Estimation of Individual Tree Metrics using

Structure-from-Motion Photogrammetry

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Abstract

The deficiencies of traditional dendrometry mean improvements in methods of tree mensuration are necessary in order to obtain accurate tree metrics for applications such as resource appraisal, and biophysical and ecological modelling. This thesis tests the potential of SfM-MVS (Structure-from-Motion with Multi-View Stereo-photogrammetry) using the software package PhotoScan Professional, for accurately determining linear (2D) and volumetric (3D) tree metrics. SfM is a remote sensing technique, in which the 3D position of objects is calculated from a series of photographs, resulting in a 3D point cloud model. Unlike other photogrammetric techniques, SfM requires no control points or camera calibration. The MVS component of model reconstruction generates a mesh surface based on the structure of the SfM point cloud.

The study was divided into two research components, for which two different groups of study trees were used: 1) 30 small, potted 'nursery' trees (mean height 2.98 m), for which exact measurements could be made and field settings could be modified, and; 2) 35 mature 'landscape' trees (mean height 8.6 m) located in parks and reserves in urban areas around the South Island, New Zealand, for which field settings could not be modified.

The first component of research tested the ability of SfM-MVS to reconstruct spatially-accurate 3D models from which 2D (height, crown spread, crown depth, stem diameter) and 3D (volume) tree metrics could be estimated. Each of the 30 nursery trees was photographed and measured with traditional dendrometry to obtain ground truth values with which to evaluate against SfM-MVS estimates. The trees were destructively sampled by way of xylometry, in order to obtain true volume values. The RMSE for SfM-MVS estimates of linear tree metrics ranged between 2.6% and 20.7%, and between 12.3% and 47.5% for volumetric tree metrics. Tree stems were reconstructed very well though slender stems and branches were reconstructed poorly.

The second component of research tested the ability of SfM-MVS to reconstruct spatially-accurate 3D models from which height and DBH could be estimated. Each of the 35 landscape trees, which varied in height and species, were photographed, and ground truth values were obtained to evaluate against SfM-MVS estimates. As well as this, each photoset was thinned to find the minimum number of images required to achieve total image alignment in PhotoScan and produce an SfM point cloud (minimum photoset), from which 2D metrics could be estimated. The height and DBH were estimated by SfM-MVS from the complete photosets with RMSE of 6.2% and 5.6% respectively. The height and DBH were estimated from the minimum photosets with RMSE of 9.3% and 7.4% respectively. The minimum number of images required to achieve total alignment was between 20 and 50. There does not appear to be a correlation between the minimum number of images required for alignment and the error in the estimates of height or DBH (R^2=0.001 and 0.09 respectively). Tree height does not appear to affect the minimum number of images required for image alignment (R^2=0.08).

External parameters, which include things such as the position of the tree relative to its surroundings, the background scene and the ambient lighting, appear to be the primary determinants of model success.

The results show that SfM-MVS is capable of producing estimates of 3D and 2D metrics with accuracy at least equal to that of laser scanning and potentially much more accurate than allometric models and traditional dendrometry techniques. SfM-MVS provides a low-cost alternative to remote sensing technologies currently used such as terrestrial laser scanning, and as no specialised equipment is required it is able to be used by people with little expertise or training. Future research is required for exploring the suitability of SfM-MVS for specific applications requiring accurate dendrometry.

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Chapter One

Introduction

1.1 Background

The ability to obtain accurate tree metrics is important for a variety of applications within the fields of commercial forestry (Næsset, 1997; Clark *et al*., 2000b; Henning & Radtke, 2006), urban forestry (Moskal & Zheng, 2012; Tanhuanpää *et al*., 2013; Saarinen *et al*., 2014), ecology (Dandois & Ellis, 2010; Liang *et al*., 2014b) and horticulture (Rosell *et al*., 2009). Dendrometry, which is the measure of tree structure and dimension (Morgenroth & Gomez, 2014) is fundamental for resource appraisal (e.g. wood volume, biomass and tree growth) and analysing forest structure (Næsset, 2002, Skowronski *et al*., 2014) particularly for commercial forest management. Biophysical and ecological information to be derived from tree metrics, include carbon stocks (Houghton, 2005; Strahler *et al*., 2008), biofuel potential (Dassot *et al*., 2011; Kankare *et al*., 2013a) and fire spread risk (Dandois & Ellis, 2010), habitat size and quality (Moskal & Zheng, 2012), storm water attenuation (Xiao & McPherson, 2011) and contribution to reduction of urban air pollution (Nowak *et al*., 2010). Traditional field methods of dendrometry are prone to error, so they do not always adequately measure tree size and architecture. As a consequence, error is inherently introduced into commercial, biophysical and ecological characteristics which rely on accurate mensuration. Structure-from Motion with Multi-View Stereo-photogrammetry (SfM-MVS) is a relatively new photogrammetric approach allowing automated reconstruction of 3D models using sets of overlapping 2D digital images. SfM-MVS has the potential to provide accurate estimations of tree size and architecture, whilst significantly reducing the difficulties, cost and error associated with traditional dendrometry. Though the method has previously been shown to accurately measure the height and diameter of one individual tree accurately (Morgenroth & Gomez, 2014), it is untested for 3D metrics (e.g. volume) and methodological aspects of its use remain in their infancy with no standardised methods developed yet.

1.2 Current Methods for Traditional Dendrometry

Traditional dendrometry involves terrestrial field mensuration of tree metrics and has been widely adopted due to its simplicity and standardisation, though it is partly due to this simplicity that it is inherently flawed (Clark *et al*., 2000b; Hopkinson *et al*., 2004; Morgenroth & Gomez, 2014). Traditional dendrometry is error-prone, laborious, time consuming, expensive (Hopkinson *et al*., 2004; Melkas *et al*., 2008; Watt & Donoghue, 2005) and sometimes accessibility to conduct them can be limited by dense vegetation, rough terrain or remoteness (Næsset, 1997; Clark *et al*., 2000b; Li *et al*., 2012). Tree height and stem diameter (diameter at breast height, DBH) are among the most important metrics in commercial forest management (Elzinga *et al*., 2005; Kitihara *et al*., 2010; Vastaranta *et al*., 2013) as they provide the means to allometrically estimate the volume of wood, which is the principle commercial product of forestry (West, 2009) and the world’s largest source of renewable construction material.

Field mensuration of tree height is a challenging task, especially for inexperienced observers (Kitahara *et al*., 2010). At present hypsometers are commonly used (Kitahara *et al*., 2010; Liang *et al*., 2014b). These combine clinometers and laser rangefinders and use geometric and trigonometric functions to estimate tree height (West, 2009). Hypsometers are subject to error as they assume that all angles and distances have been measured correctly and that the observer has correctly identified the tallest part of the tree (Morgenroth & Gomez, 2014). Errors can also occur when observers fail to consider ground-slope, tree lean or crown shape (Bragg, 2008). Height is difficult to measure in closed-canopy forests (which the majority of commercial forest plantations are), where the tops of trees are often not visible (Chave *et al*., 2005). Small trees can be measured with height poles, but the utility of this tool is limited with tall trees. Error in tree height and DBH measurements can be reduced with training but it cannot be totally eliminated, even in experienced observers.

DBH is typically measured with callipers or a diameter tape, depending on the thickness of the stem. While the name suggests a somewhat arbitrary height, DBH is most commonly measured at 1.3 m above the ground in literature (Brokaw & Thompson, 2000), and 1.4 m above the ground in New Zealand. DBH provides a repeatable measure that can be applied to almost any tree, though error in its measurement can arise from a number of sources; placement of the tape above or below the recorded height, failure to place the tape perpendicular to the tree axis, or through misreading the tape (Elzinga *et al*., 2005). Procedural decisions made in forest management, such as thinning and felling are often made directly from DBH measurements; however, the stem form and taper is the key characteristic that determines the yield and quality of the merchantable wood in the stem (Kankare *et al*., 2013a).

