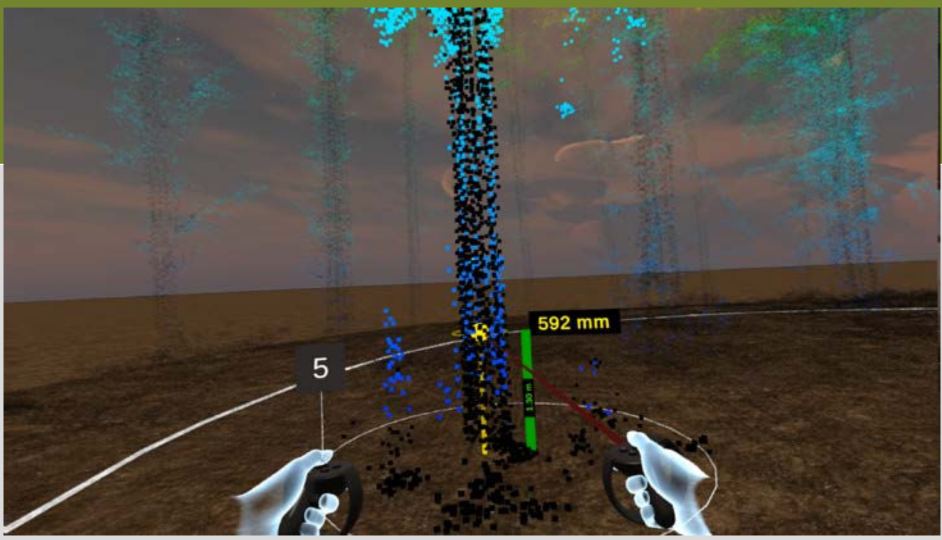
RESOURCE

Enhanced forest inventory practice using immersive visualisation and measurement of dense point cloud data

Project number: PNC464-1718 November 2019



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Enhanced forest inventory practice using immersive visualisation and measurement of dense point cloud data

Prepared for

Forest & Wood Products Australia

Final Report editors

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Cover image: User interacting with the VR Forestry software application.

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1. Summary for Industry

Rapid developments in VR (Virtual Reality) technology make it timely to explore the potential of advanced 3D visualisation to support forest inventory. The emergence of promising segmentation algorithms and software increasingly make it possible to extract stems and stem measurements from dense point cloud data. VR offers the potential for field staff to transfer their skills to within a 3D and 1:1 scaled immersive environment and to use natural interface functionality to measure tree dimensions within a point cloud dataset.

The goal of this research was to develop methods and workflows to support VR visualisation and measurement of plot-level point-cloud data in plantation forests and to assess the potential of VR tools and very high-resolution point cloud data to replace current forest inventory fieldwork practices.

In a pilot project, conducted as part of a previous FWPA Research Project (FWPA PNC326-1314), dense point cloud data from a pre-harvest *Pinus radiata* inventory plot, together with the output from two stem segmentation algorithms, was successfully imported into an immersive VR environment.

Broadly, the research question addressed by this project has been: *Can forestry field operators perform tree stem assessments using remotely acquired dense point cloud data in an immersive VR environment?* This question has been assessed in terms of the following:

- Which components of standard inventory stem assessments translate easily into a VR environment and processes, and which are complex or more difficult to implement?
- What tools are required within a VR environment in order to execute standard inventory stem measurements?
- How effectively can tree metrics extracted automatically from point cloud data, such as stem circumference measurements, tree height and branching be assessed for accuracy (spatial and attribute reliability) by a human operator in a VR environment?
- How do VR stem assessments, in terms of task competency and cost, compare to current field stem assessments?

The deliverables for the current project are:

i. A virtual reality software application that enables industry partners to trial VR stem assessments of high-resolution point cloud data representing inventory plots and that is a platform for future research
ii. An operational workflow for virtual stem assessments of forest dense point clouds in a VR immersive environment
iii. A usability testing analysis, assessing and comparing the use of VR stem assessment methods with current forest inventory field operations
iv. Technology transfer support through development and distribution of a VR application and associated User Guide, one-to-one support as requested for industry partners during the period of the research project, demonstrations of the VR application at industry meetings, and associated project reporting.

Section 2 of this report reports on the design, development and functionality of the VR application. Development of this application was the major focus of this project. Software development was undertaken by a team within the HIT Lab (Human Interface Technology Laboratory) at the University of Tasmania. User feedback during the development cycle was primarily through beta testing and participant experiments undertaken in collaboration with Interpine New Zealand, together with industry workshops (ForestTECH, New Zealand and Australia, https://foresttech.events/).

The VR application operates on commercially available VR hardware (Oculus Rift or Oculus Rift S). Functionality includes multiple options for users to move within a point cloud and to record observations on a virtual control pad. VR measurement tools include a highlight tool (to set up an active region, typically isolating a single tree for measurement), a DBH tool, a crutch tool and a stem tool (to create stem nodes when a fork is detected), a height tool (to measure tree height), and a labelling tool for stem and branch features.

Section 3 reports on usability tests. These were undertaken during software development in order to guide software design and to gather initial data on software and user performance. Two usability tests were undertaken, both onsite at Interpine offices in Rotorua NZ:

1. A pilot experiment (August 2018) to determine how effectively users were able to learn to use the VR tools which, at that stage of the development, comprised user navigation tools and key measurement tools (a line tool to measure tree height and a circle tool to measure DBH). Users were also asked to report their views on the ease of use and the usefulness of the tools. This experiment had 31 participants with a mix of experiences in terms of forest inventory fieldwork and also in terms of immersive VR.
2. A second experiment (February 2019) using an updated version of the software, to assess how reliably users were able to measure or estimate tree metrics: tree height, branching, sweep and other features normally recorded in field inventory. Again, users were also asked to report their views on the ease of use and the usefulness of the tools.

In both experiments, the point cloud data was a sample from very high resolution LiDAR acquired in February 2018 over a *P. radiata* planation within the Carabost State Forest NSW, managed by Forestry Corporation of NSW.

The key findings from the pilot experiment were that:

- All participants demonstrated a capacity to work within the VR environment, successfully acquiring the skills required to manipulate the hand controllers and to use natural body movements. All but seven of the participants were able to complete a set of measurement tasks within a reasonable (specified) time.
- VR height measurements indicate a high precision (repeatability) between participants (standard deviation of 0.287 and 0.152 metres for each of two trees assessed).
- VR height measurements indicate an acceptable accuracy (closeness to field measured values) for all participants (for each of the two sample trees: mean VR height measurement of 24.28 m compared with field measurement of 25.8 m, and mean VR height measurement of 26.51 m compared with field measurement of 29.4 m). These differences include potential errors due to missing LiDAR data at the top of each tree, potential errors in the field-based tree height measurements, and a known bias introduced by an error in the normalisation of the point cloud height data for this experiment.
- VR DBH measurements, using a manual circle fitting tool within the VR software application, for the same two sample trees provided data on precision (repeatability between participants), with a standard deviation of 50 mm and 65 mm for each of the two trees.
- VR DBH measurements showed a significant bias in accuracy (closeness to field measured DBH). For both sample trees, VR estimates were larger than field measured DBH values. Participants tended to select a circle in the VR environment that included all LiDAR points, rather than estimate a best-fit (in a least square sense) through the points. The estimated

DBH from the VR observations for each of the trees were 594 mm compared with a field measurement of 461 mm, and 495 mm compared with a field measurement of 345 mm.

Figures 1.1and 1.2 show VR-based measurements of the circular circumference for each of two trees, recorded by 24 participants. DBH and stem location was derived from these VR observations. In the figures, a circular estimate of stem location is superimposed (thick orange circle) based on field-measured DBH and located within the point cloud manually by direct observation of the cross-sectional point cloud data outside of the VR environment.

These figures illustrate significant overestimation of stem diameter by the VR users. Further training within the VR environment may be enough to remove this bias, but the results also point to the value in developing alternative visualisation methods such as a meshed and draped surface, particularly for critical and usually clean (free from noise due to nearby vegetation) data at the region from which DBH is measured. The differences apparent in Figures 1.1 and 1.2 may also be due to errors in the LiDAR data, errors in the location of the 1.3 m breast height within the point cloud due to normalisation of the point cloud for terrain elevation, or possibly errors in the field measurements, although the latter is very unlikely.

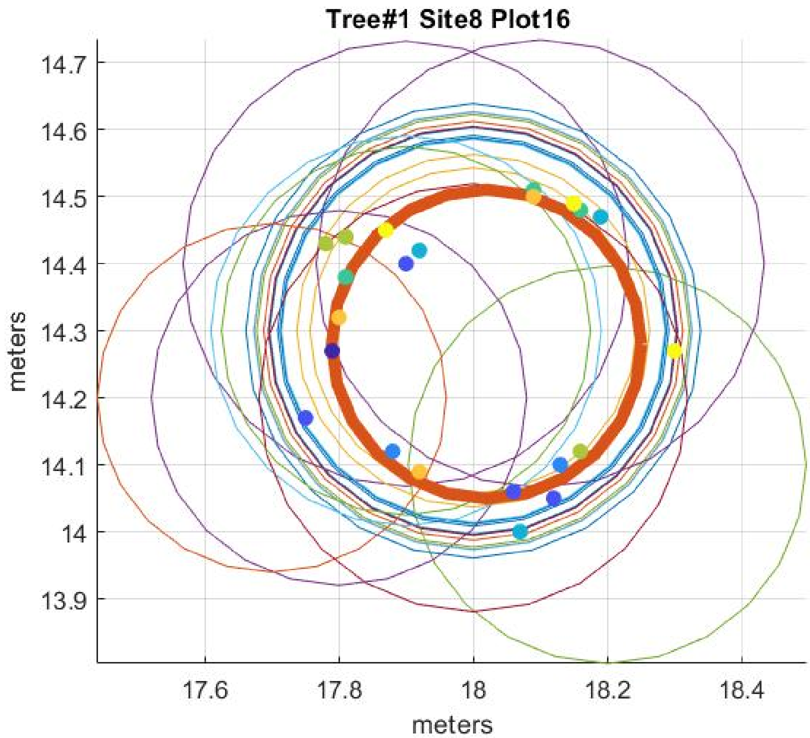

Figure 1.1 Circular stem circumference plotted for sample tree (t1) measured in VR by 24 different users (thin bordered circles with colour by user). LiDAR points (dot points with colour by height) are shown for a section of the stem from 0.05 m below to 0.05 m above the 1.3 m DBH line. A circular estimate of stem location is superimposed (thick bordered orange circle) based on field-measured DBH and located within the point cloud manually by direct observation of the cross-sectional point cloud data outside of the VR environment.

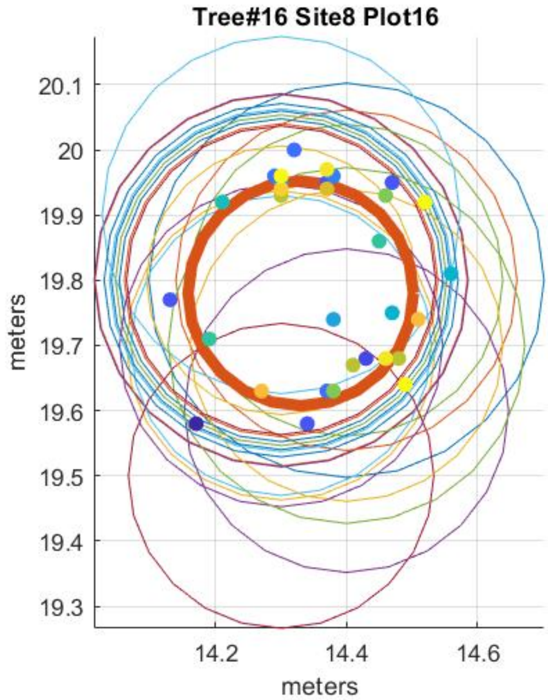

Figure 1.2 Circular stem circumference plotted for sample tree (t16) measured in VR by 24 different users (thin bordered circles with colour by user). LiDAR points (dot points with colour by height) are shown for a section of the stem from 0.05 m below to 0.05 m above the 1.3 m DBH line. A circular estimate of stem location is superimposed (thick bordered orange circle) based on field-measured DBH and located within the point cloud manually by direct observation of the cross-sectional point cloud data outside of the VR environment.

A post experiment subjective questionnaire assessed how useful and how easy to use participants found the software to be. Responses were predominantly positive, with a small number of neutral responses against some criteria and only one tool being assessed as difficult to use by some participants. That tool was the stem diameter circle fitting tool, which is the most complex of the VR tools tested in the first experiment. Subsequently, a semi-automatic DBH measurement tool was developed which requires users to select point cloud data from a stem as input that automates DBH measurement from the selected data.

