 Volt "Shrubber" (https://www.ryobitools.com/products/details/18v-one-plus-grass-shear-and-shrubber, last accessed on 10 March 2021), was disassembled and placed into a custom, 3D printed housing with a removable sampling container. As this device did not require any logic-based control, the original electronics were not retained, being replaced with a simple PWM controlled relay for controlling the motor. Figure 4 show this hedge trimmer-based sampling payload. A safety switch was also added to allow the operator to manually prevent the tool from activating unexpectedly, though this aircraft should not be manually handled while powered.

Figure 4. A single-handed hedge trimmer was modified and integrated into a custom 3D printed housing with a removable sample container. A manual safety switch is shown in the top-right of the left image, which allows the operator to prevent the tool from running unexpectedly. Right shows a camera view of the tool while in flight, about to collect a canopy sample.

This payload was designed to easily fit onto the existing frame in place of the previously tested tool. From the first test of this alternative approach, it was clear that this was considerably easier to operate and more effective than the secateur-style approach. The second sample collection test with this system is shown in Figure 5.

Figure 5. Version 2 of the canopy sampling drone made use of a hedge trimmer-based sampling tool. This tool was considerably easier to operate than the previous, secateur-based design. Left and right images show the before and after the collection of a canopy sample, respectively.

The sampling operation requires the front of the aircraft to be flown underneath a branch of interest, then hold a horizontal position while gently raising altitude until the hedge trimmer cuts through the required sample. The collision protecting mesh had not yet been installed on Version 2, so additional care was required not to fly the tool too deep into the canopy, or a crash would be almost guaranteed. The operation of the sampling tool is visualised in Figure 6.

Figure 6. A visualisation and photos showing how canopy samples are collected using this hedge trimmer based approach. Holding altitude, the UAS is piloted gently forward into the vegetation until the collision shield prevents forward motion. The pilot then holds horizontal position while gently raising the altitude until the UAS has cut through to the top of the sample region. The sample will fall into the sample container for retrieval upon landing. Version 3.1 is visualised here due to better photos of operation, but all hedge trimmer based designs in this study used this same sampling approach.

Version 2 has successfully demonstrated the approach was feasible; however, the size of the aircraft required a large vehicle for transportation. Thus a foldable and more portable design was sought.

2.4. Version 3.0—Foldable Airframe with Ducted Fans

Version 3.0 made use of 3D printed ducts to provide protection to the propellers while also allowing the aircraft to fold in half for ease of transport, shown in Figure 7. The eCalc multirotor design tool [45] was used as a tool for estimating the performance of a potential UAS configuration; however, the predictions were found to be too optimistic for this configuration. This version was too heavy for the components used, and while able to hover, was unable to fly out of ground effect, which was approximately 1 m above the ground. The propellers used in this configuration were smaller (407 mm diameter) than the rest of the configurations, as the duct diameter was limited by the print volume of the available 3D printer.

The ducts on this system weighed 600 g each, so these were removed to enable the use of the larger diameter propellers and a considerable mass reduction of 2.4 kg.

Figure 7. Version 3.0 protected the propellers with the use of 3D printed ducts. The design was capable of folding for ease of transport. The calculations used for estimating flight performance were found to be optimistic, with the system unable to fly out of ground effect.

2.5. Version 3.1—Foldable with Collision Shield

Full protection of the propellers remains highly desirable; however, it is the front of the aircraft at the greatest risk of collisions with leaves/branches during the sampling operation. Therefore, a lightweight (approximately 300 g), forward-facing shield was implemented in place of the ducts on the same foldable airframe as shown in Version 3.0. The shield is angled backwards to minimise the risk of the top of the shield catching on a branch while cutting a sample. The offset mass of the shield is counterbalanced by adjusting the battery position to keep the centre of gravity in line with the centre of thrust. This version is shown in Figure 8.