The taper of the stem is fundamental as it depicts the stem diameter as a function of height (Yang *et al*., 2009) and ultimately estimate stem volume. Stem form cannot be measured in a cost-efficient manner with traditional dendrometry so allometric models are mainly relied upon to describe stem taper; each of these incorporate the height (or length) of the stem, and the diameter at various points along it. Much research has gone into developing these models to describe the stem taper of different tree species in different growing regions, which allow the volume to be derived from DBH and height alone (West, 2009). However, studies have shown that stem tapers vary greatly globally due to different growing conditions and therefore their applicability is limited due to their inaccuracy (Liang *et al*., 2014a). Stem taper models were developed for commercial forestry to calculate the volume of merchantable timber in tree stems and although they are sufficiently accurate for this purpose, they have little value for tree mensuration in non-commercial forest settings. Perhaps the most obvious limitation of field mensuration is that it can only be conducted at a local scale. Commercial forest plantations often cover thousands of hectares, and the time and labour required dictates that only a small plot sample in a fixed area can be measured (Breidenbach *et al*., 2014), typically in the shape of circular plot or transects, as this is more efficient than measuring a random sample of trees. The key assumption in plot sampling is that the trees selected are representative of the whole plantation.

There are modern tools and methods capable of calculating stem volume to a more precise degree (e.g. xylometry and remote sensing) though none of them are always practical nor appropriate for field mensuration of standing trees, and traditional dendrometry is still relied upon for ground-truth validation (West, 2009; Berger *et al*., 2014). Stem volumes of standing trees derived from allometric equations contain errors due to their often-unrealistic assumptions of natural tree form (Dassot *et* *al*., 2011). As trees in nature never have perfect geometric form (e.g. perfectly cylindrical or conical with no irregularities and an even taper) error is inevitable in stem volume calculations (West, 2009; Morgenroth & Gomez, 2014).

Felling trees offers the most accurate method of volume measurement, as in most cases diameter measurements from the middle and top of the stem are not possible to obtain from standing trees without dangerous climbing techniques, optical dendrometers (Henning & Radtke, 2006; West, 2009) or logging machines (Liang *et al*., 2014a). However, felling the tree often defeats the purpose of taking the measurement, as the method should in no way cause disruption to the tree's growth (Clark *et al*., 2000b). Felling a tree means no future growth can be monitored, not to mention the fact that felling is usually unacceptable in non-commercial forestry settings, such as urban forests or conservations areas (Parker & Matney, 1998; Liang *et al*., 2014b). For non-destructive field measurements DBH is normally used as the sole diameter for the stem (Melkas *et al*., 2008; Vastaranta, *et al*., 2009) and has become the standard height for diameter measurement.

Merchantable stem volume is not the only important commercial product of forestry. There is increasing interest in mensuration of biomass (Repola, 2009; Lin *et al*., 2010; Skowronski *et al*., 2014) which is sought for a variety of applications, including carbon accounting and quantification of the amount of organic fuel available for energy production (biofuel). The biomass of a tree comprises of its entire mass, including the stem, branches, bark, foliage and roots. The density of the wood is also considered, as biomass is measured by weight rather than by volume. Biomass is often measured as 'above-ground' biomass (AGB) because the roots are difficult to measure. Field estimation of biomass largely involves the same aforementioned methods used for measuring stem volume, and therefore error is inevitable, especially because the crown branches and foliage are much more difficult to measure and large errors can be made (Dassot *et al*., 2012).

Until recently, remote sensing forest biomass estimates have been carried out with medium resolution satellite imagery and radar, which while efficient in terms of the area they cover, have only had limited success (Houghton, 2005; Kankare *et al*., 2013a). Currently laser scanning provides the most accurate and efficient method of measurement due to its ability to measure canopy attributes as well as forest structure beneath (Lin *et al*., 2010) and because biomass is linearly related to volume, estimations can be made from commercial forestry inventories if the data is available (Houghton, 2005; Boudewyn *et al*., 2007). Data for the latter is primarily based on the volume of merchantable wood (i.e. the emphasis is on the biomass of the stem) (Fraver *et al*., 2007; Dassot *et al*., 2012) and while they provide reasonable estimates there is much room for improvement when it comes to monitoring high resolution changes, i.e. at an individual tree scale (Lin *et al*., 2010; Kankare *et al*., 2013b). Laser scanning also has limitations that mean it is not always the most appropriate method to use. Biomass models must produce reliable estimates and be applicable at a national scale (Repola, 2009). National and regional biomass estimates would ideally be derived from a probability design sample of ground plots representing a variety of typical forested and vegetated cover types, species composition, age and vertical structure (Boudewyn *et al*., 2007), but this is not a feasible option considering the high costs that would be involved.

The only way to get a true measure of total biomass is by felling the tree, digging up the roots, and weighing individual components of the tree successively (Lin *et al*., 2010) or by using xylometry (and converting the volume to mass). This is clearly not feasible in practice (Repola, 2009; Kankare *et al*., 2013a), and therefore like stem volume, the development of models to calculate biomass from standard tree metrics has been the subject of several studies over the last few decades (e.g. Marklund, 1988; Repola, 2008; 2009). Regression models for different tree species have been developed from extensive field measurements of standard tree metrics (Houghton, 2005; Zianis *et al*., 2005; Repola, 2009). Despite this, no species-specific model can be applicable to any tree of a certain species without at least some error. Like stem taper, biomass is specific to particular species and growing regions. For a given species, the biomass of individual trees in a particular plot is more closely correlated to other trees within that plot as opposed to trees of the same species in other plots, showing that local conditions play an important role in tree growth (Repola, 2008).

1.3 The Need for Accurate Tree Mensuration

Commercial forestry inventory is dependent on height and DBH, as well as stem taper and volume. Commercial inventories require frequent gathering of accurate metrics to determine the potential merchantable timber yield, as well as for future modelling and planning of the forest resource. Stem-only harvesting in particular is concerned with the volume of the tree stem, as this contains the largest proportion of a tree's mass (75-85%, Kankare *et al.*, 2013b) and is the largest continuous section of the tree from which lengths of timber can be cut; therefore it holds the most value in harvesting for various forms of timber products. The roots, small branches and foliage of trees are seldom used as their few potential uses are of little commercial value.

Knowledge of forest biomass is essential for carbon accounting, which has become an integral component of forest mensuration due to rising awareness of the effects of greenhouse gases on the world's climate (West, 2009). Carbon dioxide (CO_2) is the dominant greenhouse gas in the atmosphere and its increase is attributed to combustion of fossil fuels (80%) and global deforestation (Nowak & Crane, 2002). Trees act as a sink for atmospheric CO_2 by using it as part of the photosynthesis process and storing it in their tissue. And consequently, a large proportion of the world's carbon is locked within tree biomass (Nowak & Crane, 2002; Hyyppä *et al*., 2012; Kankare *et al*., 2013b) and therein lays the need for biomass quantification. Measuring the carbon sequestered in biomass requires laboratory equipment and cannot be done in the field, though past research has established the typical carbon content for various species of tree, meaning carbon content can be calculated from biomass alone. The carbon content is usually close to 50% of a tree's biomass and does not vary much between species or different parts of the tree (West, 2009).

