REPORTS

Dances with Branches: Developing a Micro-drone for Close Proximity Tree Inspections

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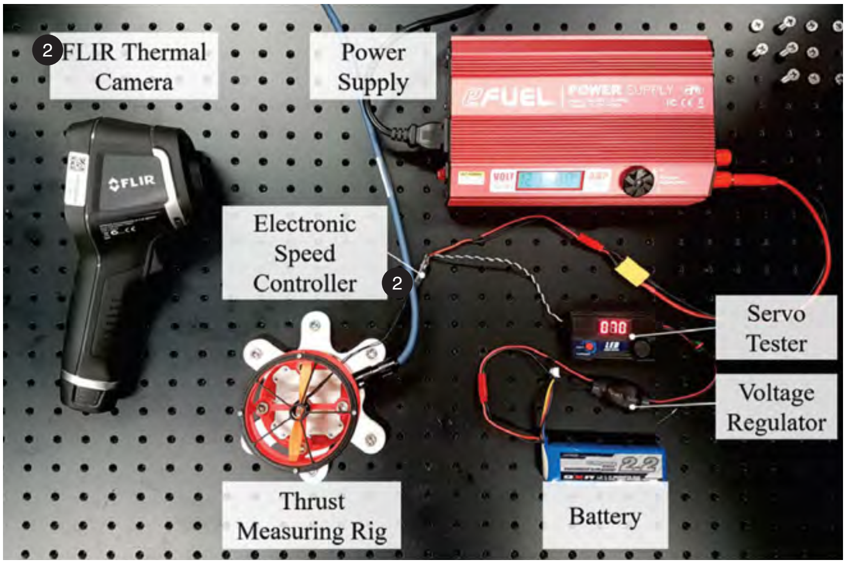


Tree inspections are an integral part of the maintenance of Singapore's City in a Garden. One of the most laborious portion of an aerial inspection is accessing the major branch unions or other hard to reach portions of the tree crown in order to evaluate their conditions. A typical method for doing this would be to utilise a mechanical crane or to physically climb the tree (Fig. 1), both of which incur considerable cost and time to perform. The alternative presented here is the micro Unmanned Aerial System (UAS), also known as Unmanned Aerial Vehicle (UAV) or simply "drone", that has been specially developed, increasing the productivity of an arborist by assisting in this time consuming activity.

Drones have gained much traction in recent years across multiple sectors as a result of maturing technology and lowered barriers of entry. Today, drones are being used for aerial imaging, mapping, deliveries, transportation as well as inspections. Aerial inspections using drones are already being explored for buildings, powerlines, bridges, refineries, boat hulls and other infrastructure whereby the drone provides a means to visually access an otherwise inaccessible location. While the same idea can theoretically be ported over for tree inspections, unfortunately the platforms used for infrastructural inspections tend to be unsuitable to fly into and navigate within the confines of the tree canopy.

Drones vary immensely in terms of size, cost, agility, flight time, payload, complexity and other technical details depending on their designed usage. In choosing a suitable platform for tree inspection, it was decided that a purpose built micro-drone would be required to be developed as no off-the-shelf solution was readily available for the task at hand.

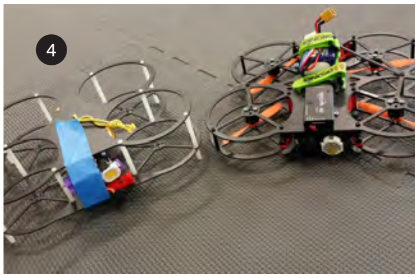
Development of Micro-Drone

The idea of developing such a prototype was brought to light by the National Parks Board (NParks) and was subsequently taken on and developed in collaboration with the Singapore University of Technology and Design (SUTD). The goal was to utilise advancements in the area of miniaturised components to produce a micro sized drone that is lightweight, low cost and carries a low risk factor in order to perform the task of inspecting trees.

One critical issue is the protection of the propulsion system so that close-contact flying is possible and safe. The prototype micro-drone has a unique and highly optimized propeller guard to extract aerodynamics gains while protecting the spinning propellers from striking obstacles within the tree canopy.

The theoretical aerodynamics gain over an unducted and unprotected propeller was analysed and it was found that two parameters have significant bearing on the performance: the duct length and number of spokes at the duct outlets. Experiments were carried out to explore these effects to determine the optimal design parameters using a specially conceived experimental setup (Fig. 2) to measure the thrust produced by the specified ducted rotor configuration [1]. While it was found that a ducted design would perform

1. A highly trained arborist physically ascends a tree to carry out the inspection—a laborious and time consuming task and not without a degree of risk.
2. Experimental setup to explore effects of duct length and number of spokes at duct outlet.