The second round of usability tests (February 2019) focused on qualitative measurement tasks, specifically assessing branching, sweep and identifying stem features. Tree height was also captured in these tests. Participants (17) with inventory cruising experience were selected from the pilot group and the data was the same as for the pilot tests. Users were asked to assess 6 trees from two plots. Performance was assessed using standard demerit calculations detailed in the PlotSafe guidelines. Detailed results are provided in Section 3 of this report. Broadly, and with caveats because of the limited scale of this experiment, the evidence is that participants were not able to reliably identify wobble and some stem damage, most likely because the spatial resolution (density) of the point cloud was not sufficiently high. And in the higher parts of stems (above 12 m) participants were not able to reliable identify forks and spikes. The challenges in the higher parts of stems are likely to be more complex since increasing the spatial resolution (density) of the point cloud is likely to also increase the complexity of interpretation because of the denser vegetation.

Tree height measurements were repeated in this second round of usability tests, with the potential systematic bias identified following the pilot test resolved. Results are presented in Section 3 (Usability Testing Experiments). These show that all but one of 6 trees were measured in the VR environment with high precision and with VR estimates within +/- 1 m of field measured height. The one exception was a tree consistently (precisely) measured by users but with the VR estimates differing from the field measurement by approximately 1.5 m. This suggests a possible gap (missing crown data) in the LiDAR data or a possible error in the field measurement.

Section 4 provides an indicative comparison of the cost of acquiring plot-based inventory tree measurements using dense LiDAR data acquisition and the VR application in comparison with estimates of the current cost of acquiring plot-based inventory tree measurements using current field-work methods. The costing of LiDAR acquisition used in these comparisons is largely based on experience gained from helicopter campaigns in a related FWPA project (PNC377-1516, 2018). The comparisons shows that the per plot cost of measurement using helicopter acquired LiDAR and the VR application is currently dominated by the high cost of data acquisition because of the cost of LiDAR-equipped helicopter hire, and that this is likely to remain the case even if this cost is reduced in the future because of the reducing cost of LiDAR equipment and the potential to use less costly (e.g. ultralight) helicopters. The comparisons show that using UAV-mounted LiDAR and the VR application is likely to result in per-plot costs that closely approach the current cost of field-base inventory.

Section 5 addresses possible avenues for future work, drawing on the findings of the current project.

- Further testing of the LiDAR-VR approach for a greater variety of forest and data conditions: The current work has been necessarily limited to a *P. radiata* study site where very high-density LiDAR data was available. Further testing on Eucalypt plantations and, particularly, further testing in plantations that have difficult (rugged) terrain and significant understorey weeds would provide a better understanding of the robustness of the LiDAR-VR approach and its potential to reduce field work in regions that present significant WH&S issues for field crews. Scoping application of the LiDAR-VR approach to strategic inventory in native forests is also recommended.
- Further integrate automatic tree measurement segmentation processes: Software machine-learning methods to extract stem and branch metrics from point cloud data are continuing to develop. Features extracted automatically from a dense point cloud can be imported into the VR environment for quality-assurance and editing, and those human supervised processes can feed back, and improve the performance of, the automated classification routines. Within the VR environment there is scope to allow users to seed the extraction of stem and branch features by identifying key points. There is also a scope to allow users to view, within the VR environment, log products superimposed onto the standing tree as derived from a specified log bucking plan.
- Investigate mesh and surface rendering: This project has focussed on point cloud data. An area for future consideration is the construction of meshed and rendered surfaces, either for tree stems or for more complicated branching and an investigation of the relative performance of operators using these surface representations rather than a point cloud.
- Field based visualisation and decision-making using Augmented Reality: There is scope to use augmented reality (AR) to allow forestry staff to view tree metrics or derived labels spatially superimposed onto trees in the field. This may have useful application for auditing/validation work and during harvesting operations. Similarly, machine mounted ground-based LiDAR together with rapid automated feature detection and AR methods has potential application to real-time guidance in thinning operations.

Appendix 1 is the User Guide for the VR Cruising application, which is a standalone VR software application. To operate the application, users require three components: the software, point cloud data and VR hardware. The User Guide provides recommendations for hardware. Demonstration data, acquired as part of this research project, will be made available from the FWPA website.

Appendix 2 is the Airborne LiDAR specifications, which details the specifications of the ultra-dense LiDAR acquired at 30, 60 and 90 meters height – 60m was used in the usability testing experiments. The section also reports a comparison to the specifications of the normal-dense LiDAR acquired at 850 meters height.

2. The VR application

The capability of Virtual Reality (VR) technology in creating an immersive environment has seen it applied to training in overseas forestry (Zheng et al. (2018), Fabrika et al. (2018)). CTRL Reality, Finland also presented their VR application for visualisation and planning of forestry operations and harvesting at ForestTECH 2018. Our VR application differs from those VR situations in that we focus on the operations of tree stem assessment for pine plantation inventory using LiDAR point clouds data. The key contribution of this VR application is enable forestry field operators to perform tree stem assessment using dense airborne LiDAR point cloud data in an immersive VR environment.

2.1 Design and Development

The development of the VR application in this project has continued from the initial design and development of the VR application initiated in the previous FWPA project, PNC326-1314: *Deployment and integration of cost-effective high resolution remotely sensed data for the Australian forest industry*. The Unity 3D game engine[1] is used to develop the VR software application.

Figure 2.1: Operational workflow on the VR application

Figure 2.1 shows an operational workflow of the VR application. An ultra-dense point cloud data is required as input LiDAR data, which is detailed in Appendix 2 Ultra-Dense LiDAR specifications. The detail of each step in the workflow are described below:

1. Import LiDAR data

To import LiDAR data, the VR application requires the use of a specific commercial Unity asset, called "Point Cloud Viewers and Tools"[2]. This utility allows point cloud data to be loaded into the VR environment. The utility supports a variety of formats of point cloud data: XYZ, XYZRGB, CGO, ASC, CATIA, PLY(ASC), PTS and LAS. For (compressed) LAZ data format, CloudCompare[3] an open source 3D point cloud processing software can be used to convert to LAS format. The Unity Point Cloud Viewers will convert the point cloud data into a binary format, which can be rendered inside the Unity 3D VR environment. This process allows the original point cloud and the segmented stem data to be visualised in an immersive environment.

2. Interactive VR application

The next step in the workflow in Fig 2.1, is the interactive VR application. The structure of the software application is modularised into different components with specific functionalities, illustrated in Figure 2.2.

- Avatar: control view points of the users and hand controllers
- Tools: manage all tools (Height, DBH, Cruising, Manual line/circle tools, Edit, Delete)
- Viewer: render binary point cloud
- Configuration loader: read specific dictionary (pre-determined cruising codes)

3. Export measurement data

The last step of the workflow in Fig 2.1 is the export of the measurement data. All measurement that users made inside the VR application are automatically stored and exported after the closure of the VR application. The measurement output file is located insider the VR application's internal file structure, see Appendix 1 for more detail. The file is in a simple text file which can be open with any text editors. The output file records information such as tree numbers, height positioning and corresponding stem diameter, branch size, sweep and features.

[1] http://unity.com/
[2] http://assetstore.unity.com/packages/tools/utilities/point-cloud-viewer-and-tools-16019
[3] https://www.danielgm.net/cc/

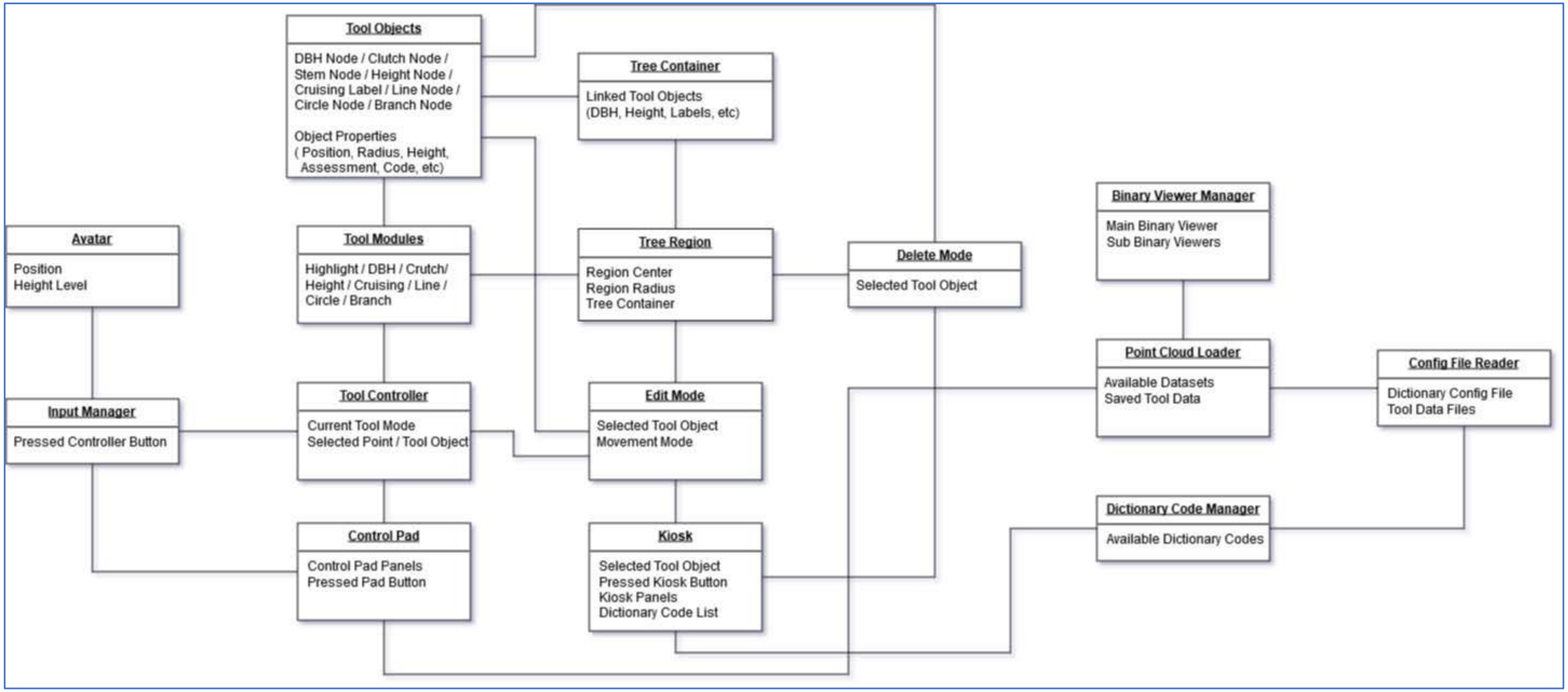

Figure 2.2: Simplified working diagram of the VR application

2.2 Functionality

The VR application is a standalone VR software application. To operate the application, users requires three components: this software, point cloud data and VR hardware. An overview of different key components is described below.

VR hardware

The VR Cruising application was developed and operated with the 'Oculus Rift' commercial VR hardware. As of May 2019, the Oculus Rift has been replaced with the company's new flagship VR hardware called 'Oculus Rift S', https://www.oculus.com/rift-s/. The application is not compatible with any other VR hardware.

Input /Output configurations

The VR Cruising application makes use of different folders, configuration files, and data files to implement its functionalities such as point cloud loading, tool data saving/loading and importing a custom dictionary.

Movement

One of the main functionalities of the application is the ability to move around loaded point cloud data in the same way as moving in a real forest. There are multiple movement options available: conventional horizontal and vertical movement via the joysticks on both touch controllers, instant teleportation towards a selected area, and instant teleportation to ground level from any mid-air position.

Head Up Display (HUD)

The application features both a VR HUD and desktop GUI that serves to display important information for users inside and outside the headset. The VR HUD will keep track of the headset's movement so that displayed information will be available regardless of the user's current viewing angle.

Control Pad

The control pad is a virtual pad that allows users to access multiple functionalities of the application within one convenient platform. The control pad is activated by selecting the appropriate buttons using the left and/or right index finger. The control pad features are split among three different panels (data selection, cruising tools and manual tools), which can be accessed individually by pressing on the right tab button at the top of the display.

Application Functionalities

The control pad will provide access to two types of tools: cruising tools and manual tools as detailed below. The cruising tools enable user to perform cruising operations on trees, and are summarised below:

- Highlight Tool – allows users to create a tree region and effectively make the region active and ready for user interaction. A tree region is a numbered circular area within the VR environment indicated by a white circle on the ground. When a tree region is active, it will highlight any point found within its radius and disable selection of points outside its radius and make those points appear semi-transparent.
- DBH Tool – allows users to create a DBH node which automatically measures diameter of a trunk at 1.3m height level. A green 1.3m height post next to the tree is created for a visual reference. Note that the aim of this automatic DBH measurement is to seed an approximate

fit that can then be adjusted by human VR operators and not necessary to achieve high accuracy estimation, which is not an objective of this study.