There remains uncertainty around the magnitude of carbon uptake by global forests and the distribution of carbon stocks in forest ecosystems (Houghton, 2005; Pan *et al*., 2011). When calculating carbon flux on a global scale, an accumulation of inaccuracies in biomass calculations will result in significant overall error. The vast boreal forests of Canada, Russia and Scandinavia are estimated to store 30% of global carbon, though research of urban forests has been of particular interest as the latter are subject to the highest concentrations of air pollution due to their proximity to industrial areas, as well as being home to the high densities of people. In 2010 Nowak *et al*. estimated that in Chicago trees sequester a gross amount of 25,200 tons of carbon annually, with an associated value of $521,000. These same Chicago trees are estimated to hold 716,000 tons in long term storage with a value of $14.8 million. Atlanta and New York City potentially hold even larger stores, with an estimated 1.34 million and 1.35 million tons respectively. Zhao *et al*. (2010)

estimated that urban forests in the province of Hangzhou, China sequestered 1.33 million tons of carbon annually, accounting for an annual offset of 18.6%. Russo *et al*. (2014) estimated that urban trees in Bolzano, Italy sequester 12-17 kg of carbon per year

A number of international initiatives have been implemented to encourage countries to decrease rates of carbon emission and offset what they do emit by planting new forests that will act as a sinks. These include the United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries, United National Framework Convention on Climate Change and Land Use, Land Use Change and Forestry section in the Kyoto Protocol (Skowronski *et al*., 2014). In accordance with the Intergovernmental Panel on Climate Change (2006), countries that plan to mitigate climate change through forestry must provide verified reports (including the uncertainty) on national forest carbon stocks and subsequent contribution to the global carbon cycle and effects on climate change (Næsset & Gobakken, 2008; Berger *et al*., 2014). The accuracy of biomass mensuration has major implications on the potential for financial compensation which can be achieved through increased offset, as well as introducing bias for future projections (Breidenbach *et al*., 2014). It is therefore in each country's best interest to ensure that biomass is calculated to the most accurate degree possible. Biomass at regional through to global scale is changing constantly, particularly because of rapid deforestation that is occurring in tropical regions (Houghton, 2005; Pan *et al*., 2011). Natural events like cyclones, forest fires and insect swarms can also cause major changes in short duration. It is therefore necessary to conduct continuous or at least very frequent monitoring of biomass in order to know the absolute spatial distribution. This presents a huge challenge considering the necessity for high accuracy (Kankare *et al*., 2013a).

While the commercial value of wood products has been the major driver behind advances and refinement of dendrometry methods, accurate dendrometry is also important for other applications that do not have as much of a commercial bent. Urban forestry is a growing research discipline regarding the processes and interactions between trees and their surrounding urban environments. Trees and forests in urban landscapes are environmental assets and contribute a range of positive environmental and social effects to the surrounding urban area (Nowak *et al*., 2010). It is difficult to put a monetary value on these benefits as there is often there is no real way to measure the benefit they have, though some recent efforts have been made (e.g. Nowak *et al*., 2002; 2010), the more recent of whom developed a valuation system based on environmental, social and economic criteria. Urban forestry includes the management and research of trees in parks, public land and street plantings. The need for information on urban trees is increasing (Holopainen *et al*., 2013; Saarinen *et al*., 2014) and inventories are being developed in many cities to manage urban tree populations (Tanhuanpää *et al*., 2013) which can number in the millions and cover a large proportion of a city's area. For example, Chicago is estimated to have 3.5 million trees which cover 17.2% of the urban area (Nowak *et al*., 2010).

Typical tree registries contain location, height and DBH, as well as information on the vitality of trees (Holopainen *et al*., 2013). As urban trees are not considered for their timber volume, accurate mensuration of some standard tree metrics (e.g. DBH) is not as important as it is in commercial forestry. However, the spatial dimensions of trees may be required for a variety of other urban planning purposes, as well as assessment of ecosystem services, such as storm water attenuation, effects of wind flow, effects on land stability, shading or neighbouring property, air pollution reduction, fire spread risk and biodiversity assessment. Qualitative data may also be sought to provide information on tree health for maintenance purposes, such as recognizing trees that require watering or pruning and identifying dying trees or trees that have been damaged by strong winds or heavy snowfall may be hazardous to citizens (Tanhuanpää *et al*., 2013). Interpretation of aerial photography and field mensuration are the conventional methods used to update urban tree registries. Updating tree registries with field mensuration is inefficient, particularly when tens of thousands of trees need to be monitored (Holopainen *et al*., 2013). In the last decade laser scanning has been commonly used and in many cases datasets for these has already been collected for other urban planning purposes, as well as generating virtual city layouts (Saarinen *et al*., 2014).

The role of urban trees in mitigating urban pollution has been the subject of much research. Air pollution, which includes gases such as ozone, nitrogen dioxide, carbon monoxide and particulate matter <10 microns in size, is harmful to human health, can cause damage to buildings and ecosystem processes and reduces visibility (Nowak *et al*., 2010). Trees help to improve urban air quality in a number of ways, including direct removal harmful gases and pollutants through uptake into their leaves, reducing air temperature and lowering the energy consumption of buildings (as well as the subsequent emissions from power stations). They also help by passively capturing airborne particles on their surfaces. Some particles can be absorbed into the tree, though most particles remain on the surface and are washed off by rain or dropped to the ground as the leaves or branches fall (Nowak *et al*., 2006). Therefore trees can be considered as a temporary storage of pollution. The rate at which pollutants are removed is dependent on the species and size of the tree. Nowak *et al.* (2010) estimated that Chicago's trees are responsible for the removal of 888 tons of air pollution annually, which has equates to a value of $6.4 million (based on national median externality costs associated with pollutants).

The deficiencies of traditional dendrometry have encouraged the development of new terrestrial remote sensing technologies for forest resources. Structure-from-Motion with Multi-view Stereo-photogrammetry (SfM-MVS) is one such technology, and its applicability for estimating tree metrics will form the basis of this thesis. Though it is still a relatively recent development, SfM-MVS may yet prove to be a superior method to traditional dendrometry.

1.4 Thesis Structure

This thesis is divided into four chapters; a comprehensive literature review immediately follows this introduction chapter, while the final two chapters present the results of the research itself. Trees used in the study were divided into two subsamples (nursery trees and landscape trees) based on the different research aims for each and therefore the results corresponding to nursery and landscape trees have been divided into separate chapters.

Chapter Two

Remote Sensing in Forestry

Remote sensing refers to the ability to obtain information of something from a remote location without making physical contact. It includes technologies such as radar, laser scanning, satellite imaging and digital photogrammetry, all of which are highly useful for analysing tree metrics and forest resources (Kankare *et al*., 2013a; Fernández-Sarría *et al*., 2013). Remote sensing is so useful due to the versatility of the collected data and the numerous ways the data is able to be interpreted, i.e. "a picture paints a thousand words". The practicalities of analysing the vast land areas associated with commercial forest plantations (thousands of ha) mean that aerial platforms often provide the highest efficiency in terms of the area able to be covered at once and thus aerial laser scanning and digital photogrammetry are the primary remote-sensing methods with which forest resources are analysed in modern times (West, 2009; Kaartinen *et al*., 2012).

These methods have been shown to provide results at least as accurate as traditional dendrometry (Næsset, 2004; Melkas *et al*., 2008), the latter of which have been in use for over a century (West, 2009). However, no single remote sensing method is suited to all forestry applications– each has its own drawbacks and limitations depending on the nature of the research. Large scale analysis often requires plot-size ground validation, meaning supplementary field mensuration is still relied upon. Not all applications that require acquisition of tree metrics involve such large spatial areas, so remote sensing methods applicable to small-scale analysis (i.e. at plot and individual tree scale) are also important.

Remote sensing of forest resources began with hand-held optical dendrometers in the early 19th century (Drew *et al*., 2009) and advances in the technology of the sensors and the platforms on which they are based on has seen progression to modern day instruments. Hand-held devices are still commonly used, due to the necessity of field mensuration for many applications, though there is an increasing reliance on automatic extraction of forest metrics from modern digital datasets. Continuing advances mean forest mensuration, particularly for inventory, is trending towards full automation and manual field measurement may eventually become redundant (West, 2009).

The following literature review provides an introduction to relevant remote sensing technologies and will help to identify study methods and also thresholds for success, against which the SfM-MVS technology used in this thesis, can be compared. Particular attention is given to laser scanning, optical dendrometry and photogrammetry techniques. The current state of SfM-MVS use for tree mensuration is also summarised and gaps in the research identified.