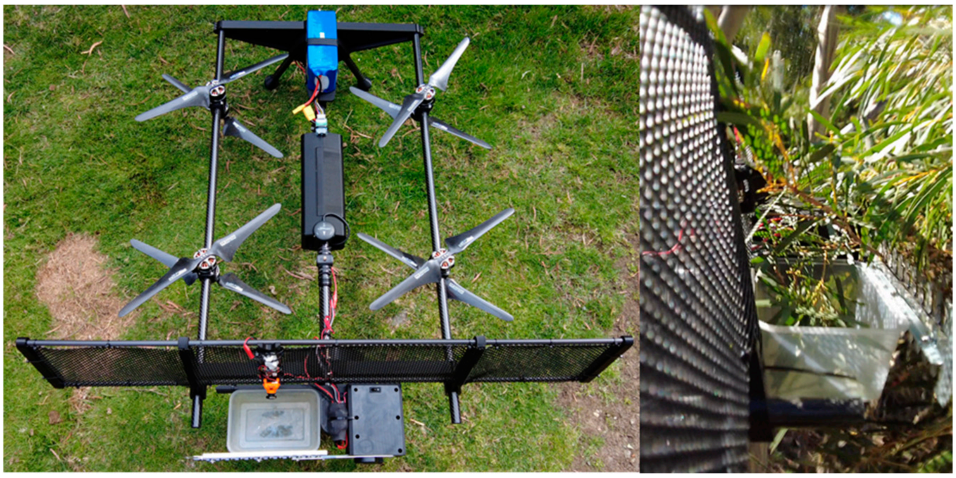

Figure 8. Version 3.1 of the canopy sampling UAS replaced the heavy, ducted fan system with a simple and lightweight, forward-facing shield to prevent collisions between the propellers and the canopy.

The first two iterations required completely manual control of the aircraft during sampling; however, this required considerably more pilot skill and concentration to operate than most modern UAS due to a lack of a precise position holding mode/capability. A means of precise movement control was desired to assist the pilot, so Visual Inertial Odometry (VIO) and a position hold mode which made use of this, was added to the system. VIO was provided by an Intel Realsense T265, which uses a stereo camera and Inertial Measurement Unit (IMU) to precisely track the position and orientation (pose) of the aircraft. An Nvidia Tegra X2 companion computer running Robot Operating System (ROS) [46] provided this information to the Pixhawk 4 flight controller, which used this information for holding a set position.

The VIO sensor was mounted on the rear of the aircraft, as the front of the aircraft was to be intentionally flown into vegetation, which would block the cameras and prevent useful visual tracking. Downward facing VIO was also briefly tested; however, frequently lost position tracking. It was suspected that this was a result of the vegetation beneath this aircraft moving erratically in the propeller wash of the aircraft. The sensor was initially mounted rigidly; however, the frame vibrations from propellers and the hedge trimmer were too severe for the sensor to function correctly, causing a loss of position tracking. This sensor was highly sensitive to vibration and had to be soft mounted with vibration-damping, double-sided tape. The VIO sensor can be seen on the back of the aircraft in Figure 9, with the companion computer hardware inside the centre of the aircraft.

Figure 9. Visual Inertial Odometry (VIO) was used to provide precise flight control to Version 3.1 of the UAS. The VIO sensor was an Intel Realsense T265 and was soft mounted on the rear of the aircraft.

Tuning the flight controller to safely use VIO was particularly challenging for this aircraft, as the large moment of inertia about the pitch axis caused the pitch response to be sluggish. While it could be tuned for stable flight in still conditions, even gentle gusts of wind would cause oscillations about the pitch axis, compromising the efficacy of the sampling operation, even in a gentle breeze. While any breeze is undesirable during a canopy sampling operation due to the canopy becoming a moving target, this design placed too strict of a requirement on the absence of a breeze. To address this, a way of decoupling the pitch of the airframe (for control) from the large moment of inertia about the pitch axis for the payload was sought.

2.6. Version 4—Pitch-Decoupled Hedge Trimmer and Battery

There was no requirement for the battery or sampling payload to be rigidly connected to the airframe, so a novel approach of decoupling the pitch axis of the battery and hedge trimmer from the main airframe was designed. The goal was to allow the aircraft to respond to disturbances (i.e., wind and physical interactions with the canopy) rapidly in the pitch axis while avoiding the need to rotationally accelerate and decelerate the heaviest components of the aircraft, which may also be restrained by the canopy being sampled. This joint should constrain yaw and roll movements; however, the system should also keep a short lever arm for the mass in the roll axis (i.e., keep the roll moment of inertia small). Further, the hedge trimmer should ideally remain level during sampling. The chosen solution was a pinned joint from which the battery and hedge trimmer could hang from, as depicted in Figure 10.