- Crutch Tool – allows users to create a crutch node. A crutch node displays a green plane 1.3m above the node's position. Stem nodes that are created nearby this crutch node will automatically gravitate towards the green plane.
- Stem Tool – allows users to create stem nodes when a fork is detected.
- Height Tool – allows users to create a height node. The node is positioned at the automatically calculated highest point of the tree's canopy. A green line connecting the peak point to a corresponding stem node, indicates the direction and position of the stem structure. The line will run from the stem node closest to the selected point to the height node. If there is no stem node (i.e. no fork) within the active tree region, the line will run from the DBH node (at 1.3m height) to the height node.
- Branch/Features/Sweep/Alive/Resin/Internode/Structural Tool – allows users to create cruising labels with the appropriate assessment type. These labels can be assigned dictionary codes using the virtual kiosk, detailed in Appendix 1.

In the VR application, users can also choose to manually perform the height and diameter measurement with the manual tools, as summarized below:

- Line Tool – allows users to measure a distance between two chained nodes. This tool does not require an active tree region.
- Circle Tool – allows users to measure a radius of a cluster of points. This tool does not require an active tree region.
- Branch Tool – allows users to estimate a branch size. The tool will display different size diameters an as a visual aid for estimating the branch size.

More details of the functionalities of the VR application are in Appendix B: VR Software User Guide.

2.3 Hardware and Software Specifications and Cost

Table 2.1 details the hardware and software requirements of the VR application.

Table 2.1 Hardware and Software Requirements

Hardware/Software requirements	Specifications	Cost (AUD)
1 VR hardware	Oculus Rift S https://www.oculus.com/rift-s/	$650

2 Computer hardware	• Windows Operating System
	• Graphic card: NVIDIA GTX1060
	• CPU: Intel i5-4590
	• Memory RAM: 8GB+
	• Connectors (required):
	  o DisplayPort 1.2 (or Mini DisplayPort with an adapter)
	  o 1x USB 3.0port
		• $3,000+ for a VR-ready laptop (e.g. https://www.dell.com/en-au/shop/dell-laptops/alienware-m15-gaming-laptop/spd/alienware-m15-laptop)
		• $2,000+ for a VR-ready desktop (e.g. https://www.dell.com/en-

		au/shop/dell-desktop-computers/xps-tower/spd/xps-8930-desktop
3 Software	1 This project's VR application 2 Unity 3D software application (http://unity.com/) 3 Unity asset, "Point Cloud Viewers and Tools" (http://assetstore.unity.com/packages/tools/utilities/point-cloud-viewer-and-tools-16019) • The asset is used to convert the point cloud data formats into a specific binary format required for the VR application	$100 for the Unity asset
	Total Minimum Cost	$2,750 (desktop) and $3,750 (laptop)

References

Fabrika, M., Valent P. & Scheer, L. (2018) Thinning trainer based on forest-growth model, reality and computer-aided virtual environment. *Environmental modelling & software, 100*, 11-23.

Zheng, Y., Cheng, B., Huang, Q., & Liu, J. (2018). Research on Virtual Driving System of a Forestry Logging Harvester. *Wireless Personal Communications*, 1-16.

3. Usability Testing Experiments

3.1. Experiment Design

The usability testing experiments were divided into two separate experiments, outlined below:

1. Pilot usability test
   The key aim of the first experiment was to determine participants' ability to use the VR tools to perform tasks such as navigation and measurement of height (H) and diameter at breast height (DBH). A secondary aim of the experiment was to survey participants on the usefulness and ease of use of the VR tools.

2. Final usability test
   The aim of this second experiment was to determine how accurately participants were able to use the VR tools to perform qualitative measurements (branch (Br), sweep (Sw) and features (F)) and quantitative measurement (Height (H)) of trees compared to field measurement. A secondary aim of the experiment was to survey participants on the usefulness and ease of use of the new/updated VR tools.

The experiments have the following procedures:

1. Introduction to the experiment
   - Participants were provided with information sheet detailing the purposes of the experiment and were required to sign a consent form before taking part in the experiment.
2. Familiarization with VR application
   - An overview was provided of the VR application, headset, hand controllers and point cloud dataset.
3. Train/Test tasks with VR Tools
   - Pilot usability test
     i. It was demonstrated how to use relevant VR tools required to perform navigation, H and DBH measurements.
     ii. Participants then practiced using the tools.
     iii. Participants were then asked to perform the task on pre-selected trees that were different to the practice samples. A plot with 2 trees was used for each of the tasks.
   - Final usability test
     i. Overall features and tools of the VR application, including new and updated features were demonstrated to participants.
     ii. Participants then practiced using the tools.
     iii. Participants were asked to cruise the pre-selected trees. The cruising task includes identifying branches (Br), sweep (Sw), stem features (F) and total tree height (H) (but no DBH). There were 3 trees in each of the 2 plots used.
4. Feedback and questionnaires

- Participants were asked to participate in a post-experiment questionnaire to provide their subjective ratings and comments.

3.2. Pilot Usability Test

The test took place from 27th to 31st of August 2018 at Interpine in Rotorua, New Zealand. Due to this tight scheduling, each experiment was strictly to no more than 1 hour.

Participants:

- 31 participants: 28 males and 3 females
- VR prior experience: 12 no experience, 15 one-two times, 4 more than two times
- Expertise: 10 crew leaders, 8 second-in-charge, 5 planner/trainer, 3 auditors, 3 consultant and 2 others

Datasets:

The data used in the experiment were from on the site 8 plot 15 of Interpine's LiDAR dataset of *Pinus radiata* planation (February 2018) within the Carabost State Forest, NSW, managed by Forestry Corporation of NSW.

- Height Test: Tree #4 and #12 on the site 8 plot 15 (acquired at 60m scan height)
- DBH Test: Tree #1 and #16 on the site 8 plot 16 (acquired at 60m scan height)

Results and Analyses:

1. Participants were able to use the VR tools to perform tasks. All can use a combination of their natural body movement and joystick on hand controllers to navigate around the VR plot. All but seven participants demonstrated that they could use the VR measurement tools to measure height and diameter at breast height (1.3m). The seven participants ran out of the 1-hour allocated timeslot and therefore, did not get a chance to work on the circle tool. This suggested that participants were able to use the VR tools to assess the height and DBH of the selected trees.

2. Height measurements (with the VR line tool) were compiled from all participants and an average and standard deviation was computed as listed on Table 3.1.

Table 3.1: Height measurement

Tree	Field measurement (m)	Averages of VR height measurement (m)	Standard deviation of VR height measurement
No 4	29.4	26.51	0.152
No 12	25.8	24.28	0.287

There are notable differences in the VR and field measurement due to the VR data set used, the later from a non-normalized point cloud dataset, which resulted in some parts of the ground appearing under the ground plane of the VR environment. This offset caused the VR tree height measurement to be smaller. The small standard deviation (0.287) showed that participants' measurements are very close to one another and strongly indicated a high level of repeatability of the VR height measurement.

3. DBH measurement (with the VR circle tool) were compiled from all participants and the average and standard deviation was computed as listed on Table 3.2

Table 3.2: DBH measurement

Tree	Field measurement (mm)	Average of VR DBH measurement (mm)	Standard deviation of VR DBH measurement
No 1	461	594	50
No 16	345	495	65

The results show that the average of the VR DBH measurements was larger than the field measurements and no VR DBH measurement was smaller than the field measurement. Figures 3.1 and 3.2 plot the locations of LiDAR point cloud data between 1.25m and 1.35m above ground (dot points). The thin circles represent the diameters created by participants (thin edge circles, unique colour for each participant), whilst the thick orange circle represents the circle diameter of the field measurement. The center of the field measurement circle was placed manually using the point cloud as a guide. Figures 3.1 and 3.2 show the measurements for Tree #1 and Tree #16 respectively.

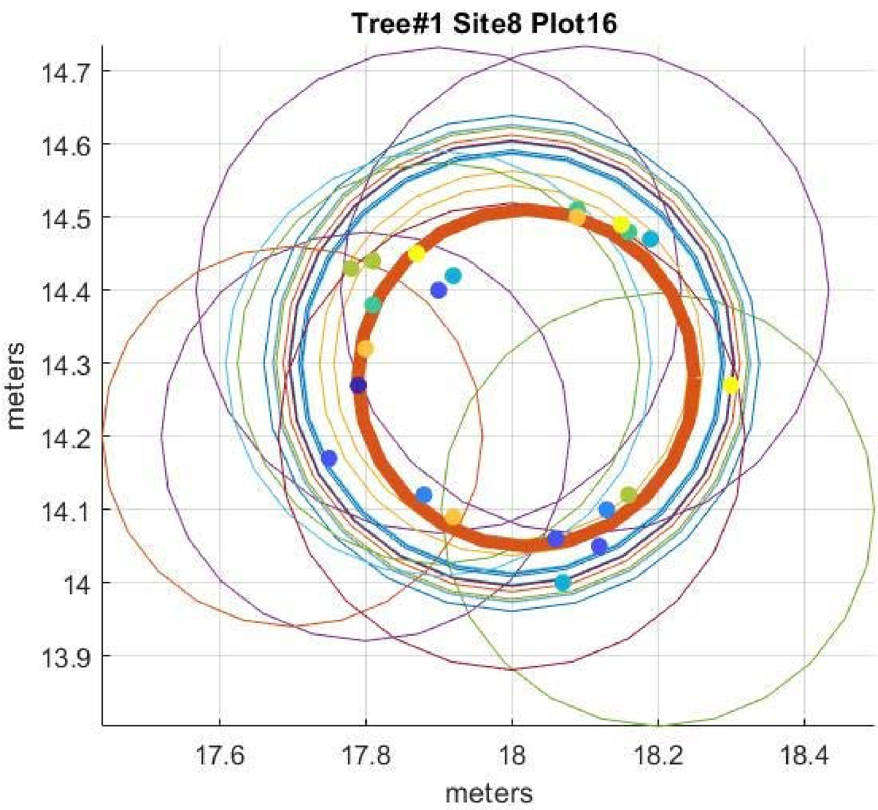

Figure 3.1: Tree#1 of Site 8 Plot 16: Comparison of point cloud data (dot points with colour by height), participants' measurement (thin bordered circles) and field measurement (thick orange bordered circle)

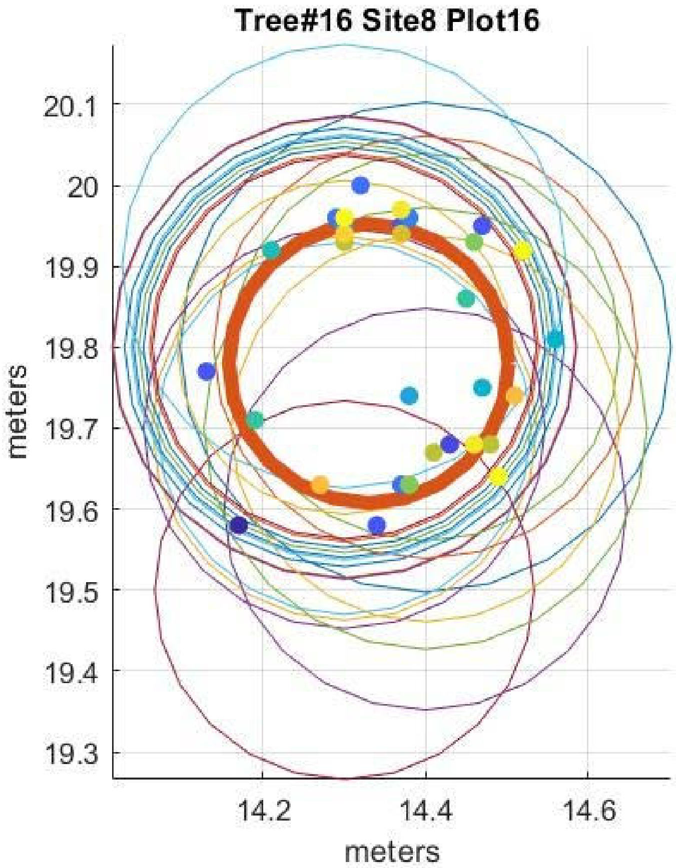

Figure 3.2: Tree#16 of Site 8 Plot 16: Comparison of point cloud data (dot points with colour by height), participants' measurement (thin bordered circles) and field measurement (thick orange bordered circle)

Both figures show that participants had the tendency to create a diameter circle that covers or contains all the point cloud within their circle diameter, causing an overestimation of DBH. The location inaccuracy of the point cloud data (inconsistent point formation) also contributed to the inaccuracy of the VR DBH measurement. It is important to also recognize that field measurement could contain some error as well, although, this is accepted to be potentially a small source of error.

The relatively large standard deviations of the VR DBH measurement (50 and 65 mm) indicate a diverse range of participant's visual perception and estimation. This suggests that further research on the visualization techniques is required to the estimation/measurement be more consistent and more accurate.

4. Post-experiment subjective questionnaires were collated. The ratings for the questionnaire ranged from 'Strongly Disagree' (SD), 'Disagree' (D), 'Neutral' (N), 'Agree' (A) and 'Strongly Agree' (SA). Table 3.1 shows the percentages in each of the rating categories.