3. The first few prototypes were laser cut from plywood in order to rapidly experiment with various configurations for space optimisation.
4. When the design was more finalised, the frames were milled from carbon fibre sheets which have a much higher strength to weight ratio compared to plywood.
5. The final version of TIM has an onboard video recorder as well as an adjustable camera and high powered LED for illumination.
6. The integrated propeller guards provide additional protection against the multiple obstacles to be found within the confines of the canopy.

better, the added weight would negate this benefits gained and hence the decision was made to do without it. The number of spokes as well as their positions were also optimised to minimise thrust loss while maximising structural integrity.

Further design decisions went through several rounds of iterative rapid prototyping (Fig. 3 & 4) and testing which included optimising the throw of the servo adjusting the camera angle, the inclusion of a high powered light emitting diode (LED) alongside the camera, different iterations of custom milled bodies as the design was improved, modified high definition cameras to record and transmit the in-flight footage, optimised pairing of motors to propellers to maximise efficiency and other purposefully designed elements catered for the task of carrying out the inspection.

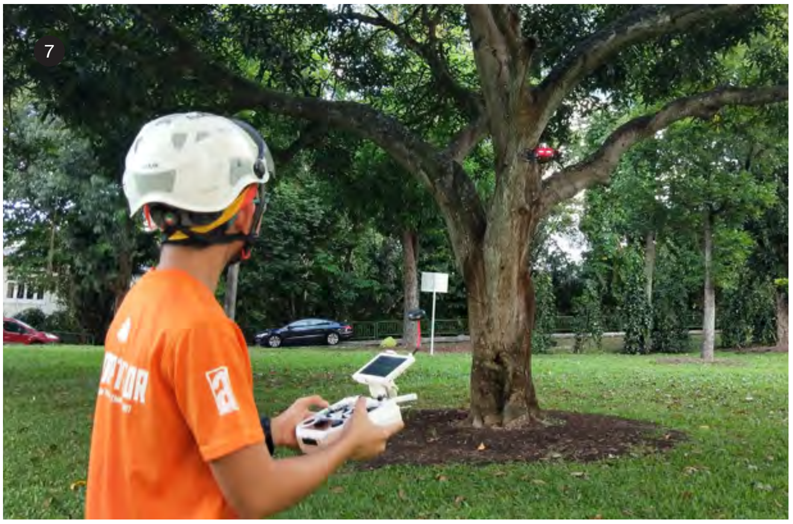
The final prototype (Fig. 5 & 6), appropriately named the Tree Inspection Micro-drone (TIM), weighs only 260 grams and has a flight time of about 5 minutes per battery. While the flight endurance might seem limited, testing in the field showed that it was more than enough to inspect a single tree at a time and if more flight time was required, it would only require a quick change of battery. The adjustable camera along with the high powered LED transmit a live video feedback (Fig. 7 & 8) which allows the operator to more easily navigate through the confines of the canopy while the in-built guards prevent the propellers from striking major obstacles along its path.

Real World Testing

From preliminary testing alone, it was evident that there is a potential for time savings as multiple locations within the same tree could be inspected in a single 5-minute flight (Fig. 9). The design, size, weight and structure of the micro-drone also made it safe and possible to navigate between the tree branches to perform visual inspections of unions, tree holes and other areas of interest within the tree crown (Fig. 10 & 11).

Other than the advantage of being able to fly into the confined spaces, TIM's lightweight and unobtrusive characteristic also makes it suitable for use in the public domain compared to a larger platform which would be more obstructive in terms of noise or a perceived danger by passersby. This also means that should an incident occur, the potential risk of damage to a third party is minimal, making it more beginner friendly than less forgiving drones.

While it was found that TIM could indeed assist in tree inspections, a surprising alternative use was uncovered in the area of close proximity in-situ plant identification and documentation whereby TIM was deployed within forested areas to film and document otherwise hard to reach plants high up in the tree canopy (Fig. 12). Notably, it resulted in the in-situ documentation (Fig. 13) of a previously presumed nationally extinct species, *Acriopsis ridleyi* [2]. In performing this test flight, one additional advantage that TIM had over other off the shelf drones was discovered. TIM was capable



7. The arborist uses a remote control to steer TIM towards the intended inspection location.
8. A live video feedback provides a first person's view of what the drone's camera is looking at and allows the arborist to navigate and carry out the necessary inspection, if required a high definition video feed is also recorded onboard for further evaluation after the flight.
9. Seven or even more different inspection locations can be carried out in a single 5 minute flight providing a close up view of the potential defects.