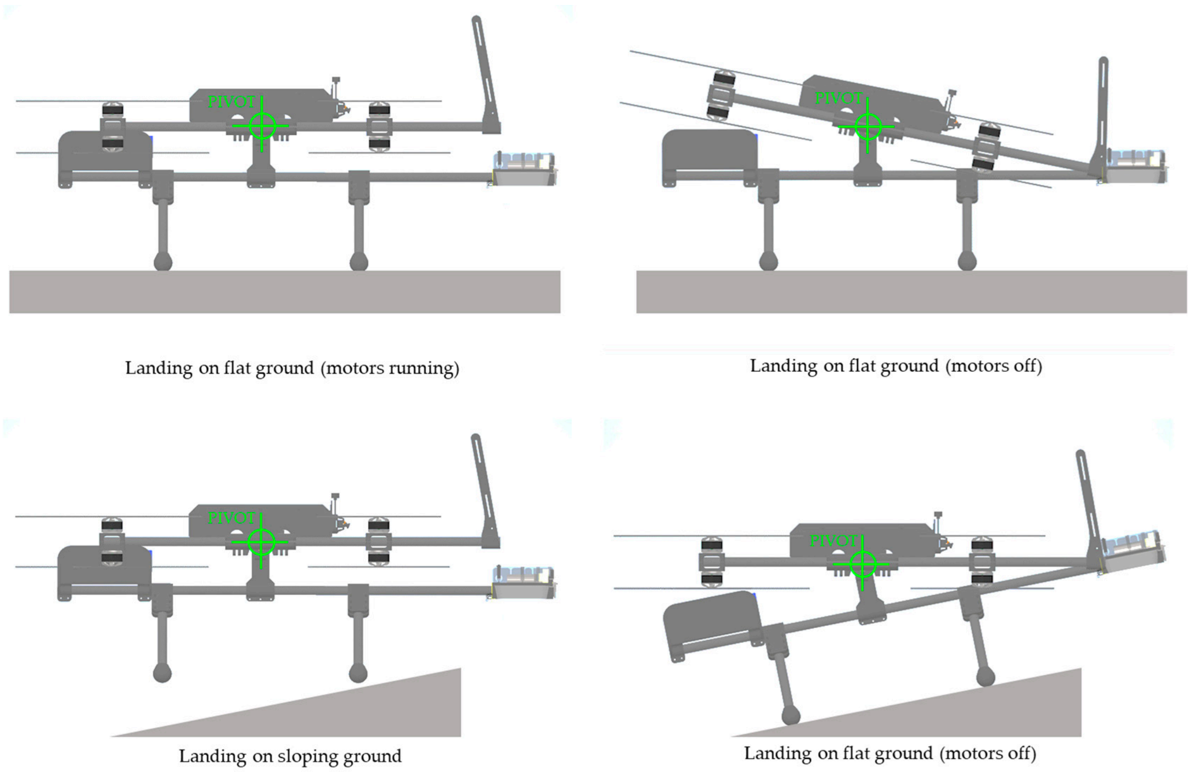

Figure 10. The battery, landing gear and hedge-trimmer sampling system were decoupled in the pitch axis from the flight controller and motors. The result was a highly responsive aircraft with the additional benefit of allowing landing on sloped ground. The prior version required flat ground, which was difficult to come by in the chosen test site.

While designing this aircraft to decouple the main airframe from the payload, an opportunity to provide the aircraft with passive adaptive landing gear was identified and implemented. By putting the landing gear beneath the pivot point, the aircraft was able to safely take-off and land on sloped surfaces, facing either up-slope or down-slope, removing the strict requirements of the previous iterations for a flat landing site. All four legs were able to make contact with a sloped surface while maintaining a vertical thrust vector.