Table 3.3: Subjective ratings (in percentages) of the usefulness and ease of use of the VR tools in the pilot usability test

	SA	A	N	D	SD
The tool is useful					
Fly up and down	61%	35%	3%	0%	0%
Change of point cloud size	31%	48%	21%	0%	0%
Highlight of a selected area	35%	55%	10%	0%	0%
Easy to do/use					
Navigate	32%	52%	16%	0%	0%
Control pad (to select different tools)	10%	84%	6%	0%	0%
Line tool (height)	39%	48%	13%	0%	0%
Circle tool (diameter)	7%	31%	48%	10%	3%

Table 3.3 shows that participants thought all the VR tools (except the circle tool) are either useful or easy to use – with 0% disagreed or strongly disagreed. The diameter circle tool has the most complex procedure among all the VR tools introduced. Participants found it difficult to master the skills in the limited time during the experiment. This led to the development of a semi-automatic DBH measurement in which users select a point cloud data within a tree as an input to the automatic DBH measurement of the point cloud data within the area.

3.3. Final Usability Test

The final usability test took place from 11th to 14th of February 2019 at Interpine in Rotorua, New Zealand. The key focus of this test was on the qualitative measurement tasks, specifically branch (Br), sweep (Sw) and features (F). However, a height (H) quantitative measurement was also captured in the process. Due to the cruising skills required, this experiment is limited to those who had experience cruising trees. Additionally, we specifically targeted participants who had taken part in the pilot usability test six months earlier.

Participants:

- 17 participants: 15 males and 2 females
- VR prior experience: 8 used once or twice, 9 used a number of times
- All except 2 participants had participated in the pilot test; however, the two were familiar with our VR software
- Expertise: 7 crew leaders, 2 second-in-charge, 2 auditors, 3 consultant and 3 others

Datasets:

Same with the pilot test, the data used in the experiment were from Interpine's LiDAR dataset of *Pinus radiata* plantation (February 2018) within the Carabost State Forest, NSW, managed by Forestry Corporation of NSW. The data are from 6 trees in two plots: Site 4 Plot 4 (Tree #1, #10 and #11) and Site 8 Plot 15 (Tree #4, #12 and #13) acquired at 60m scan height. Table 3.4 shows the field measurement of the 6 trees. The measurement was reported in a format according to Interpine's PlotSafe Overlapping Feature Cruising, Forest Inventory Procedures, February 2007.

Table 3.4: Field measurement of the trees used in the experiment (from two plots: Site 4 Plot 4 and Site 8 Plot 15)

S4P4 T1						S4P4T11						S4P4 T10					
Stem	Level	Position	Br	Sw	F	Stem	Level	Position	Br	Sw	F	Stem	Level	Position	Br	Sw	F
												0	0	1.3		S	
0	0	2.5	0			0	0	2.5	0								
						0	0	3.4		S	NONE						
0	0	4.5	6			0	0	5			D	0	0	4.6	0		
Canopy starts at 9.45m						0	0	9.3		W							
0	0	10		L													
0	0	11	3			Canopy starts at 11 m						Canopy starts at 12 m					
0	0	13.1	6		NONE												
0	0	13.3	8	S	S10+	0	0	14.1	3			0	0	14	3		
						0	0	14.2	6								
												0	0	15		L	
												0	0	19.8	6	S	NONE
												0	0	19.9			S6+
0	0	21.3	6			0	0	21.2	3	S							
						0	0	22	6								
												0	0	25.6	3	2	
0	0	30	3	L		0	0	28.6	3	2							

S8P15 T4						S8P15 T12						S8P15 T13					
Stem	Level	Position	Br	Sw	F	Stem	Level	Position	Br	Sw	F	Stem	Level	Position	Br	Sw	F
												0	0	9.7	3	L	NONE
0	0	4.8	0			0	0	4.5	0								
												0	0	10	20		S15+
Canopy starts at 11 m												0	0	11		S	
						Canopy starts at 13 m						Canopy starts at 11m					
												0	0	14.7			
						0	0	17.1	3	L		0	0	15.5		6	
						0	0	19.2	8	S		0	0	17.1		L	
0	0	17.8		6		0	0	20.5				0	0	18.4			
						0	0	22.6	6	1		0	0	25	6		
												0	0	29.6	3	S	
						1	1	19.2									
						1	1	20.5									
						1	1	25.8	3	1		1	1	17.1			
0	0	23.7	6	L								1	1	18.4			
						2	1	22.6				1	1	28.5	3	S	
						2	1	23.9									
						2	1	26	3	1							
						3	1	22.6				2	1	17.1			
						3	1	23.9				2	1	18.4			
0	0	29.4	3	S		3	1	26	3	1		2	1	28.6	6	S	

Results and Analyses:

1. We used the demerit calculation methods detailed in the PlotSafe guidelines and in consultation from Bruce Hill, an experienced forest inventory auditor with Interpine. The experiment consists of two types of demerits: Heights Demerits (HD) and Tree Demerits (TD). The following outlines the matrix used to assess the VR measurement:

    - HD for 20-30m height
        - Tolerance +/- 1.0m
        - 2 demerit points per 0.5m (beyond the tolerance)
    - TD consists of Structural demerits (S) and Quality demerits (Q). The S and Q are classified based on the types of feature, as outlined below for each of the categories:
        - In Branch category, only fork is structural error and missing branch size is quality error
        - In Sweep category,
            - Quality error
                - "2" - moderate sweep
                - "S" - gentle sweep over 4m length
                - "L" - gentle sweep over 6m length
                - "6" -straight
            - Structural error
                - "1" – excessive sweep
                - "W" – wobble back and forth
                - "K" – kink sharp change direction
        - In Feature category, there are only spike and damage in the dataset we used and both are quality error
    - Table 3.5 shows the demerit score for S and Q demerits occurred at different heights. A combination of all demerit scores in a plot is used to calculate a plot grading system for audit process. Structural demerits are considered twice as serve as quality demerits.

Table 3.5: Structural and Quality demerit scores

	Demerit scores	
Level from ground	Structural demerits	Quality demerits
0-12m	6	3
12-20m	4	2
>20m	2	1

2. Table 3.6A reports the combined demerit scores of all 17 participants. The yellow highlights indicate where most participants made their assessment error. Table 3.6B shows the detail of the demerits that caused the demerit score for most participants. The height demerits are within the tolerance level (+/- 1m) with an exception of tree #11 on Site 4 Plot 4, which had a height demerit of 2.7 (approximately 0.5m beyond the tolerance). This shows the height measurement in VR is very close to the field measurement.

Table 3.6A: Audit results – Height demerits (HD) – averaged and Tree demerits (Br, Sw, F) with structural (S) and quality (Q) demerit scores -- accumulated over all participants

S4P4 T1 Black	HD = 0					
	Br		Sw		F	
	Q	S	Q	S	Q	S
0-12m	6	0	7	0	7	0
12-20m	3	0	2	3	14	0
>20m	5	0	0	1	0	0

S4P4 T11 Black	HD = 2.7					
	Br		Sw		F	
	Q	S	Q	S	Q	S
0-12m	3	0	2	13	14	0
12-20m	2	0	3	0	0	0
>20m	3	0	3	2	0	0

S4P4 T10 Black	HD = 0					
	Br		Sw		F	
	Q	S	Q	S	Q	S
0-12m	9	0	3	1	4	0
12-20m	4	0	2	1	1	0
>20m	8	0	4	0	15	0

S8P15 T4 Black	HD = 0.1					
	Br		Sw		F	
	Q	S	Q	S	Q	S
0-12m	9	0	2	2	13	0
12-20m	4	0	3	1	2	0
>20m	3	0	0	1	0	0

S8P15 T12 Black	HD = 0.1					
	Br		Sw		F	
	Q	S	Q	S	Q	S
0-12m	1	0	0	0	4	0
12-20m	5	17	2	0	0	0
>20m	3	0	0	14	0	0

S8P15 T13 Black	HD = 0					
	Br		Sw		F	
	Q	S	Q	S	Q	S
0-12m	6	0	3	1	6	0
12-20m	8	15	2	3	1	0
>20m	4	0	1	0	0	0

Table 3.6B: Significant demerits from yellow highlighted in Table 3.6A

	Branch		Sweep		Features
Level from ground	Structure	Quality	Structure	Quality	Quality (no structural error presented)
0-12m			Missed Wobble		• Damage • Spike called when no spike
12-20m	Missed forks				Missed Spike 10+
>20m			Missed "1" excessive sweep		Missed Spike 6+

For stem heights of less than 12m, Table 3.6B shows that features associated with a non-smooth movement of the stem structure, such as wobble, were very difficult for participants to detect in VR (13 of 17 missed wobble). Visually detecting this type of structure change requires high point density to form a perceivable structure over the stem where the profile movement occurs. The low detection rate indicated that the density of the point cloud around those parts of the stem was insufficient. Additionally, viewing point cloud data without surface rendering can create view-dependent perception of the structure, particularly when the structure movement is straight toward the user's viewpoint. This can diminish the viewers' ability to perceive the movement of the structure. Table 3B also shows that the damage feature on the Site 4 Plot 4 tree #11 (reduction in stem diameter) was difficult to notice in VR (14 of 17 missed the damage). In this case, the point density and participants' observing viewpoint were also the key contributors to this error.

Above 12 metres, Table 3.6B shows significant structure demerits in forks not detected (all missed forks) as well as spike not detected (14-15 of 17 missed the spikes). The tree features inside the canopy are a real challenge for VR users. It is not simply a matter of having high point density (to perceive the structure) which would be improved with future more-advanced LiDAR technologies. In the opposite, having more point density would make it more difficult to have a clear view of the structure due to points around the outside perimeter of the canopy obstructing view of the tree's features and structures on the inner part of the canopy. This suggests that further research on the visualization techniques is needed to render the point cloud in the canopy for optimal human perception.

3. Post-experiment subjective questionnaires were collated. The ratings for the questionnaire ranged from 'Strongly Disagree' (SD), 'Disagree' (D), 'Neutral' (N), 'Agree' (A) and 'Strongly Agree' (SA). Table 3.7 shows the percentages in each of the rating categories.

Table 3.7: Subjective ratings (in percentages) of the usefulness and ease of use of the VR tools in the final usability test.

	SA	A	N	D	SD
The tool is useful					
Fly up and down	69%	31%	0%	0%	0%
Change of point cloud size	31%	50%	19%	0%	0%
Highlight of a selected area	56%	31%	6%	6%	0%
Height reference tool (new feature)	75%	25%	0%	0%	0%
Overlay of colour all-return LiDAR data (new feature)	27%	73%	0%	0%	0%
Easy to do/use					
Navigate	31%	62%	6 %	0%	0%
Estimate height	80%	7%	0%	13%	0%
Estimate branch	8%	8%	38%	23%	23%
Estimate sweep	0%	44%	44%	6%	6%

Estimate feature	0%	18.75%	56.25%	18.75%	6.25%

Table 3.7 shows there were generally positive comments about the usefulness of the tools (fly up/down, point size change, highlight area) that were consistent with the previous pilot usability test. Participants agreed on the usefulness of the two new tools (height reference and overlay of colour-coded all-return LiDAR data) with 0% neutral, disagreed or strongly disagreed. The navigation tool is easy to use, as was found in the pilot usability test. However, of the estimation tools, only height estimation had majority (87%) agreed or strongly agreed to the ease of use; whilst all other estimation (branch, sweep and feature) received mixed ratings with more than 50% either neutral, disagree or strongly disagree. This is reflected in the high demerit scores, shown on the Table 3.6A, for the tree demerits as well as the low score for the height demerits.

4. Operational cost of the VR approach to plot measurement

LiDAR point cloud data acquired using normal (current) ALS scanning specifications does not provide point clouds sufficiently dense or sufficiently accurate for human visualisation and measurement in a VR environment, or for reliable application of automated measurements methods. This project used (ultra-dense) point cloud data acquired as part of a separate FWPA research project (PNC377-1516). Appendix 2 provides specifications for the LiDAR data. It was acquired from a helicopter mounted Riegl VUX-1LR LiDAR over a *Pinus radiata* plantation located within the Carabost State Forest, NSW, managed by Forestry Corporation of New South Wales (FCNSW).

LiDAR acquisition costs

A per plot cost of acquiring very high-density LiDAR has been estimated using costs associated with two LiDAR campaigns flown for PNC377-1516. The first of these campaigns was a 2016 trial that employed a helicopter mounted Rielg VUX1-UAV (475 pulses per m^2, 1,077 returns per m^2). Results indicated that 80 (13.82 m) plots could be acquired in a single day. The second trial (2019) employed a VUX-1LR LiDAR, and provided the data used in the VR research. In this trial, a 36-hectare site flown as nine 200 x 200 m sub-sites. Data was acquired over the whole of these nine sub-sites at three different flying heights (30 m, 60 m, 90 m AGL). Data acquisition was completed in approximately 6 hours. The cost of LiDAR data acquisition and processing using the scanner and helicopter platform for this campaign was approximately $30,000.