2.1 Laser Scanning

Laser scanning was first applied in forestry several decades ago (Nelson *et al*., 1984) and since then advances in the technology and associated methodologies have led to widespread application for mensuration of forest resources. It is now the preferred tool for making 3D measurements of forest structure and analysing forest resources (Dandois & Ellis, 2010; White *et al*., 2013). Laser scanning, namely LiDAR (a portmanteau of 'light' and 'radar' or an acronym for Light Detection and Ranging) has overcome many of the limitations and reduced the errors associated with traditional field mensuration. It has proven to provide accurate estimates of a range of metrics (e.g. height, DBH, stem volume) across a range of coniferous species (Næsset, 1997; Lim *et al*., 2003; Kaartinen *et al*., 2012) and is becoming cheaper and more widely available with time (Henning & Radtke, 2006; Tanhuanpää *et al*., 2013). LiDAR works by determining distance to an object by measuring properties of light reflected off it. The distance to the object or surface is calculated by measuring the time delay between the transmission of the laser and the reception of the reflected signal (Lim *et al*., 2003; Li *et al*., 2012). LiDAR pulses are able to penetrate forest canopies offering the ability to capture detailed information on both horizontal and vertical forest structure (Moorthy *et al*., 2011). Aerial platforms are most commonly used for inventory as they offer the ability to study large areas efficiently, though terrestrial based scanners are frequently used for research and small scale analysis.

2.1.1 Remote Sensing in Forestry - Aerial Laser Scanning

Aerial laser scanning (ALS) is being increasingly used for commercial forest inventories (Kaartinen *et al.*, 2012) and urban tree inventories (Saarinen *et al*., 2014). It has been the subject of extensive research over the last decade and is used for a range of applications in mensuration of forest resources such as tree height, basal area, plot characteristics, timber volume, biomass, canopy structure and species type (e.g. Næsset, 1997; 2002; 2004; Lefsky, *et al*., 1999; Li *et al*., 2012; Kankare *et al*., 2013b; Vastaranta *et al*., 2013). ALS is used almost exclusively for analysis on a large spatial scale as the costs and logistics involved render it an inefficient tool for mensuration of small study areas. In many cases ALS data is available through external sources; as of 2011 it was estimated that 30% of the United States land area had ALS coverage of some form and some provinces in Canada are gradually analysing more of their land area (White *et al*., 2013). In some Scandinavian countries, ALS is becoming the preferred tool for monitoring national forest inventories (Kaartinen *et al.*, 2012) and several other European countries are in the process of acquiring nation-wide ALS coverage (White *et al*., 2013).

The weight of the equipment required in ALS means it is operated from small aircraft, flying at altitudes between 400 m (e.g. Vastaranta *et al*., 2012) and 700 m (e.g. Næsset, 2002); the swath width, or footprint of the laser scan depends on the flying altitude. Both small-footprint (e.g. Næsset, 1997; 2002) and large-footprint (e.g. Lefsky *et al*., 1999) have been used, and 50% overlap between swaths is targeted in order to ensure total coverage of the study area. ALS systems can generally be categorised as either discrete or full waveform. Full waveform laser scanners are the most commonly used ALS system (Wulder *et al*., 2008) and are capable of penetrating several layers of forest canopy, providing estimates of vertical vegetation distribution and forest structure as well as ground elevation (Dassot *et al*., 2011; White *et al*., 2013). ALS data is used to produce 3D point cloud models based on all features intercepted by laser pulses. From this, information on tree dimension and forest structure can be extracted using the various proprietary software programmes that are available for post-processing of ALS data. This process is mostly automated and the refinement of algorithms has been on going over the last decade. The point clouds can be geo-referenced, allowing the creation of digital elevation, surface and canopy models.

Though ALS has proven itself to be a highly accurate method of forest mensuration, it isn't without its limitations. As laser pulses are transmitted from above, ALS can directly measure tree height, but relies on allometric relationships and statistical inference for other metrics required for inventory calculations (e.g. DBH, basal area). It is the major uncertainty around the predicted metrics that leads to inaccuracies when extrapolated to plot-scale volume measurement (Vastaranta *et al*., 2012). ALS is a very expensive tool and while its cost has reduced over time, the high cost presents a major obstacle to application. Though it has proven to be cost-effective and cheaper than traditional field mensuration for commercial forest plantations where the area of analysis often spans thousands of hectares, (Holopainen & Talvitie, 2006; Kaartinen *et al.*, 2012; Jakubowski *et al*., 2013) it is usually totally unaffordable for small-scale analysis or non-commercial purposes. When applied over large areas it generally costs $0.05-0.2 per ha, though typical commercial ALS often costs a minimum of $20,000 per flight, regardless of study area size (Dandois & Ellis, 2013). Javernick *et al*. (2014) was quoted $28,000 for an ALS survey covering 1.6 x 0.65 km^2, with $26,000 for repeated surveys. Such high cost means ALS datasets are typically acquired at low temporal frequency (Eitel *et al*., 2013). Generally higher laser pulse density is sought for forestry applications due to the higher precision that can be achieved, though this results in an increase in cost (Baltsavias, 1999). The cost is ultimately determined by the duration that the aircraft is in flight (Jakubowski *et al*., 2013).

2.1.2 Remote Sensing in Forestry - Terrestrial Laser Scanning

Terrestrial laser scanning (TLS) or ground-based scanning has been used in many previous studies to measure such forest metrics as tree height and stem diameter (Watt & Donoghue, 2005; Henning & Radtke, 2006; Maas *et al*., 2008; Vastaranta *et al*., 2009; Eitel *et al*., 2013; Liang *et al*., 2014a), tree location (Liang *et al*., 2012), stem count density, timber volume (Hopkinson *et al*., 2004), leaf area index (Strahler *et al*., 2008), crown volume (Moorthy *et al*., 2011) and biomass (Kankare *et al*., 2013b; Yu *et al*., 2013; Skowronski *et al*., 2014). As they are ground-based, TLS systems are good at capturing vertical vegetation structure and distribution (Moorthy *et al*., 2011) and are capable of directly measuring tree metrics to millimetre accuracy (van Leeuwen & Nieuwenhuis, 2010; James & Robson, 2012) rather than relying on allometric relationships to derive metrics like ALS. Being positioned on the ground means TLS is more suitable for applications involving only a small sample area (a few tens of metres, Holopainen *et al*., 2013) and where small detail changes over time are of interest (Hopkinson *et al.*, 2004; Kankare *et al*., 2013b). It also means they are closer to the target objects, resulting in higher point cloud densities. In a sense TLS fills the niche between ALS and traditional dendrometry (Maas *et al*., 2008; Dassot *et al*., 2011).

TLS systems are typically mounted on some form of tripod with a pan and tilt rotator on top. The scanning range of a midrange TLS system is 800 m (Kankare *et al*., 2013a) though for most applications the required range is less than 100 m. Algorithms are typically used to autonomously identify trees in the LiDAR point cloud in the various post-processing software that are available. Mobile laser scanning (MLS) is an adaptation of TLS which involves a laser scanner operating from a moving vehicle or some other form of mobile platform (Lin *et al*., 2010; Holopainen *et al*., 2013). In many ways it faces the same issues as TLS, with the only real advantage of MLS over TLS being that due to being mounted on a vehicle it is very mobile, though it is limited to places with vehicle access.

Estimation of tree heights has not been as successful as stem diameter, especially compared with ALS data (van Leeuwen & Nieuwenhuis, 2010), mainly due to occlusion from the canopy. In some studies canopy occlusion has meant an accuracy of only 3-5 m could be achieved (e.g. Maas *et al*., 2008). However, some studies have still reported relatively high accuracy of <2 m or <10% (e.g. Hopkinson *et al*., 2004; Eitel *et al*., 2013; Kankare *et al*., 2013b).