In practice, this idea was found to be highly effective, albeit slightly unusual to pilot, as such a large portion of the aircraft does not respond directly to the control inputs as would typically be expected on a more conventional multirotor UAS. The system was able to land facing upslope on a surface of approximately 25 degrees from the horizontal and downslope to approximately a 20-degree slope while maintaining a vertical thrust vector. The difference is due to the offset mass of the collision shield on the main airframe, which shifts the centre of gravity forward. A sequence of taking off and landing from upward and downward sloped surfaces is shown in Figure 11.

Figure 11. Real-world testing of the landing gear concept found it was highly effective on both upward and downward slopes, albeit unusual to pilot due to the large portion of the aircraft not responding directly to the control input.

While the flight controller assumes rigid body motion, the controller caused no issues in the slow control regime this aircraft was intended for; provided the Proportional, Integral, Derivative (PID) controllers were appropriately tuned. The lower section does act as a pendulum; however, the slow natural frequency meant that it was not an issue in practice. That said, the pilot is required to fly gently, as aggressive flying will cause the lower section to oscillate and potentially reach the angle limit stops (±30 degrees), imparting an undesirable pitching moment on the main airframe.

An additional challenge with lateral reaching canopy sampling UAS which collect samples is that the sample weight shifts the centre of gravity forward, leading to reduced performance and potentially leading to instability. With this pitch-decoupled design, the lower section passively adjusts the weight distribution as samples are captured, keeping the centre of gravity in line with the centre of thrust at all times, an important consideration for any UAS.

2.7. Safety Considerations

Throughout discussion with members of the forestry industry and public, a frequently raised concern about a canopy sampling UAS with a power tool is that it is perceived to be a particularly dangerous creation. These concerns are often raised by people who are not operators of UAS, and perhaps underestimate the severity of the hazard already presented by the propellers on any UAS. While power tools must certainly be respected, we argue that the propellers of any large UAS represent a greater hazard than a hedge trimmer; particularly if someone was particularly cautious of the hedge trimmer but perhaps not so concerned about the propellers. Adult fingers would be unable to fit into the cutting area of this hedge trimmer, and with the exception of a high-energy collision with the tool, the hedge trimmer would be unlikely to cause severe injuries even with skin contact. Large carbon-fibre propellers, on the other hand, contain considerable rotational kinetic energy, are almost invisible when in operation, and may cause large and severe lacerations or even amputations. Thus, we argue that this UAS is no more dangerous than any other similarly sized UAS. That said, any physical interaction with the canopy using a UAS does constitute a greater risk of a crash than one used for remote sensing applications, so it must be operated with care and by an appropriately skilled pilot.

The risks associated with UAS based sampling must also be considered within the context of other, more conventional canopy sampling techniques. The use of pole saws can involve the risk of the cut branch falling on the operator. The use of arborists for sample collection may involve the use of chainsaws at height, while the rope access itself comes with potentially fatal consequences in the event of an accident. Discharging firearms into the air to knock down samples comes with the risk of missing a targeted branch, and while this has a low probability of hitting a bystander, the consequences of which could be fatal. When operated with appropriate skill and caution, and within UAS operational laws, a UAS is highly unlikely to collide with a human, even in the event of a crash since the physical interaction with the canopy, the most likely cause of a crash in the operation, occurs at a considerable distance from the operator.

2.8. Test Site

This study took place in a private forest near Hobart, Tasmania, Australia. The sampled trees consisted of eucalyptus pulchella, eucalyptus globulus and acacia dealbata. The site is steep, with an average slope of approximately 24 degrees.

2.9. Sample Collection Test

To understand the range of sampling times for this system, 30 samples were collected using the final iteration (Version 4) of the aircraft. All samples were within a 50 m horizontal radius from the pilot in these tests, as an unaided line of sight was required to be maintained at all times for both operational reasons and to ensure compliance with Australian UAS regulations. Sampling times were measured using the transmitter/ground station, with a timer automatically starting upon arming and finishing upon disarming the aircraft. An additional 5–10 min was required for both set up and pack down at each field site; however, the typical use case would involve the collection of multiple samples per site.