(a) (b)

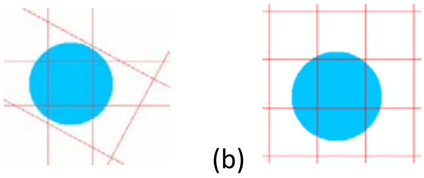

Figure 4.1 Helicopter flight paths used in (a) the 2016 trial and (b) the 2018 trial.

VR plot measurement costs

Trials of the VR application with forest practitioners show that with little prior experience of the VR software participants are able to complete cruising of 12 trees within one hour and including 10-15 minutes spent on experiment and training procedures not directly related to the cruising task. This reasonably suggests that, for crew who are trained with the VR software, a single operator could measure one plot (e.g. 13.82 m radius, 15-20 stems per plot) within 30 - 45 minutes. Allowing for a rest period of 15 minutes for every hour of VR work, an operator could measure approximately 8 plots per day in the VR environment. The direct labour cost, excluding organisational overheads, of plot measurement in the VR environment is therefore in the order of $75 per plot.

Fieldwork plot measurement costs

The current cost, per plot, of traditional field-based inventory measurement will vary depending on forest type, inventory requirements, forest location, forest conditions and organisational decisions regarding whether the work is being planned and undertaken in-house or outsourced. Broadly, and for the Table 4.1 shown below, the costs have been separately estimated for:

- Operational inventory for timber products: *Pinus spp.* or Eucalypt plantations with efficient road access and good field conditions
- Operational inventory for timber products: *Pinus spp.* or Eucalypt plantations with poorer road access and difficult field conditions (e.g. rugged terrain, blackberries, etc)

- Operational inventory for wood volume: Eucalypt plantations
- Strategic inventory: native forests.

Comparing VR and fieldwork plot measurement

Assuming that the costs associated with planning an inventory measurement campaign are similar for the LiDAR/VR and field-based approaches, then a summary of the relative costs shows that the cost of LiDAR acquisition does need to reduce significantly in order to be cost-competitive with current field-based inventory measurement methods, but that if sufficiently dense and accurate data can be acquired from low-cost helicopter or UAV platforms then the LiDAR/VR methods may become cost competive. Table 4.1 below summarises the costs. The column showing a per-day LiDAR acquisition cost of $30,000 represents the current cost of helicopter-based data acquisition using an advanced LiDAR sensor. The two columns showing per-day LiDAR acquisition costs of $20,000 and $10,000 are not currently viable but indicate the cost projections required in order to reduce the per plot cost of LiDAR data – and which might be associated with a move to using ultralight helicopters. The columns showing per-day LiDAR acquisition costs of $5,000 and $2,500 are associated with a LiDAR equipped UAV and include a cost attributed to depreciation, risk, insurance on the platform and scanner (currently available LiDAR-equipped UAV retail at over $200,0000). In the case of UAV LiDAR the estimated number of plots that could be flown per day has been reduced by 25%. The figures do not include the cost of VR equipment and audit operations.

Table 4.1: Indicative direct costs of plot measurement using a LiDAR-VR approach compared with traditional field crew. Note that some columns use prospective costs for smaller manned helicopters and for UAV platforms, to indicate likely trends. Per plot costs for strategic inventory in native forests are included below but noting that field inventory data collection and LiDAR structural measurements are not directly comparable.

LiDAR and VR per plot cost					
LiDAR data acquisition and VR plot measurement	Helicopter LiDAR			UAV LiDAR	
LiDAR per day ($)	30000	20000	10000	5000	2500
Number of plots flown	80	80	80	60	60
LiDAR per plot ($)	375	250	125	63	31
VR inventory per plot	75	75	75	75	75
Total LiDAR/VR per plot	**450**	**325**	**200**	**138**	**106**
Traditional field measured inventory plot costs					
P.spp. or Euc. (timber product) plantations with good field conditions.	**120-150**				
P.spp. or Euc. with difficult field conditions (limited road access, understorey weeds etc).	**150-250 (or higher in some locations)**				
Euc. Plantations (pulp volume inventory)	**100**				

Native forests - strategic inventory plot measurements	**1000-2500**

The figures in Table 4.1 are approximate and intended to provide only an indication of the relative efficiencies of inventory plot measurement based on VR measurement of remotely acquired LiDAR point cloud data in comparison with current field-based manual inventory plot measurement. The cost of the LiDAR-VR approach is greatly influenced by the cost of data acquisition – and these costs will need to be reduced before there is scope for significant financial savings. It is very reasonable to assume that the cost of LiDAR data acquisition will reduce as scanner technology and platform technology continue to develop, for both manned aircraft and UAV based campaigns. The costs of VR plot measurement shown in Table 4.1 are based on the data required for routine pre-harvest tree level inventory for product yield estimates (rather than for example LiDAR reference/calibration plots).

A driver for remote sensing and VR methods is the potential to reduce WH&S risks associated with field work. These risks, and the dollar cost of fieldwork, are likely to be highest when the terrain is rugged and where there is a dense understorey. These considerations are potentially very significant and are separate to the direct operational costs indicated above. Additionally, the potential value of collecting rich point data at the plot level and having that data available for reassessment and analysis at future dates has not been included in this initial assessment.

5. Future Directions

The goal of the current project has been to develop and assess VR-based software for measurement of tree metrics using high resolution point cloud data.

If VR-based measurement of point cloud data and VR-based quality -assurance of automatically extracted tree metrics is considered by the forest industry as likely to become operationally useful, then the current project can be extended on several fronts.

Given the findings of this project, we suggest consideration of possible future directions:

i. **Assess the performance of the VR application for a greater variety of forest and data conditions:** This would include work to determine the minimum data requirements, particularly point cloud density and spatial accuracy, to support VR-based tree measurement in a variety of different forest types and conditions. Alongside potential cost savings, a significant driver for remote sensing and VR methods is the potential to reduce WH&S risks associated with field work. These risks, and the dollar cost of fieldwork, are likely to be highest when the terrain is rugged and where there is a dense understorey. Capturing high quality LiDAR data and visualising and assessing that data using VR is also likely to be more difficult in these conditions. The current project has been limited to *P. radiata* plantations and so another avenue for future work is to extend the trial to Eucalypt plantations, other *Pinus* spp., *Araucaria* spp. and native forests. In the case of native forests this can include strategic inventory operations to determine sustainable yield as well as pre-harvest inventory measurements.

ii. **Integrate automatic tree measurement segmentation processes in order to minimise reliance on human labour for routine extraction of tree measurements and this improve efficiency**: Software machine-learning methods to extract stem and branch metrics from point cloud data are continuing to develop. Tree architecture extracted automatically can be incorporated into the VR environment in a number of ways:
    a. Features extracted automatically using standalone machine learning software can be imported into the VR application. Within that environment users can be enabled to:
        i. quality-assure these automatically extracted features
        ii. edit/amend/adjust these automatically extracted features
    b. User input can be used to train/refine parameters of the machine learning algorithms in order to improve the performance improvement of these algorithms
    c. Users can, within the VR environment, seed the extraction of stem and branch metrics by identifying key points in the point cloud (stems, branches, etc), with the feature extraction algorithms operating concurrently within the VR application. This approach does rely on very rapid computation because in a real-time interactive VR application these computations must not cause appreciable lag in the user-experience.

iii. **Investigate mesh and surface rendering:** This project has focussed on point cloud data. This allowed the software development and the user assessment to concentrate on representation and measurement of raw data, as is acquired from ALS, terrestrial laser scanning, airborne or terrestrial photogrammetry. This project did not extend to construction of meshed and rendered surfaces, either for tree stems or for more complicated branching. A possible future direction is to investigate the visualisation and user assessment of meshed and rendered surfaces.

iv. **Increase capability of the VR application to handle very large datasets:** The current version is limited to approximately 15 million points in a scene. Current limits to LiDAR data density mean this is only likely to be exceeded if the area imported is substantially larger than a typical inventory plot or if an ultra-high-density point cloud acquired with terrestrial laser scanning or Structure from Motion photogrammetry.

v. **Integrate log bucking algorithms into the VR environment:** For training and for value recovery studies this functionality would allow users to view in VR the merchandisable standing tree products.

vi. **Field based visualisation of data derived from VR assessments using Augmented Reality:** There is scope to use augmented reality (AR) to allow forestry staff to view tree metrics or derived labels (derived from VR-based measurements or external software) spatially superimposed onto trees in the field. This may have useful application for auditing/validation work and during harvesting operations. A valuable future goal would be for harvester operators to be visually advised using AR of the optimal way individual trees could be cut into logs. This may improve the skills of an experienced operator and assist in training new operators.

vii. **Field based thinning decision making and visualisation using Augmented Reality**: Experiences from the current project and future VR research are likely to inform allied R&D addressing incorporation of machine mounted ground-based LiDAR to determine the trees for removal in a thinning operation. The results of the thinning decision making could be displayed for the operator using Augmented Reality

There are significant opportunities for increased collaboration between the UTAS (HIT Lab) group and the team headed by Dr Mitch Bryson at the University of Sydney (Australian Centre for Field Robotics), particularly in terms of aligning the VR methods with the machine learning applied to assessment of tree and stem characteristics.

Appendix 1: USER GUIDE

OVERVIEW

The VR Cruising application is a standalone VR software application. To operate the application, users requires three components: this software, point cloud data and VR hardware. An overview of different key components is described below.

VR HARDWARE

The VR Cruising application was developed and operated with a commercial VR hardware, called 'Oculus Rift'. As of May 2019, the Oculus Rift has been replaced with the company's new flagship VR hardware called 'Oculus Rift S', https://www.oculus.com/rift-s/. The application is not compatible with any other VR hardware.

INPUT/OUTPUT CONFIGURATIONS

The VR Cruising application makes use of different folders, configuration files, and data files to implement its functionalities like point cloud loading, tool data saving/loading, and importing custom dictionary.

MOVEMENT

One of the main functionalities of the application is the ability to move around loaded point cloud data like you would in a real forest. There are multiple movement options available: conventional horizontal and vertical movement via the joysticks on both touch controllers, instant teleportation towards a selected area, and instant teleportation to ground level from any mid-air position.

CONTROL PAD

The control pad is a virtual pad that allows users to access multiple functionalities of the application within one convenient platform. To make use of the control pad, you'll need to press on the appropriate buttons using your left and/or right index finger. The control pad's features are split among three different panels, which can be accessed individually by pressing on the right tab button at the top of the display.

HEAD UP DISPLAY (HUD)

The application features both a VR HUD and desktop GUI that serves to display important information for users inside and outside the headset. The VR HUD will keep track of the headset's movement so that displayed information will be available regardless of the user's current viewing angle.

Detail of Operations

1. INPUT/OUTPUT CONFIGURATIONS

- **Point Cloud Data:** the application uses a specific data format (*.bin) produced by a third-party commercial product. The product is a toolkit software package operating inside another commercial software (Unity 3D: https://unity.com/). The toolkit package can be purchased here: https://assetstore.unity.com/packages/tools/utilities/point-cloud-viewer-and-tools-16019
- **Data folder**: The data folder locates in the "Virtual Reality Forest_Data/PointData" folder. Each data folder represents individual plot. The application scans the content of this folder upon start-up and displays the available datasets on the control pad. Within each data folder, there are an output file and persistence folder as detailed below:
    - **Output file:** '*.table' file locates inside the folder that stores the loaded dataset (data folder). This '*.table' file will get created to record information such as tree numbers, positioning, stem numbers and levels. The file is formatted to be reminiscent of the format of PlotSafe tables.
    - **Persistence folder:** 'ToolData' folder will be created to store '*.data' files that keep track of tool object attributes (e.g. label created). This will enable the application to re-load those attributes when the application is next open. Users don't need to interact with these files.
- **Configuration file**
    - 'dictionary.cfg' file – locates at the root of the application folder. All codes stored inside this config file gets loaded into the application which can then be assigned to created cruising labels. The file is split into 7 sections (branch, feature, sweep, resin, alive status, internode, structural) for each of the different assessment types. The default code used on the control pad is the very first code found in the section.

Importing point cloud data

To be able to load datasets into the application, you'll need to import it by placing it inside the PointData folder. This folder can be found inside the Virtual Reality Forest_Data directory from the root of the application's folder.

Once inside the PointData folder, create a brand new folder and place the dataset files inside. The name displayed on the control pad buttons will be based on the folder's name, so assign names that will make sense to you.

Tool.data files

If any tree regions and/or tool objects exist within a dataset before the application loads in a different dataset or closes, the application creates .data files to save the attributes of all existing objects so that the application can re-create them again later when the same dataset is loaded again. All .data files are stored in the ToolData directory, which is created inside the dataset's folder.