Retrieval of stem diameter and DBH values has been particularly successful (e.g. Kankare *et al*., 2013; Liang *et al*., 2014a) though generally only in the lower stems where occlusion from branches is not an issue, (Henning & Radtke, 2006; Maas *et al*., 2008). The DBH accuracies achieved have typically been 1-2 cm (e.g. Hopkinson *et al*., 2004) though some of the more recent studies have produced accuracies to within >1 cm (e.g. Liang *et al*., 2014a).

There have been fewer studies utilising TLS to measure tree volume than linear metrics, and those that have mainly focused on stem volume. Remaining branch volume and total tree volume have also been estimated. The results have been mixed, with some studies producing estimates containing <10% error (e.g. Hopkinson *et al*., 2004), while others have been much less accurate with error >15% (e.g. Kankare *et al*., 2013). Remaining branches have not been estimated by many studies but the few that have produced quite inaccurate results (e.g. Dassot *et al*., 2012; Kankare *et al*., 2013).

Examples of the accuracy achieved in previous TLS studies for height, DBH and volume can be seen in Tables 2.1, 2.2 and 2.3). Not all studies report full statistics so they are only included where provided.

Table 2.1: Examples of the accuracies of height estimates achieved in previous TLS studies.

	Hopkinson *et al*. (2004)	Maas *et al*. (2008)	Moorthy *et al*. (2011)	Eitel *et al*. (2013)	Kankare *et al*. (2013b)
RMSE (%)	7	-	-	-	8.1
RMSE (m)	1.5	4.6	0.21	0.01-0.1	1.5
R^2	-	-	-	0.98-1.0	-

Table 2.2: Examples of the accuracies of DBH estimates achieved in previous TLS studies**.**

	Hopkinson *et al*. (2004)	Strahler *et al*. (2008)	Eitel *et al*. (2013)	Kankare *et al*. (2013b)	Liang *et al*. (2014)
RMSE (%)	-	-	-	7.1	4.2
RMSE (cm)	1	-	2.2	1.5	0.8
R^2	-	0.34-0.66	0.99	-	-

Table 2.3: Accuracy of tree volume estimates achieved in previous TLS studies (all values are RMSE %).

	Hopkinson *et al*. (2004)	Dassot *et al*. (2012)	Kankare *et al*. (2013b)	Yu *et al*. (2013)	Liang *et al*. (2014a)
Stem volume	7	<10	15.3	-	-
Remaining branch volume	-	10-30	23.4-31.1	-	-
Total volume	7	-	16.7	-	9.5
Above ground biomass	-	-	11.9-12.9	12.5	-

While TLS provides advantages to ALS, there are still disadvantages that may render it unsuitable for certain applications or users. Occlusion of trees is a significant issue; in forests with high tree density the usefulness of TLS decreases due to occlusion, especially in the upper canopy (Watt & Donoghue, 2005; van Leeuwen & Nieuwenhuis, 2010). Laser pulses cannot penetrate beyond the trees that are immediately in front of them and leaves and undergrowth can limit the field of view, preventing distant trees from being identified (Maas *et al*., 2008). Occlusion resulted in Moskal and Zheng (2012) reporting a capture rate of only 18% of the total tree volume for the plot. Strahler *et al*. (2008) only managed to find 40% of the total trees that were manually identified in their study; of these, 33% were either partly or fully occluded. For plot-scale analysis multiple scans from different positions may be required to help overcome occlusion of individual trees (Moskal & Zheng, 2012; Kankare *et al*., 2013b). TLS may even be better suited for analysis of individual trees (Watt & Donoghue, 2005) as their short and limited working range reduces their practicality for large-scale inventory analysis (van Leeuwen & Nieuwenhuis, 2010).

Forest mensuration using TLS is subject to the same accessibility issues as traditional dendrometry, perhaps even more so as bulkier equipment is required. It is expensive, labour-intensive and time consuming to conduct repeated surveys (Moskal & Zheng, 2012) and the equipment required can be heavy, with some TLS systems being as heavy as 13 kg (e.g. Maas *et al*., 2008, Moorthy *et al*., 2008, Kankare *et al*., 2013b and Liang *et al*., 2014a) and some even weighing upwards of 20 kg (Dassot *et al*., 2011). There are lightweight (<5 kg) models available (e.g. Eitel *et al*., 2013) though a tripod, pan-tilt unit, battery or generator and field computer are also necessary items in the field.

TLS systems are costly; entry-level systems can cost tens of thousands of dollars (Eitel *et al*., 2013; Liang e*t al*., 2014a) and high-end systems can be upwards of $500,000. Less advanced rangefinder TLS systems such as that used by Parker *et al*. (2004) can cost up to $8000 and even the laser system assembled by Eitel *et al*. (2013) using 'off-the-shelf' components cost nearly $12,000. Though 2D LiDAR sensors can offer a cheaper alternative to 3D sensors the cost is also relatively high (Rosell *et al*., 2009). Some expertise is necessary to operate them and the time required for data acquisition as well as post-processing should also be considered. The high resolution scans can run for up to two hours and the amount of data obtained is enormous (West, 2009).

2.2 Optical Dendrometry and Photogrammetry

Though laser scanning is the leading tool for mensuration of forestry resources and tree metrics in modern times, remote sensing in the field had far more modest beginnings. Optical dendrometry refers to mensuration of tree height and stem diameter made with sight which does not require any contact with the tree (Clark *et al*., 2000b). Optical dendrometry includes hand-held instruments like optical callipers, rangefinder dendrometers, relascopes, clinometers and cameras, all of which have been shown to provide accurate measurements of diameter (Parker, 1997). These instruments were developed to fill the niche afforded by their ability to remotely capture information from parts of the tree that could not be physically accessed, e.g. the upper stems of tall trees. Development of new instruments is on-going (Liang *et al*., 2014b) and laser relascopes, hypsometers and digital callipers are among the most recent. These instruments still rely on manual retrieval and some are limited in what parts of the tree they can measure (i.e. stem diameter or height). Traditionally, hand-held or ground-based cameras have not been commonly used for tree mensuration but digital cameras may hold the most potential as field instruments because as well as being able to capture information quickly, they are also able to store it indefinitely, meaning data can be extracted and used in the future.

Photogrammetry is the science of obtaining measurements of objects and surfaces from photographic images. When the scale of an image is known, distance measurements can be made between two points on a plane parallel to that of the image; this is the simplest example of a two-dimensional calculation, though 2D photogrammetric measurements are relatively straight forward compared with 3D measurements made with multiple images. A basic example in two overlapping images, the 3D location relative to the camera can be calculated for a set of given pixels that appear in both images (Bemis *et al*., 2014). Photogrammetry is useful for situations where physical measurements are difficult or impossible to obtain, due to their inaccessibility or the fact that the object of interest doesn't exist anymore (but photos of it remain). It is also useful for material that can be 'easily transformed', e.g. water and loose sediment (Agisoft LLC, 2012).

One of the first to use a hand-held camera as a form of dendrometry was Marsh (1952), who took photos of tree diameters and reported errors of 63.5 mm and 20.3 mm for horizontal and oblique photos respectively. The results from this study were improved by Ashley and Roger (1969) who designed a frame that reduced problems associated with scale and orientation of the setup. This study produced errors of 7.6 mm for diameter measurements in their laboratory setting. Bradshaw (1972) was another to use a camera to measure the diameter at 26 points along a single stem, which ranged in width from 30 to 76 cm. An accuracy of 9.9 mm was reported. Crosby *et al.* (1983) used a handheld camera to photograph pine trees in order to extract diameter and height information. The study produced relatively accurate estimates of tree diameters, with error of <2% for trees with diameters less than 50 cm. Clark *et al.* (2000b) trialled the ability of a commercially available digital camera to collect the heights and diameters of trees and from these measurements, estimate their subsequent stem volumes. In this study the camera proved itself to be a promising instrument in assessing forest metrics, with stem volumes derived from photographs found to be within 8% of those calculated using physical measurement techniques.