2.10. Demonstration Video

To demonstrate the effectiveness of the presented systems, a video demonstration of all iterations of the aircraft (excluding Version 3.0) is provided.

3. Results

3.1. Sample Collection Test

Sampling times ranged from 1 min and 23 s, up to 3 min and 41 s, with the main factor being proximity to the pilot. The mean and median sampling times were 2 min, 25 s and 2 min, 20 s, respectively. The distribution of the sampling times is shown in Figure 12.

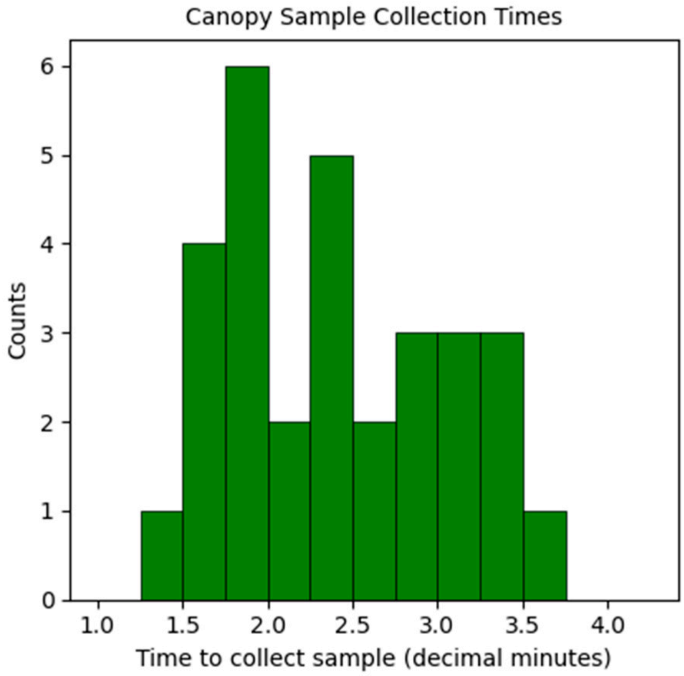

Figure 12. The distribution of the times taken to collect a canopy sample from arming to disarming the aircraft (n = 30). An additional 5–10 min is required at the start and end of any sampling session to set up and pack away the equipment.

Ten of the canopy samples collected during this testing are shown in Figure 13.

Figure 13. A collection of samples captured using Version 4 of our canopy sampling UAS. Samples were collected from eucalyptus pulchella, eucalyptus globulus and acacia dealbata species.

The set up and pack down of the system requires an additional 5–10 min; however, multiple flights would typically be performed at each site. The individual flight times are provided in Table A1 in the Appendix A. Version 4 of the aircraft was capable of flying for approximately 12 min, which enables 3–6 samples to be collected per battery, depending on proximity to the take-off/landing site. While the aircraft had a first-person view (FPV) camera on-board, with a live video feed displayed on the ground control station to aid the pilot, a high level of situational awareness was critical during the sampling procedure due to the cluttered environment around the aircraft. Direct line of sight (LOS) is also required by law in Australia (without complex approval processes), so the aircraft was operated by line of sight with only brief checks of the FPV view to assist with aiming of the sampling tool. Most samples were collected by LOS only, without the use of the FPV view; however, this approach becomes increasingly difficult with increasing distance from the pilot, leading to an increased reliance on the FPV system for the sampling action. Stereoscopic depth perception degrades with increasing distance, which makes the precise flying during sample capture considerably more challenging as the distance from the pilot increases. The additional difficulty likely increased the sampling time more than just the added distance to fly to and from the sample location.

3.2. Demonstration Video

An accompanying demonstration video is provided here: https://youtu.be/iM0RSLVlETY, last accessed on 30 October 2021, which shows all of the designs presented in action.

4. Discussion

As seen in the demonstration video, the described system is capable of rapidly and easily collecting samples from most locations on most trees. By using Visual Inertial Odometry (VIO) and Robotic Operating System (ROS) to provide position control of our aircraft, it was possible to facilitate precise cutting movements with the aircraft, while the simple collision shield reduced the risk of branch-propeller interactions and prevented the aircraft from flying too deeply into the canopy. Precision flight capabilities are not critical for this application, as the hedge trimmer sample collection approach is relatively simple for an adequately skilled pilot to perform in calm conditions; however, VIO based position control makes this operation considerably safer, simpler, and more precise, especially at greater distances from the pilot.