- .branch.data – stores branch node data.
- .circle.data – stores circle node (manual) data.
- .crutch.data – stores crutch node data.
- .height.data – stores height node data.
- .label.data – stores cruising label data.
- .stem.data – stores stem node data.
- .tree.data – stores tree region and DBH node data.

Viewing tree table output

If any tree regions and/or tool objects exist within a dataset before the application loads in a different dataset or closes, a PlotSafe table gets saved in the dataset's folder. The file itself will use the dataset's name and use the .tree.data format. To view the table, simply open this file with any text editor program.

Modifying dictionary codes for cruising labels

1. Open the dictionaries.cfg file found in the root application folder with a text editor program.
2. The file is split into 7 different sections: Branch, Feature, Sweep, Resin, Alive Status, Internode, and Structural. Don't make any changes to these section headings to avoid formatting errors.
3. To add a new dictionary code, simply write your dictionary code on a new line witihin the appropriate section. Ensure that you use the format "CODE:DESCRIPTION" (without the double quotes), and that there is an empty line in between the last dictionary code line and the next section heading to avoid formatting errors.
4. Save the changes and close the dictionaries.cfg file. The application will recognize the changes made to the file on startup and add the new codes to the dictionary code list on the kiosk display.

2. MOVEMENT

Calibrating for the height of headset

After the initial setup of Oculus, there often remains an offset between the real-world ground plane (floor) and the virtual ground plane inside the VR environment. To adjust the offset, press the Up1/Up10/Dn1/Dn10 buttons within the computer monitor GUI (see Figure 1) using the mouse cursor. Up1/Dn1 moves the headset 1cm upwards/downwards, while Up10/Dn10 moves the headset 10cm upwards/downwards. A simple way to gauge the offset is to hold a hand controller on the physical floor and from within VR environment, the offset can cause either the digital representation of the controller floating above or being underneath the ground.

Figure 1: GUI on the computer monitor (not inside VR views)

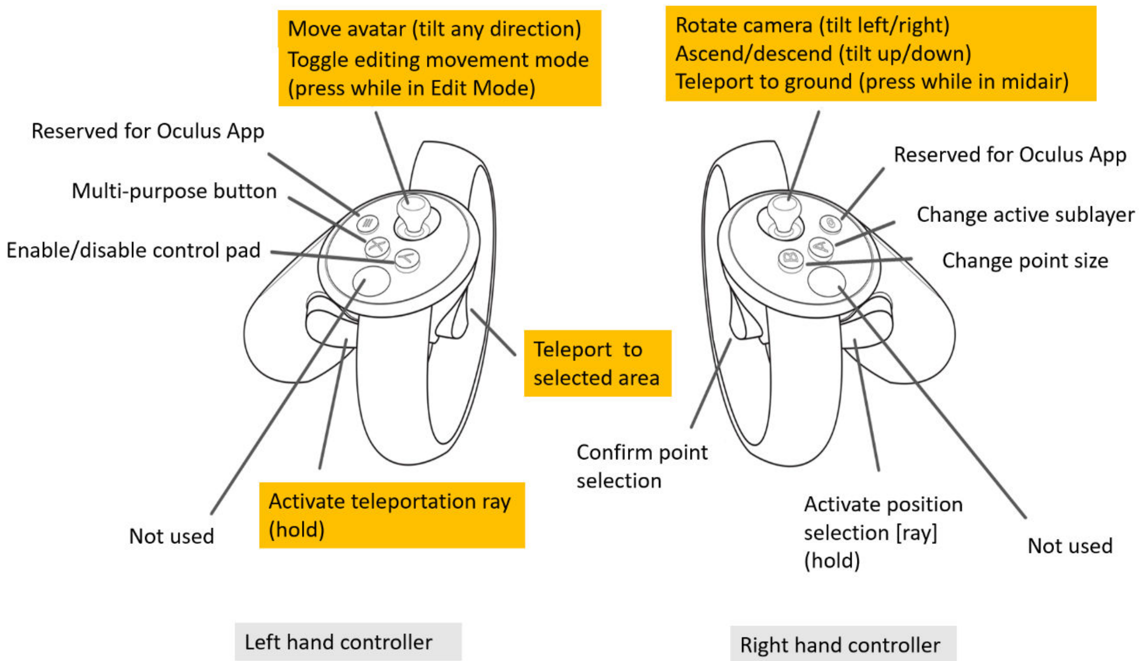

Figure 2: Movement – relevant control buttons highlighted in yellow

Moving your avatar via joystick

To move your avatar within the horizontal axis, push the joystick (illustrated in Fig.2) on the left touch controller towards the direction you want to move to. And to move your avatar within the vertical axis, push the joystick on the right touch controller up or down to make your avatar fly upwards or downwards.

Moving your avatar via teleportation

1. Hold down the side trigger (illustrated in Fig.2) on the left touch controller to bring up the movement laser selection.
2. Point the laser at the location that you want to move towards. This area will be indicated by a large green circle. Note that you can only teleport to a new location that's within the same vertical level as your current position.

3. Press the index trigger on the left touch controller to instantly teleport to the indicated area. You can keep repeating this action as long as the side trigger is held down.

Teleporting to ground level while in mid-air

1. Press on the joystick on the right touch controller to initiate ground teleportation. Note that this feature is only available if your avatar is located above ground level.
2. A black screen with a 3 second countdown should pop up, along with an audio cue to signal the start of the teleportation. After 3 seconds, the black blank screen disappears and your avatar should now be located on ground level.

3. CONTROL PAD

CONTROL PAD

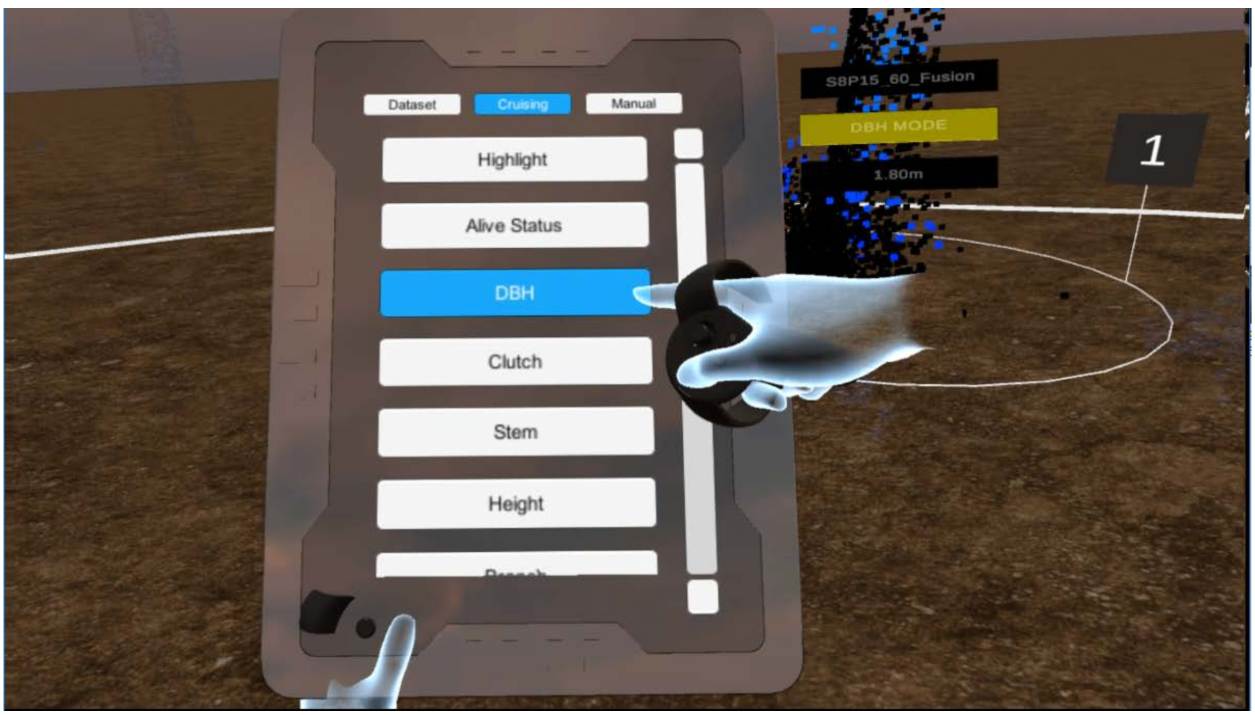

Figure 3: Control pad with top-level three-tab panels: Dataset, Cruising (selected) and Manual

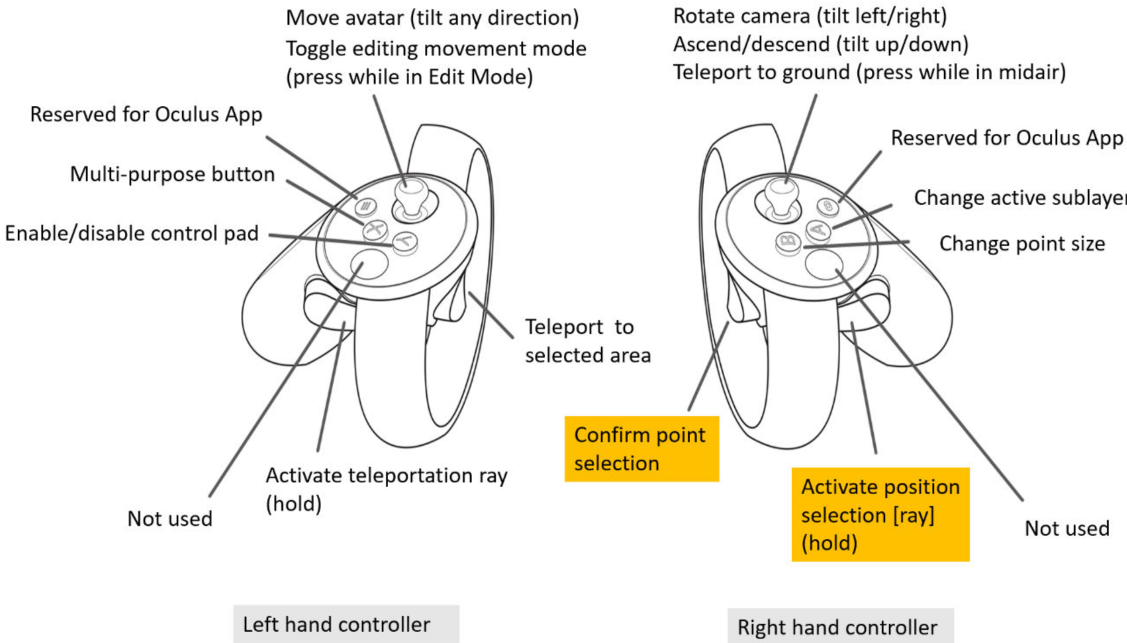

Figure 4: Selection– relevant buttons highlighted in yellow

Figure 3 illustrates the application's control pad. It is a virtual tool that allows users to make use of the various functionalities of the application. To bring up the control pad, press the Y button on the left touch controller.

The control pad contains three different panels:

1. Dataset Selection – this panel contains buttons that lets the user load different point cloud data. Each button represents a folder inside the PointData directory that contains .bin files.
2. Cruising Mode – this panel contains buttons that lets the user switch to automated and cruising tools that can be used to do tree assessments.
3. Manual Mode – this panel contains buttons that lets the user switch to manual tools that can be used to aid with miscellaneous assessment tasks.

Upon application start up, the Dataset Selection panel gets loaded by default when the control pad becomes active. Once the user loads a dataset into the application, the control pad automatically switches to the Cruising Mode panel when it becomes active again.

To select different panels or tools, simply place an index VR finger on the appropriate button as if you were in the real world with a physical button and finger.

KIOSK

Figure 5: Kiosk display when editing a cruising label object

The kiosk is a virtual interface that appears whenever a tool object is being edited. The information displayed is dependent on the currently selected tool object. It is updated in real time so users can use the kiosk as a guide when they're doing adjustments on tool objects.

Tab 1: DATASET SELECTION panel

Loading point cloud data

1. Press the Y button on the left touch controller to bring up the control pad.
2. Press the Dataset tab button located at the top of the control pad screen to switch to the Dataset Selection panel.
3. The Dataset Selection panel displays all the available point clouds found inside the PointData folder that can be loaded into the application. To load any of these datasets, simply press the button which has the folder's name.
4. Once pressed, the dataset loading screen pops up and the control pad deactivates after a few seconds to indicate that the point cloud data is being loaded in.

Tab 2: CRUISING panel

Using the Highlight Tool

1. Hold down the side trigger on the right touch controller (illustrated in Fig.4) to bring up the point laser selection.
2. Point the laser at a point that belongs to a tree that you want to highlight.
3. Press the index trigger on the right touch controller to create a new tree region. The created tree region immediately becomes active and the rest of the cruising tools should now be available to use.
4. With the tree marked inside a tree region, the user will automatically be switched to the DBH tool so they can continue their tree assessment.