Examples of the accuracy achieved in previous photogrammetry for height, DBH and volume can be seen in Tables 2.1, 2.2 and 2.3). Not all studies report full statistics so they are only included where provided.

Table 2.4: Examples of the accuracies achieved estimates of stem diameter, height and volume in previous photogrammetric studies.

	Ashley & Roger (1969)	Bradshaw (1972)	Crosby *et al.* (1983)	Clark *et al.* (2000b)	Dean (2003)
Stem Diameter	0.76 cm	0.99 cm	2%	4 cm	-
Height	-	-	-	-	-
Stem Volume	-	-	-	8%	10%

The use of cameras has presented challenges for those attempting to use them as a tool for dendrometry. In each of the aforementioned studies analogue cameras were used. The cost of film and the time required for its development, and issues with exposure meant it was a tool really only suited to situations where field measurements of a tree would have otherwise been difficult to obtain. The geometry of the camera setup also caused error in the measurements, with the oblique line of sight and 2D nature of the photos contributing to an underestimation of the actual stem diameter. Forests can provide difficult conditions in which to use cameras as a means of mensuration, as undergrowth and other trees can prevent a clear line of sight (Clark *et al.*, 2000b). The inability to capture an entire tree in one image or even view the very tops of trees within a forest setting also meant that cameras could not be used for tree height measurements. For single tree diameter measurements (i.e. two-dimensional) other forms of optical dendrometry are just as capable as the camera.

2.2.1 Remote Sensing in Forestry - Stereo-photogrammetry

Since the invention of the digital camera in 1975 advances in digital image technology and reduction in cost has facilitated the emergence of digital photogrammetry, based on stereo image pairs (stereo-photogrammetry), as an effective tool for 3D topographical modelling (Clark *et al.*, 2000b; Westoby *et al.*, 2012; Vastaranta *et al.*, 2013). The development of aerial digital cameras enabled easy acquisition of collections of overlapping photos and advances in computing power have allowed development of complex algorithms capable of matching large collections of images (Vastaranta *et al.*, 2013; White *et al.*, 2013). The refinement of these algorithms designed for automated extraction information from digital images has been the subject of intense research and they are being continuously developed (Baltsavias, 1999). Forestry was one of the first fields to use aerial photographs to produce 3D models of forests and canopies (Rosell *et al.*, 2009).

For 3D reconstruction of a target object, multiple overlapping 2D images from two different perspectives are required. This is termed stereoscopic viewing, and when understanding the concept it is helpful to consider the way human eyesight works. Each eye is located in a different position and therefore has a slightly different view of a given target object, meaning the brain receives a different image from each respective eye and must interpret. Triangulation between both eyes and objects in the field of view allows for the generation of depth perception. For stereo-photogrammetry, reference points are identified across a range of these images. A line of sight extends from the camera viewpoint to a reference point in each image and triangulation is used to find the intersection of the two rays so the 3D dimensional position can be determined (White *et al.*, 2013).

Stereo-photogrammetry is based on the motion parallax principle, where the apparent motion of stationary objects relative to their background between viewing positions allows for estimation of their relative distance (White *et al*., 2013), i.e. nearby objects will appear to move while far away objects will appear to remain still.

High resolution digital stereo imagery (DSI) has been used to generate digital canopy models with accuracy close to that of laser scanning (Baltsavias, 2008; Vastaranta *et al*., 2013), measure tree and forest height characteristics and has proved to be suitable for tracking tree height growth and long-term canopy dynamics (Lisein *et al*., 2013; Vastaranta *et al*., 2013). Virtually all DSI for forest mensuration has been from aerial platforms and it is probably best suited to providing height measurements as photography cannot penetrate closed-canopy forests to provide information on the ground surface or forest structure beneath (Lisein *et al*., 2013). When coupled with an ALS-derived digital terrain model, a canopy height model can be produced through subtraction of ground elevations from canopy elevations. The quality of these height measurements are determined by the quality of the DEM that is used (Vastaranta *et al*., 2013).

Once LiDAR data has been used to produce a DEM, with the assumption that the ground elevation remains consistent in a given area, monitoring of future forest structural changes can be done using only recurrent aerial photogrammetry (St-Onge *et al*., 2004). The idea has been suggested that ALS data be acquired only periodically, e.g. every 10 years, and in between DSI used to provide more regular updates (White *et al*., 2013). Satellites may provide a potential means of imagery with which to produce surface models, though at present satellite imagery is too coarse to produce DEMs of comparable resolution to low altitude platforms (Westoby *et al*., 2012; Kankare *et al*., 2013a).

The general practical requirements of DSI place restrictions on its use; these include the need for images to be as parallel as possible and contain 60% overlap with each other, as well as the need for ground-control points of known co-ordinates for geo-ferencing (James & Robson, 2012). There are a range of issues that affect the image quality of DSI. Image-matching of vegetation is challenging in the fact that the visual texture is often very repetitive and smaller trees are often occluded (Lisein *et al.,* 2013). The cost of DSI is roughly one-half to one-third that of ALS data, though it varies constantly and is highly dependent on the nature of the work being undertaken (White *et al*., 2013).

2.3 Remote Sensing in Forestry - Structure from Motion and Multi-View Stereo-photogrammetry

Advances in computer vision technology have led to the availability of a computer-based photogrammetric method called Structure-from-Motion (SfM), which when paired with Multi-View Stereo-photogrammetry (MVS) provides a semi-automated, low-cost option for generating high resolution 3D point cloud models from collections of 2D photographic images (Westoby *et al*., 2012; Javernick *et al.*, 2014).

SfM reconstruction relies on changes in the position of features known as 'keypoints', from one image to another. As each image is captured from a different spatial position, the perspective of the scene is also different and therefore is represented by a different arrangement of pixels, and therefore keypoints, in each image. Substantial overlap between successive images is necessary in order to recognise keypoints and calculate camera positions and scene geometry.

Though the mechanics are similar to traditional stereo-photogrammetry, SfM differs fundamentally in the fact that it uses robust algorithms to solve 3D camera location and orientation and scene geometry and removes the need for a network of targets to be established prior to image capture (Morgenroth & Gomez, 2014). The point cloud models have RGB colour attributes (Dandois & Ellis, 2013) and are of comparable quality to those made with laser scanning (Westoby *et al*., 2012). The term 'motion' in SfM stems from these images which are captured from different locations and when viewed in sequence create a sense of movement (Snavely *et al*., 2008).

SfM has origins in the field of computer vision in 1979 (Ullman, 1979) and its development has continued in the following decades, with advances in image-matching algorithms (Snavely *et al*., 2010). SfM-MVS is a relatively unused technology in the fields of geoscience and natural resources (Westoby *et al*., 2012) but it has been the focus of an increasing number of studies in recent year and has been used successfully in the fields of geomorphology (e.g. James & Robson, 2012; Westoby *et al*., 2012; Bemis *et al*., 2014; Gienko & Terry, 2014 and Javernick *et al*., 2014), agriculture (e.g. Bendig *et al*., 2013) and to a lesser extent, forestry (e.g. Dandois & Ellis, 2010; 2013; Liang *et al*., 2014a; 2014b; Morgenroth & Gomez, 2014) and has been able to accurately model objects and surfaces in spatial scales ranging from centimetres to kilometres (Dandois & Ellis, 2010; James & Robson, 2012; Javernick *et al*., 2014; Gomez *et al*., 2015).

The benefits of using the camera-based method of SfM-MVS as an alternative to laser scanning methods for 3D modelling are centred on the low cost and low bulk associated with the equipment required (James & Robson, 2012; Dandois & Ellis, 2013).