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of flying in forested conditions without having to rely on obtaining a strong Global Positioning System (GPS) signal for navigation, which was difficult to obtain under dense vegetative cover.

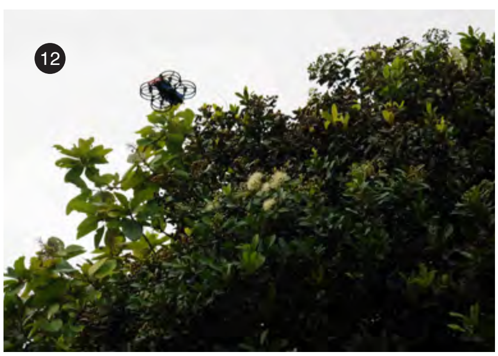
Throughout the developmental phase and after the completion of the project, NParks has utilised TIM as a demonstrative tool to showcase the possibilities of using the technology for tree inspections. This included demonstrations to in-house arborists, guests, landscape practitioners and students– all of whom were convinced of the potential benefits the technology brought to the table.

Due to its novelty and real-world problem solving nature, the developed micro-drone was also awarded the Singapore Good Design Mark (SG Mark) 2018. The SG Mark was established to set the benchmark for design quality that impacts businesses and communities in Singapore and beyond. TIM was also featured in INDESIGNLIVE. SG as one of the 10 Outstanding Winners of SG Mark 2018.

Future Developments

The first iteration of TIM was essentially a prototype, hence understandably not without fault. It functions as a proof of concept that a micro-drone is capable of the task at hand. It was designed to be simple, stripping off external sensors in place for lowering developmental costs and time. However, this meant that TIM requires a seasoned pilot capable of navigating the difficult constraints of a tree canopy and as such limits its widespread adoption by the industry.

The subsequent development of TIM v2.0 was supported by Enterprise Singapore's Gov-PACT initiative. Building on the fundamental design principles of the original TIM, one of the first critical tasks for TIM v2.0 is to enhance the operating software to enable obstacle avoidance, sensor based position-hold capabilities as well as Artificial Intelligence (AI) driven drone



10. Inspections can be carried out within minutes even for areas of interest which are high up in the canopy, a process which would otherwise have taken hours to perform via climbing or crane.

11. A high powered LED provides valuable illumination into holes, hollows and branch unions which would otherwise be difficult to clearly inspect without the additional light.

12. Going above the tree canopy to document flowers, fruits and leaves at the top of trees was also made possible with TIM, a process which typically would require high powered binoculars and camera lenses, if at all possible given the lack of a vantage point from the ground.

13. A screen capture of a high definition video recorded using TIM documenting a rare in-situ specimen of *Acriopsis ridley*, the onboard LED provided valuable illumination to the subject matter.

> TIM was awarded the Singapore Good Design Mark (SG Mark) 2018, for its novelty as well as its ability to solve existing problems.

14. The more advanced electronic components such as an external proximity sensor array to allow for obstacle avoidance and position holding capabilities are being test-bedded on a larger version of TIM (left) to be eventually miniaturised and ported over to a more compact TIM v2.0 (right).

15. The eventual goal would be to develop a system that is not only capable of performing tree inspections but to do so in any other inaccessible, GPS denied or high risk locations.

16. TIM will soon be so accessible and easy to operate that it would be another tool to help arborists carry out their inspection work.

As TIM v2.0 continues to be miniaturised to better reach confined spaces, there is also the potential to take the technology beyond the realm of arboriculture and botany to wherever it may be needed - in tunnels, mines, pipelines and the like, removing the need for people to put themselves at unnecessary risks when accessing and inspecting these high risk areas (Fig. 15).

Yet this is only the beginning, the rapid developments in drone and other related technology provide a glimpse into the possibility of even smaller versions of TIM which swarm in unison to perform independent functions simultaneously and in real-time, allowing an arborist to obtain data from multiple locations via multiple drones, all executed remotely at the touch of a button.

Due to the modular nature of TIM v2.0, other planned accessories include the possibility to attach thermal cameras to provide additional visual information, tethered power systems to negate the need for battery changes thus allowing for uninterrupted flight times and even a remotely activated pruning instrument to assist operators in collecting plant samples. It is envisioned that these developments will make TIM so readily accepted and well used that it will become another tool arborists can rely on for their daily work (Fig. 16).

Acknowledgements
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The subsequent development of TIM v2.0 was supported by Enterprise Singapore's Gov-PACT initiative.

*Gov-PACT initiative encourages co-innovation between both government agencies and enterprises to develop and test-bed innovative solutions that are not in the market today.

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