Using the DBH Tool

1. Hold down the side trigger on the right touch controller (illustrated in Fig.4) to bring up the point laser selection.
2. Point the laser at a point of a tree trunk that you want to do DBH measurements on.
3. Press the index trigger on the right touch controller to create a DBH node. The DBH node should automatically be generated at 1.3m height level of the tree with the calculated diameter. A very simple circle fitting model is used in the current version, intended to seed a stem perimeter fit that is then visually adjusted by the user.
4. With the DBH node generated, the user will automatically be switched to the Height tool so they can continue their tree assessment.

Using the Crutch Tool

1. Hold down the side trigger on the right touch controller (illustrated in Fig.4) to bring up the point laser selection.
2. Point the laser at a point of a tree trunk that you want to designate as the crutch point.
3. Press the index trigger on the right touch controller to create a crutch node.
4. The generated crutch node will display a transparent green plane to indicate the crutch zone. From here, users can manually switch to the Stem tool so they can start creating stem nodes.

Using the Stem Tool

1. Hold down the side trigger on the right touch controller (illustrated in Fig.4) to bring up the point laser selection.
2. Point the laser at a point of a tree trunk that you want to designate as separate fork stem.
3. Press the index trigger on the right touch controller to create a stem node. The stem node will automatically align itself on the same level as the green ring of the closest crutch node.
4. The user can keep generating stem nodes to represent the multiple forks in a trunk. Keep in mind that if the crutch node gets deleted, the associated stem nodes will get deleted as well.

Using the Height Tool

1. Hold down the side trigger on the right touch controller (illustrated in Fig.4) to bring up the point laser selection.
2. Point the laser at a point of a tree that you want to do height measurements on.
3. Press the index trigger on the right touch controller to create a height node. One of the endpoints of the height node's green line will depend on the existence of a stem node in the active tree region:
    a. If there is no stem node, the first endpoint of the line will be the DBH node's position.
    b. If there is a stem node (or nodes), the first endpoint of the line will be the position of the stem node closest to the selected point used to generate the height node.
4. With the height node generated, the user will automatically be switched to the cruising label tool (Branch) to continue with their tree assessment.

Using the Cruising Label Tool(s)

1. Hold down the side trigger on the right touch controller (illustrated in Fig.4) to bring up the point laser selection.
2. Point the laser at a point of a tree trunk that you want to assign a cruising label on.
3. Press the index trigger on the right touch controller to create a cruising label. The cruising label's assessment type will depend on the current tool mode that you've selected in the Cruising panel on the control pad.
4. Once the cruising label is created, you will automatically switch to Edit Mode with the newly created label as the selected tool object. Proceed as you would when editing tool objects.

Tab 3: MANUAL

Using the Line Tool

1. Hold down the side trigger on the right touch controller to bring up the point laser selection.
2. Point the laser at a point where you want to start the measurement.
3. Press the index trigger on the right touch controller to create the first line node.
4. To create a line node chain, hold down the X button on the left touch controller while creating another line node. You'll notice that the red sphere which indicates the currently selected point should change to a yellow color.
5. After creating the chained node, a measurement box should appear between the two connected line nodes that indicate distance in meters.
6. Users can keep chaining as many nodes as they need. If you want to start a new chain, simply let go of the X button on the left touch controller.

Using the Circle Tool

1. Hold down the side trigger on the right touch controller to bring up the point laser selection.
2. Point the laser at a point of a tree trunk that you want to do diameter measurements on.
3. Press the index trigger on the right touch controller to create a circle node. The circle node's diameter should be automatically calculated like the DBH node.
4. Users can keep creating as many circle nodes as they need using this process.

Using the Branch Tool

1. Hold down the side trigger on the right touch controller to bring up the point laser selection.
2. Point the laser at a point of a tree trunk that you want to place the branch node on.
3. Press the index trigger on the right touch controller to create a branch node.
4. The size of the branch node that will be created can be changed by pressing the X button on the left touch controller.
5. Users can keep creating as many branch nodes as they need using this process.

EDITING

The editing tool is different to other tools in that it does not require user explicit activation through virtual button. The tool is always active and can be used at any time.

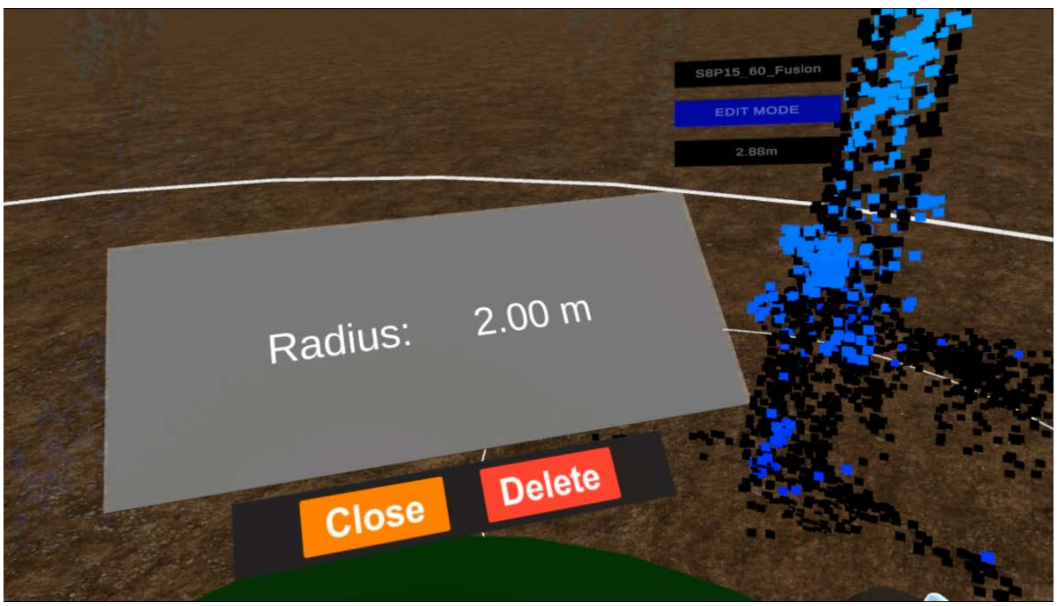

Figure 6: Kiosk panel

Editing tool objects

1. Hold down the side trigger on the right touch controller (illustrated in Fig.4) to bring up the point laser selection.
2. Point the laser at any tool object that exists within the environment.
3. Press the index trigger on the right touch controller to select the tool object and automatically go into Edit Mode.
4. Once Edit Mode is active, a kiosk (illustrated in Fig.6) will appear on the left side of the user's avatar. This kiosk will display a panel of varying layouts that present information based on the currently selected tool object.
    a. Tree Region – the kiosk will display the region's radius.
    b. DBH Node – the kiosk will display the DBH's node diameter.
    c. Crutch Node – the kiosk will display the crutch node's height level.

d. Stem Node – the kiosk will display the stem node's diameter, stem number and stem level.
e. Height Node – the kiosk will display the height node's height level, stem number and stem level.
f. Cruising Label – on the left side of the kiosk, the label's assessment type, height level, stem number and stem level will be displayed. On the right side of the kiosk will be a list of dictionary code buttons that the user can press to assign the code to the currently selected label.
g. Circle Node – the kiosk will display the circle node's diameter.
h. Branch Node – the kiosk will display the branch node's size.

5. Activating Edit Mode will initially put you in object movement mode, where it is possible to adjust the currently selected tool object's position by moving the joysticks on both the touch controllers. Pushing the left joystick will change the tool object's position in the horizontal axis, while pushing the right joystick up or down will move the object's position in the vertical axis. Pushing the right joystick left or right will change the object's radius if said object is a DBH node, stem node or a circle node.
6. To move your avatar while in Edit Mode, press the joystick on the left touch controller to toggle to avatar movement mode. While in avatar movement mode, you can move your avatar with the joysticks like you would outside of Edit Mode. Pressing the left joystick again will put you back to object movement mode.
7. To deselect the currently selected tool object and exit Edit Mode, press the Deselect button on the kiosk. This will also make the kiosk disappear and put you back to the previous tool mode you were in before activating Edit Mode.
8. To delete the currently selected tool object, press the Delete button on the kiosk. The currently selected tool object will be deleted, and you will be put back to the previous tool mode you were in before activating Edit Mode.

4. Miscellaneous Features

Figure 7: HUD on the top-right corner of the VR headset view

VR Head Up Display

On the top right corner of the user's vision is where the VR HUD is located (illustrated in Fig.7). They serve to inform the user about three things:

- The name of the current dataset that's been loaded
- The current tool mode that the user is on. Each mode will have its own corresponding colour in the HUD
- The current height level of the headset

DESKTOP GUI

The desktop HUD (illustrated in Fig.1) displays the following information:

- The current state of data logging (on or off)
- Whether data logging has been paused
- Name of the current dataset loaded
- Current tool mode that the user is on

The HUD also contains buttons that allow you to adjust the current height level of the VR headset.

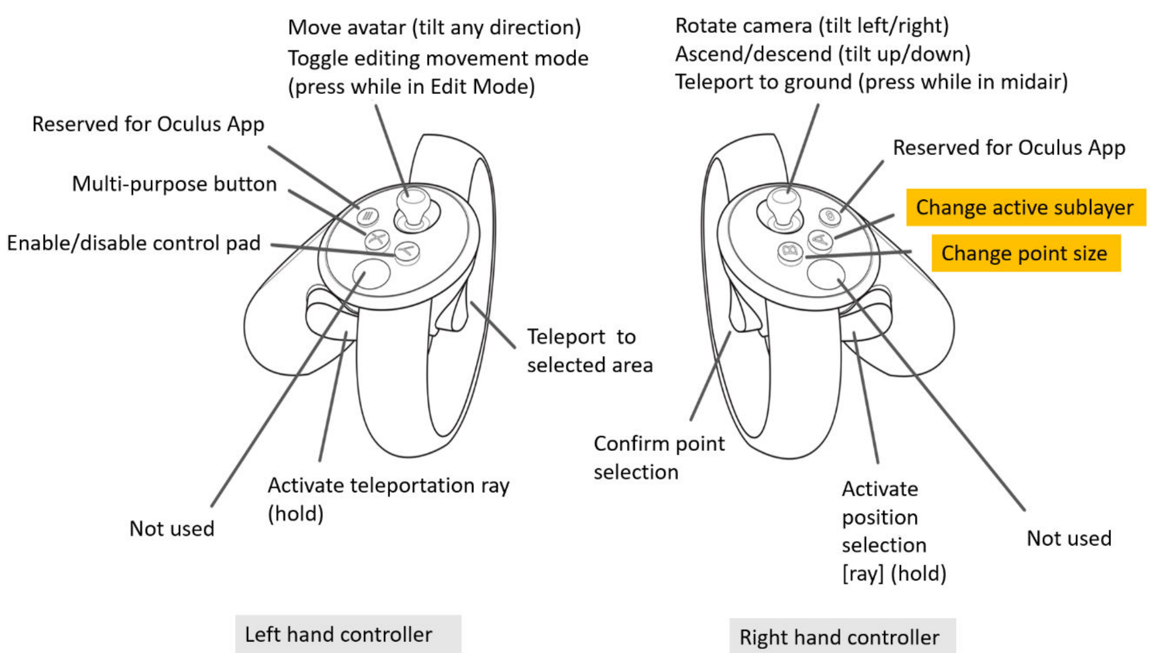

Figure 8: Changing size of point cloud data and – relevant buttons highlighted in yellow

Changing size of the point cloud

Press the B button on the right touch controller (illustrated in Fig.8) to toggle between the different point sizes. Take note that this only affects the dataset that's been loaded as the main layer.

Changing a visible point cloud secondary sublayer

Press the A button on the right touch controller (illustrated in Fig.8) to toggle between different secondary sublayers that have been loaded into the application. The (default) primary layer that is initially loaded with the dataset will remain unaffected by this toggle of the sublayers. Figure 9 shows a secondary point cloud sublayer (colour) is rendered on top of the primary layer (black). However, the Highlight tool will only work with the primary data layer as noticed, the secondary colour sublayer shows all points (trees) in view including outside the highlight area.