2.3.1 The SfM-MVS Workflow

There are several software packages for processing SfM data, some of which are freely available. Some are browser-based (e.g. Microsoft's Photosynth) while others are desktop based (e.g. Bundler Photogrammetry Package, SFM toolkit, VisualSFM and PhotoScan). Little expertise is required to use these. Image processing and camera calibration are automated and few control points are required (James & Robson, 2012).

The reconstruction of SfM-MVS point clouds involves three steps. The first step is the SfM process, in which a series of algorithms identify keypoints in a collection of overlapping digital images. Each keypoint is represented by a distinctive arrangement of pixels that are likely to be recognised in other images (James & Robson, 2012). The SfM-MVS method requires substantial overlap between photos to be successful (50%) so the more images and the more overlap between each image in a series, the more keypoints will be matched between images and the more successful 3D reconstruction will be. Higher resolution images will require more processing time due to the larger number of pixels involved though if necessary these can be downsized before they are uploaded to the software.

In PhotoScan Professional by Agisoft, this process is fully automated (Dandois & Ellis, 2013). PhotoScan uses its own proprietary algorithms, which while similar to other commonly used algorithms (e.g. scale-invariant feature transform, Lowe, 2004), are claimed to achieve more accurate image alignment. In the second step the intrinsic camera parameters (e.g. focal length and lens distortion) as well as extrinsic parameters (projection centre location and exterior orientation parameters) are identified to estimate the camera positions and orientations. These are refined later with a bundle-adjustment algorithm (Javernick *et al*., 2014). The first two steps generate a sparse point cloud model of the most prominent features in photographed object or scene (James & Robson, 2012).

The third step utilises MVS, wherein the noisy data is filtered out and pixels from all the images involved in the first two steps are used to interpolate points in the sparse point cloud. This produces a dense point cloud, which typically increases the number of reconstructed points by two or three orders of magnitude (James & Robson, 2012). Each point in the point cloud has an RGB colour based on the pixels in the input images, creating a visually realistic reconstruction of the object scene (Dandois & Ellis, 2013). This means SfM-MVS does require the parameter extraction techniques often required in laser-derived point clouds (e.g. fitting circles to the stem using a least square adjustment algorithm).

In PhotoScan Professional a dense surface ‘mesh’ can also be produced to create a ‘watertight’ model from which volume can be measured. 3D point clouds generated in PhotoScan Professional lack scale and co-ordinates; these must be assigned manually through the inclusion of at least three ground-control points of known location. The point cloud can be geo-referenced through knowledge of the co-ordinates of the photopoints (i.e. recording their locations with GNSS receiver) or inclusion of ground-control points in the imagery, which are symbols or objects placed in the study area for which exact spatial co-ordinates are known and that can be easily identified in the imagery. Geo-referenced point clouds allow various forms of surface, terrain and canopy height models to be generated.

2.3.2 Aerial SfM-MVS

The majority of SfM-MVS studies of forest resources to date have been from aerial platforms (ASfM). ASfM generally involves far-range photography from unmanned aerial vehicles (UAVs) like remote-controlled helicopters and planes, or kites and balloons (e.g. Dandois & Ellis, 2010; 2013 and Rosnell & Honkavaara, 2012) which provide a cheap alternative to aircraft and allow photos to be taken from an altitude too low for regular aircraft to fly at (<150 m, e.g. Dandois & Ellis, 2010; Lisein *et al*., 2013). They also permit greater mobility than regular aircraft and their low cost allows and makes them more attractive for small scale studies; a new UAV can cost as little as USD $4,000 (e.g. Dandois & Ellis, 2013). The only equipment required is a camera and one or more can easily be mounted to UAVs which usually have a max payload of 1-2 kg.

Harwin and Lucieer (2012) and Rosnell and Honkavaara (2012) tested the ability of SfM point clouds for extracting 3D information, though the particular techniques they used struggled with the complexity of the vegetation. Dandois and Ellis (2010; 2013) and Lisein *et al*. (2013) showcased the ability of SfM to produce DEMs and CHMs from which biomass could be estimated with good accuracy. Fritz *et al*. (2013) tested the ability of SfM to locate and reconstruct stems in small plot of mainly oak trees. The data were compared to TLS data collected from the same site, though the results show that the latter was far more accurate.

Table 2.5: Examples of the accuracies achieved estimates of height and biomass in previous ASfM studies**.**

	Dandois & Ellis (2010)	Dandois & Ellis (2013)	Lisein *et al*. (2013)
Height	-	R^2 0.63-0.84	RMSE 4.7%
Biomass	R^2 0.64	RMSE 31-36%	-

2.3.3 Terrestrial SfM-MVS

Terrestrial-SfM (TSfM) inherently involves close-range photography and the camera is usually hand-held or attached to some form of tripod or rig. As a camera is such a highly mobile instrument, many photos from multiple locations, heights and angles can be captured in a very short period of time and it is particularly suited to situations where the target object is stand-alone and enclosed. Terrestrial-SfM has been shown in other fields to produce models of stand-alone objects to a very high spatial accuracy, particularly objects that are geometrically simple in nature like buildings (Gienko & Terry, 2014).

Terrestrial-SfM offers the ability to closely study trees to a level of detail that isn't possible from the air. Close-range photography provides imagery at a resolution that allows examination of small-scale tree characteristics e.g. fine branch architecture and bark morphology, which may be of particular use in the field of ecology and horticulture.

As it is ground-based, TSfM reconstruction of tree architecture often does not face the same issue of obstruction from forest canopy as ASfM does and the mobility of the camera means that the occlusion TLS faces due to its static position is a non-issue for TSfM, as photographs can be taken from as many different locations as necessary, provided there is adequate overlap between the photos.

As of yet there has been very little forestry research using TSfM. Both Forsman *et al*. (2012) and Liang *et al*. (2014b) used TSfM at plot scale to estimate DBH and solve tree location. To date, the only study using TSfM where trees were photographed and reconstructed individually is by Morgenroth and Gomez (2014). They produced a proof of concept study wherein the heights and stem diameters of three trees were estimated. Photos were taken from all around the tree with a hand-held commercially-available digital SLR camera and PhotoScan Professional was used to produce 3D point cloud models.

Table 2.6: Examples of the accuracies achieved estimates of stem diameter and height in previous TSfM studies (all values are RMSE %).

	Forsman *et al*. (2012)	Liang *et al*. (2014b)	Morgenroth & Gomez (2014)
Stem Diameter	<10	6.6-12.1	3.7
Height	-	-	2.6

2.4 Summary

The remote sensing technologies described in the preceding sections each have their own issues associated with their methodology.

As ALS is based on aerial platforms it cannot directly measure DBH and instead must rely on allometric relationships to derive them. The cost of ALS makes it an unviable method for analysis of small spatial areas like individual trees

The static position of TLS systems has meant occlusion has been a significant issue for many studies based in densely-planted forest plots, to the point where the omission rates of trees in study plots has become a parameter in its own right (e.g. Strahler *et al*., 2008; Moskal & Zheng, 2012). TLS is also a very costly method considering the small sampling area that it is limited to.

Photogrammetric methods take advantage of the mobility and low cost of the hand-held camera, though previous studies mainly utilised analogue cameras which meant measurements of tree metrics had to be made from individual 2D images. They are also unable to utilise imagery for 3D model reconstruction like SfM-MVS can.

The accuracies achieved for 2D and 3D tree metrics across all terrestrial remote sensing technologies summarised herein ranged from being very accurate to being highly inaccurate. The RMSE for height measurements has ranged between 0.2-4.6 m and 2.6%-8.1%. Volume and biomass estimates have. Volume estimates proved more difficult with previous studies achieving stem volume RMSE from 7% – 15.3% and remaining branches volume RMSE as high as 31%. Photogrammetric and SfM-MVS have proven to be particularly accurate, with accuracies <1 cm achieved for stem diameter and RMSE 2.6% for height. These previous studies provide a benchmark for the research conducted in this thesis and will inform the interpretation of the results presented in Chapters Three and Four.