This project has successfully demonstrated an alternative approach to other canopy sampling UAS seen in the literature to date [32–43]. We do not view our approach as a replacement to approaches such as DeLeaves [32], but rather as an alternative tool for forest researchers, which is able to collect samples that tools such as DeLeaves could not reach; notably samples on the side of trees, the side of cliff faces, or those with objects above them which would prevent a hanging pole design from accessing them. Our system is currently limited to sampling from the side of the canopy, which does cover most regions of a tree; however, if the highest tip of the tree is desired, or if the canopy is closed, something such as DeLeaves may be more suitable. On the other hand, if samples beneath a closed canopy are desired, our presented system would be capable of sampling areas which a hanging pole design could not, provided that the UAS can physically fit between the gaps to reach the desired sampling location. Manual sampling of canopies with pole saws would remain more practical when samples are easily reached from the ground. Extremely dense forests, such as unpruned and unthinned plantations, without room for flying a UAS would also be unsuitable for the proposed approach, and hanging sampling systems such as DeLeaves would be necessary.

This study was limited to a single site, with three native Australian tree species sampled; however, as long as a hedge trimmer is capable of cutting the vegetation on a tree, the species should not matter. Further work should explore the effects that differently shaped tree crowns have upon the sampling operation, as the three species this system was tested upon were relatively similar in crown structure. The design presented is suitable for research use, where operators have sufficient expertise with UAS to operate and maintain the system; however, it is not yet sufficiently refined for widespread adoption in forestry. To reach a mature state for industrial adoption, more robust position tracking/holding and a higher quality FPV system would be required for longer-range operations.

There is considerable scope for future work in this space. If this project continues, the next iteration of this system will use an approach inspired by Voliro [27]. It would replace the passive hanging system by actively pivoting the motors about the pitch axis using servos. This would address the issues with the large moment of inertia about the pitch axis, improve yaw responsiveness and still enable safe landing on sloped terrain. As the hedge trimmer based tool was found to be highly effective and practical, we would use this concept to build a dedicated design to reduce weight and reduce non-cutting contact area (i.e., minimise the size of the black box holding the motor or move it out of the way) to minimise drag against the canopy during upward cutting operations. VIO would still be used; however, a pair of VIO sensors (one pointing down and one pointing rearwards) would be used for enhanced robustness, as our current implementation lost track of position occasionally (particularly while flying high up or in a breeze). Our system used the default Intel Realsense VIO package for ROS; however, other VIO packages may be more robust to the conditions. Other aspects of the design would remain similar to Version 4, such as the battery mount with integrated landing gear and the style of collision shield on the front of the aircraft, though landing gear would be integrated into this collision shield to further reduce the part count and weight. This proposed "Version 5" is depicted in Figure 14.