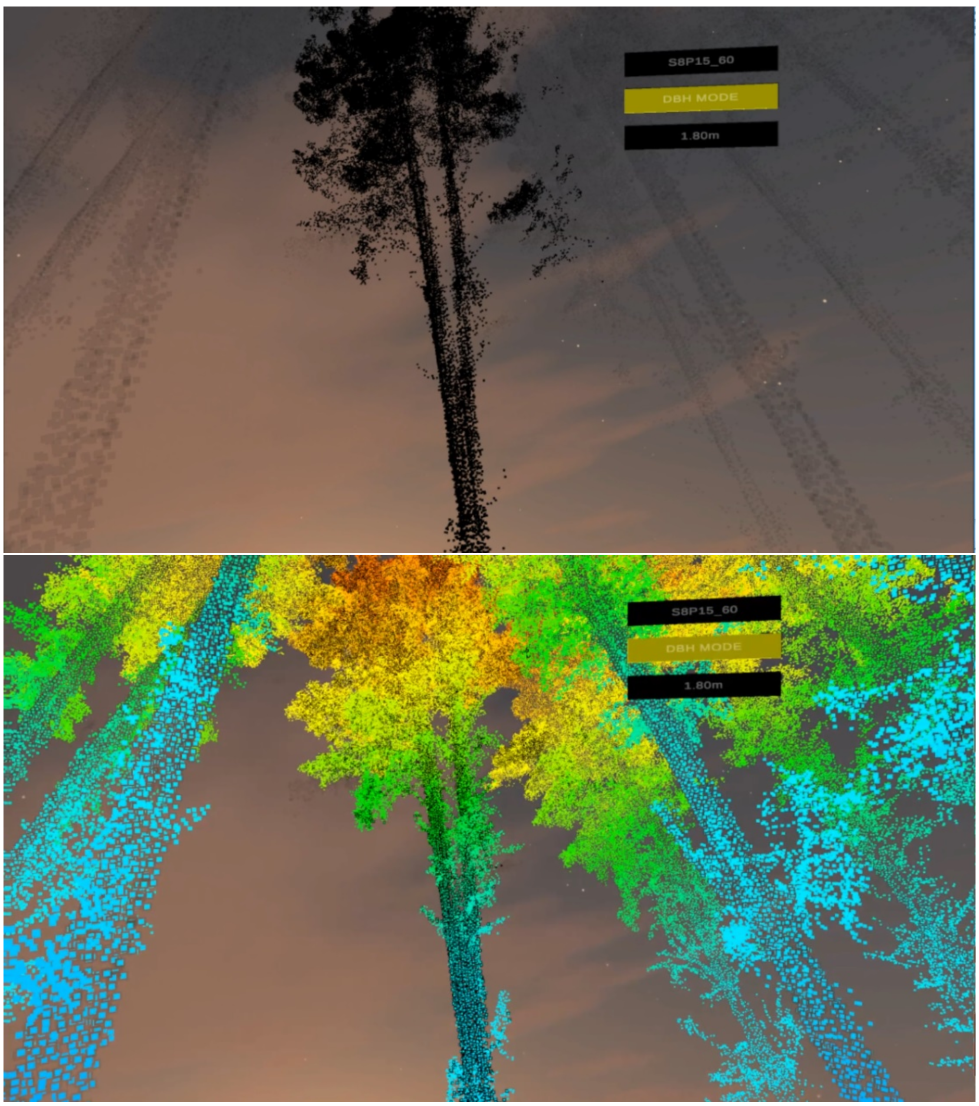

Figure 9: Top – primary point cloud data layer (black points), Bottom – secondary point cloud data layer (colour points) loaded on top of the primary data layer

Appendix 2: Airborne LiDAR Specifications

LiDAR data used in this project was acquired as part of FWPA PNC377-1516 (Optimising Remotely Acquired, Dense Point Cloud Data for Plantation Inventory). The study site was within the Carabost State Forest, NSW, managed by Forestry Corporation of New South Wales (FCNSW). The site comprised *Pinus radiata* (established 1995, pruned 2004, thinned 2017). Data was acquired in 2017 with a Trimble AX60 mounted on a fixed wing aircraft and in 2018 with a Riegl VUX-1LR scanner on a helicopter platform. For data acquisition details Table 1 below and see Del Perugia et al. (2018).

The LiDAR data is illustrated in the figures below. Figure 1 shows point cloud from the Trimble AX60 campaign acquired at 850 m AGL. Figure 2 shows data from the VUX-1LR campaign acquired at 60 m AGL -both from site 8, plot 15. Figure 3 illustrates both the Trimble AX60 and the VUX-1LR data point cloud data for a single tree.

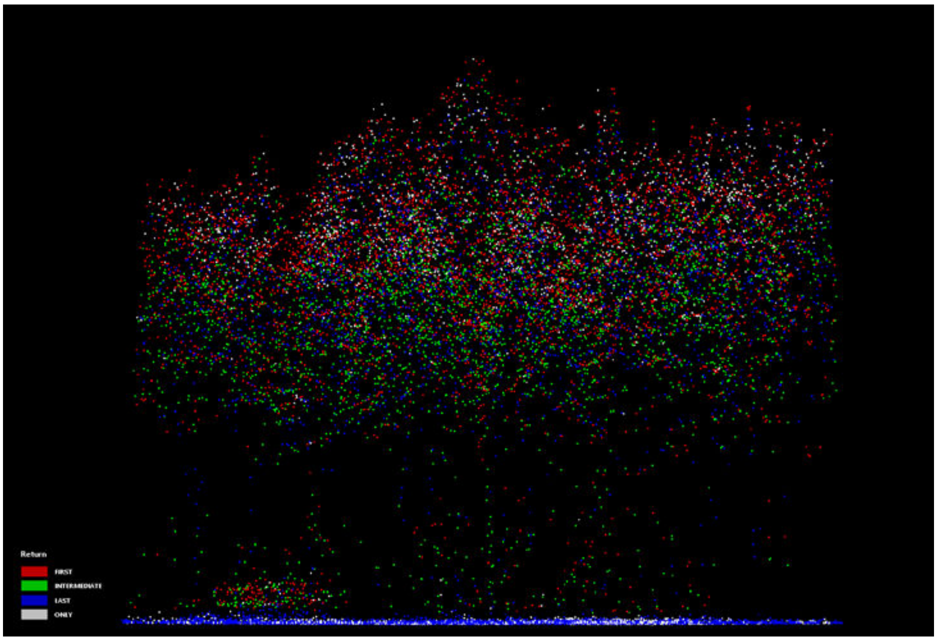

Figure 1: Trimble AX60 data, site 8 plot15, acquired at 850m AGL (normal density LiDAR)

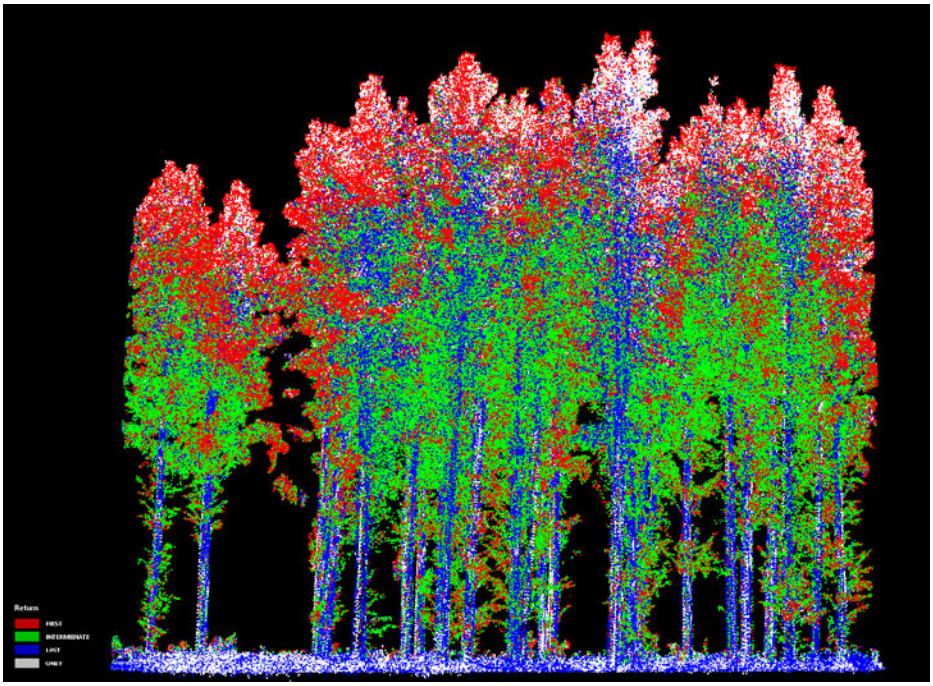

Figure 2: VUX-1LR data, site 8 plot 15 acquired at 60m AGL (ultra-dense LiDAR)

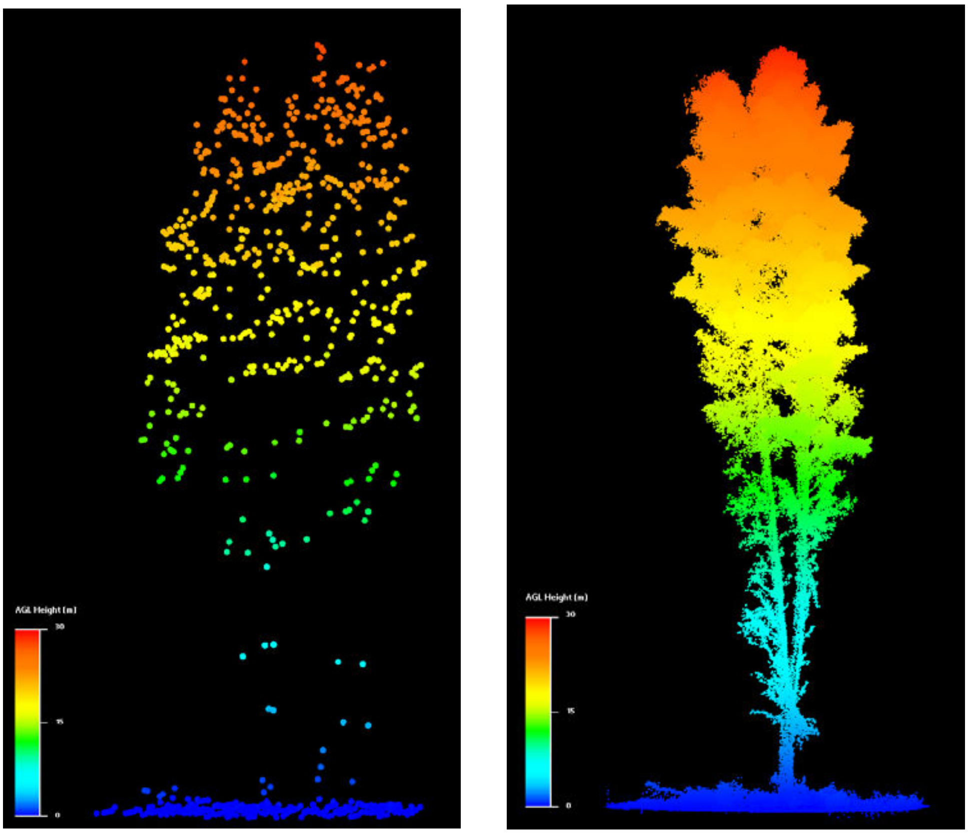

Figure 3: Point cloud LiDAR data for a single tree acquired with (left) normal density Trimble AX60 scanner at 850m AGL and (right) ultra-dense VUX-1LR scanner at 60m AGL

Table 1 details the specifications of two LiDAR scanners: Trimble AX60 (mounted on aircraft) and VUX1-LR (mounted on helicopter). The aircraft flew at 850m AGL and the helicopter flew at three different heights 30,60 and 90m AGL.

Table 1: LiDAR scanner specifications

Sensor	Year	Platform	Flying Height (AGL) (m)	Flight Direction	Flight Speed (m/s)	Pulse Rate (kHz)	Flight line spacing (m)	Maximum Scan Angle	Pulses per square meter	Returns per square meter
Trimble AX60	2016	Aircraft	850	various	62	400	350 (minimum)	60°	4.9	10.7
VUX1-LR	2018	Helicopter	30	from east to west (EW) and from north to south (NS)	5	400	15	170°	3572	6329
VUX1-LR	2018	Helicopter	60	from east to west (EW) and from north to south (NS)	5	400	15	170°	2191	3842
VUX1-LR	2018	Helicopter	90	from east to west (EW) and from north to south (NS)	5	400	15	170°	1949	3328

It is assumed that due to the poor canopy penetration of photogrammetric point data, compared to LiDAR data (Iqbal et al. 2018), that camera derived datasets would not be suitable for individual stem measurement inside a VR environment. Future studies are required to evaluate the benefits to be derived from utilising photogrammetric 3D data within a VR environment.

References

Del Perugia B., Gonzalez Aracil S., Herries D. Optimal acquisition specifications for teh Riegle VUX-1LR over a Pinus radiata plantation, in Watt, M.S., Stone, C., Bryson, M., Chinthammit, W., Dash, J.P., Del Perugia, B., Gonzalez Aracil, S., Gordon, J., Harwin, S., Herries, D. and Krisanski, S. (2018) Optimizing remotely acquired, dense point cloud data for plantation inventory. M Watt, C Stone (eds). (FWPA PNC377-1516)

Iqbal, I. A., Osborn, J., Stone, C., Lucieer, A., Dell, M., & McCoull, C. (2018). Evaluating the robustness of point clouds from small format aerial photography over a Pinus radiata plantation. *Australian forestry*, *81*(3), 162-176.