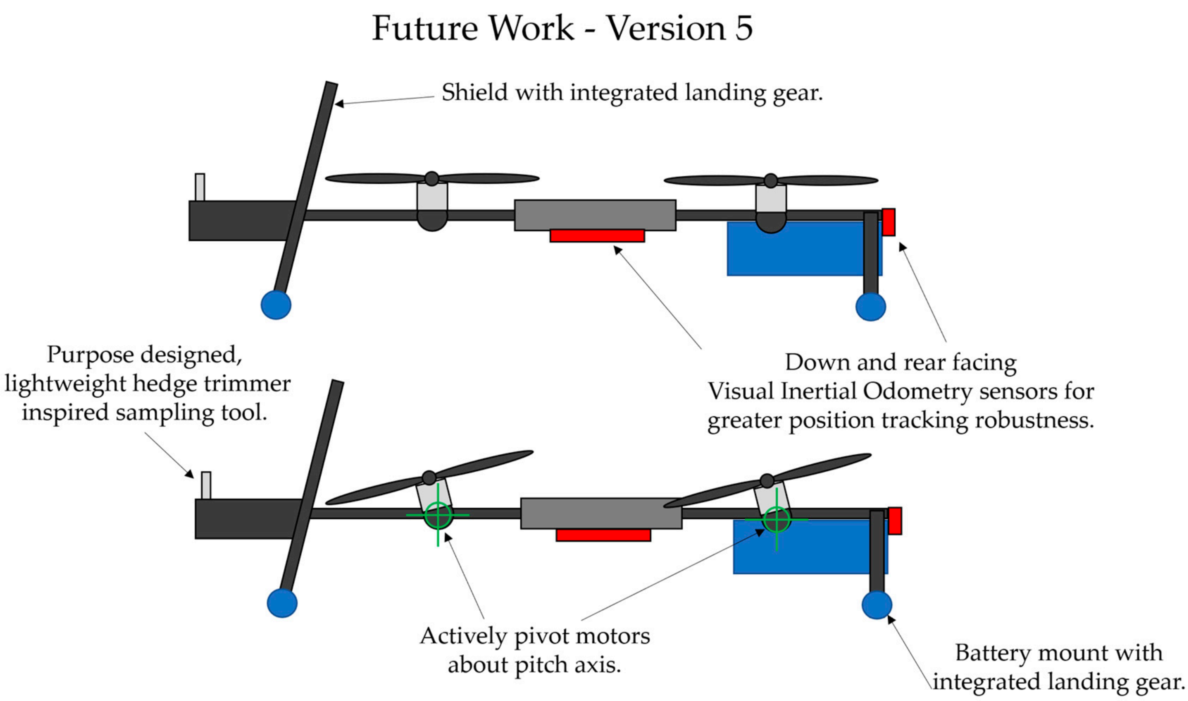

Figure 14. Our vision for the 5th iteration of this aircraft is inspired by Voliro [27], and would actively pivot the motor mounts about the pitch axis to separate forward and rearward movements from the pitch attitude of the entire airframe. This would likely be a better way to address the issues caused by the large moment of inertia about the pitch axis while also enabling take-off and landing on sloped terrain.

Additional, near-future work could see the design of a sample container for collecting multiple samples per flight. This could be achieved by using divided containers, which could rotate into place underneath the hedge trimmer for each sample, analogous to the working mechanism of a revolver. It is also suggested to add the functionality to record the GPS position when the tool is turned on and off to easily provide a GPS position for each sample.

Looking considerably further forward into the future, we could envision a system where remote sensing and physical sampling or other physical interactions could be combined. A UAS with Simultaneous Localisation and Mapping (SLAM) capabilities may not only capture a high-fidelity digital twin of the forest (in the form of a point cloud) but could also collect physical canopy samples during the process. These physical sample locations could then be localised in the captured point cloud, enabling more advanced research of canopy and leaf traits throughout a forest. Alternatively, a sampling location could be selected in a previously captured point cloud, with the UAS able to autonomously go to that position and retrieve a sample. This concept is depicted in Figure 15.

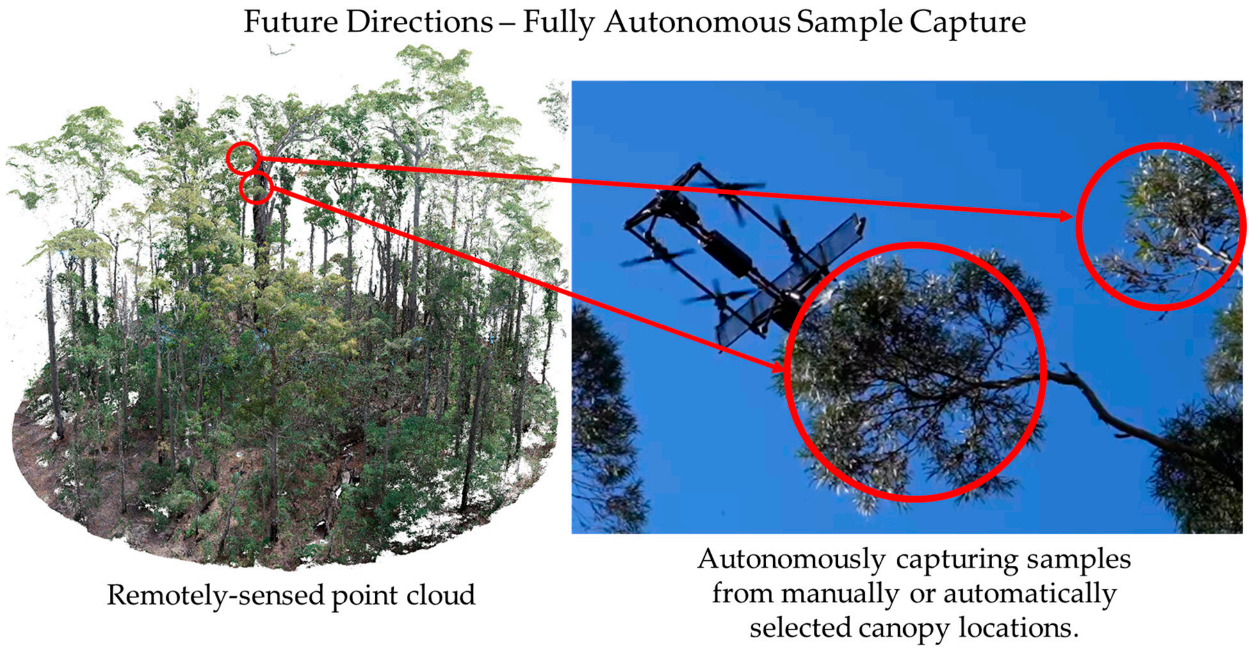

Figure 15. A visual depiction of where this technology may be headed. Advanced remote sensing techniques could be used in conjunction with autonomous sample capture UAS, automating the sample collection process and reducing the human skill required to operate such a system.

Such an approach would need to be able to tolerate the complexities and uncertainties present within point clouds caused by factors such as beam divergence, point cloud registration errors caused by wind during the sensing process, noise and variable scanning resolutions. Deep learning-based approaches such as [47] appear promising for addressing such a challenge.

5. Conclusions

A series of novel canopy sampling UAS were presented, with detailed explanations as to how each iteration informed the design of its successor. These aircraft demonstrated a reliable and rapid method for the capture of canopy samples using a novel hedge trimmer based design not yet seen in the literature. The final prototype was tested for capturing 30 samples, with sample collection times ranging from 1 min and 23 s, up to 3 min and 41 s, depending on the forest conditions and distance from the take-off/landing site to the tree. This design was demonstrated to be capable of rapidly and safely collecting canopy samples that were previously either too difficult, dangerous or expensive to capture or where existing techniques were not suitable. Future work should see to the development of a purpose-built sampling tool based upon a hedge-trimmer-like design, as well as reducing the weight and size of the aircraft carrying it. This approach should also be tested on other types of trees, such as conifers. Looking further forward, fully-autonomous sample capture and simultaneous point cloud capture could be integrated, resulting in a holistic physical and digital sample collection tool for forest research.

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validation, S.K.; visualisation, S.K.; writing—original draft, S.K.; writing—review and editing, S.K., M.S.T., J.M. and P.T. All authors have read and agreed to the published version of the manuscript.

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Appendix A

Table A1. Time to collect canopy samples from arming of the aircraft to disarming.

Sample Number	Time to Collect Sample (Arm to Disarm) Minutes:Seconds	Decimal Minutes
1	1:35	1.58
2	1:23	1.38
3	2:12	2.20
4	3:02	3.03
5	2:39	2.65
6	1:41	1.68
7	2:58	2.97
8	2:22	2.37
9	1:41	1.68
10	1:48	1.80
11	1:45	1.75
12	2:28	2.47
13	3:20	3.33
14	1:58	1.97
15	2:24	3.40
16	2:19	2.32
17	1:59	1.98
18	2:41	2.68
19	1:53	1.88
20	1:30	1.50
21	2:01	2.02
22	3:09	3.15
23	3:27	3.45
24	3:41	3.68
25	2:23	2.38
26	2:52	2.87
27	2:49	2.82
28	1:52	1.87
29	3:09	3.15
30	2:19	2.32

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