2.5 Research Questions

The gaps in research identified in the literature review highlight the need for research into the ability of SfM-MVS for estimation of 3D tree metrics across a range of species and sizes as well as the need to develop more robust methodologies.

These will be addressed in this thesis by answering three research questions: 1) can SfM-MVS be used to accurately estimate 2D (linear) and 3D (volumetric) tree metrics; 2) can SfM-MVS be used to accurately estimate tree 2D metrics across a range of tree species and sizes, and; 3) how few images are required to reconstruct an SfM-MVS model of sufficient quality to obtain 2D metrics.

Chapter Three

SfM-MVS Estimation of Tree Metrics

3.1 Introduction

Xylometry (water displacement) is known as the most accurate method of volume mensuration (Loetsch *et al*., 1973). Xylometry utilises Archimedes' Principle which involves the specific gravity of water and states that the buoyant force exerted by an object fully immersed in water is equal to the weight of the water it displaces. As 1 L of water is almost exactly 1 kg, the volume of the object (in litres) can be measured by recording the increase in weight that occurs from immersing it in water. The latter is one of the common variations of xylometry, which also includes measuring the level of water displacement through immersion of a study object and measuring the increase in weight (Özçelik *et al*., 2008). With the appropriate setup volume can be measured to millilitre resolution.

Few studies have examined the suitability of Structure-from-Motion and Multi-View Stereo-photogrammetry (SfM-MVS) for forestry purposes and those that have mainly focused on linear metrics. Morgenroth and Gomez (2014) were able to measure linear metrics (DBH, height, crown spread) of three trees using SfM-MVS. Likewise, Liang *et al*. (2014b) focused on linear metrics (DBH) and location of the tree stems within a small plot, but neither attempted to obtain any volumetric information. To the author's knowledge the only study with a volumetric element is by Dandois and Ellis (2013), who used ASfM to estimate biomass of several plots, however, they used allometric formulae from field-measured data to validate the SfM biomass estimates.

Whilst the results showed biomass estimates correlated closely with field data, there is little point validating them with data gathered using a method known to be error-prone (i.e. estimation with allometric formulae) and as of yet there remains no research evaluating SfM-MVS volume estimation against true volume data obtained with destructive sampling. The techniques and instruments used in traditional field mensuration of standard tree metrics are very capable of producing accurate measurements and any errors that may be present in these measurements are certainly an issue. Nevertheless, it is the allometric relationships assumed in the formulae that make use of these field-measured metrics for making volumetric estimations that are the fundamental issue, due to their often unrealistic assumptions of stem form and these are further exaggerated by error in the linear measurements.

3.1.1 Research Aim

The nursery tree component of this research aimed to test the ability of SfM-MVS to reconstruct spatially-accurate 3D models of individual trees from which volume and standard linear tree metrics could be estimated. The volume estimates made by SfM-MVS were validated using destructive sampling with xylometry in a laboratory setting and all linear estimates were validated with ground truth data. This research very much follows on from the proof of concept paper offered by Morgenroth and Gomez (2014).

3.2 Method

3.2.1 Overall Approach

This component of the study was based around collecting a series of images of individual trees with which to produce 3D models using the commercially available software package PhotoScan Professional (v 1.0.4, Agisoft LLC, St. Petersburg, Russia). Traditional field mensuration techniques were used to collect ground truth data immediately following photography, in order to validate the model estimates. Thirty small potted trees were included in the nursery study. The study was fortunate to be given thirty young trees by the Christchurch City Council from their urban tree planting inventory; these were fundamental to the study as their relatively small size (<5 m tall) and simple branch architecture allowed linear ground-truth measurements to be made using traditional mensuration to a high degree of accuracy. It also gave the ability to relocate and destructively sample them with ease, meaning absolute volume measures could be obtained using xylometry; this was only possible due to their small size.

The trees were individually planted in 25 L or 50 L plastic pots, so they were able to be easily relocated by hand to a wide gravel lot at the nursery for photography. The trees included 12 large-leaved linden (*Tilia platyphylos*), 10 field maple (*Acer campstre*), five walnut (*Juglans regia*) and three red maple (*Acer rubrum*), all of which are deciduous broadleaf species (Fig. 3.1). The trees were not preferentially selected for their species; they were simply those made available by the Christchurch City Council.

3.2.2 Study Area

Research was mainly based at Christchurch City Council's Harewood Nursery in northwest Christchurch, New Zealand (43°28'04"S, 172°35'17"E), where photography of the nursery trees took place in an open gravel lot. Photography began in late autumn (May, 2014) by which time the trees had lost all their leaves and continued to through to winter (July, 2014). Photographing the trees with no leaves was important so that leaves did not obstruct the view of any branches and allow SfM-MVS the best possible chance of measuring volume. Following image acquisition, traditional dendrometry techniques were used to collect ground truth data. Trees were then transported to the New Zealand School of Forestry at the University of Canterbury where volumetric measurements were undertaken.

Figure 3.1: Examples of some of the trees used in the nursery tree study. The open gravel lot allowed continuous series of images to be taken without occlusion. The coloured box that was used as a scaling device can be seen beside the trees.

3.2.3 Image Acquisition

Images were captured with an un-calibrated, hand-held, commercially-available digital SLR camera (Nikon D5000, lens: AF-S NIKKOR 35 mm). Initial trials were conducted to determine the best photography technique that could be applied to all trees in the study. The final technique for the study was based on that used by Morgenroth and Gomez (2014), wherein images of the tree were captured from photopoints at regular intervals along several concentric circular paths around the perimeter of each tree, with the tree being at the centre of each circle.

Model reconstruction works best for stand-alone enclosed objects when images are captured with converging optical axes, aiming toward the centre of the object (Gienko & Terry, 2014). The image-matching algorithms in PhotoScan are sensitive to the number of images and overlap between each image, so photos were taken in such a way that a minimum of 50% overlap (but normally 90%) existed between any sequential pair; this was achieved by moving only one or two steps (0.5-1 m) sideways between each photopoint in the inner circles and five steps (5 m) between each photopoint in the outer circle, resulting in 70 – 90 photos for each circle (150-180 photos in total). The inner circle aimed to capture fine detail in the tree structure and stem surface. The outer circle captured background elements so the software could better estimate camera location and orientation. No distance was prescribed from which to take photos from; the inner circle photos were taken from a distance where the whole tree could fit within the camera frame and be captured in one photo (usually 4-5 m away), which meant the size and shape of the tree determined the distance back and therefore the size of the circle around the tree. Outer circle photos were taken from distance where the tree took up about half of the image frame. The shape of each circle was approximate rather than exact.

Positioning the potted trees in the middle of the gravel lot at Harewood Nursery meant a continuous unobstructed series of photos could be taken from every perspective around the tree and background noise could be reduced. Photographs were, saved in medium quality (4288 x 2848 pixel resolution) JPEG format and automatic focusing and exposure were enabled. An overcast sky provided the best conditions for photography as it meant there was no preferential light source to produce shadows which could potentially darken parts of the tree and reduce detail in its branch architecture. On sunny days photography was endeavoured to be undertaken during the middle of the day to avoid encountering the sun at a low angle.

3.2.4 Ground Truth Mensuration

Immediately following photography, ground truth data was collected using traditional mensuration techniques. The small size of the nursery trees meant accurate measurements could easily be obtained. Red tape was used to mark the measurement locations so they could be easily identified in the photos and models (Fig. 3.2). The following metrics were measured for each tree;

- *Tree height***:** measured by laying the tree its side on the ground and measuring from the base of the trunk to highest point of the main stem with a measuring tape.

- *Stem diameter:* measured with vernier callipers at several points along the main stem. Starting from the highest point of the main stem, red tape was wrapped around the stem at 50 cm intervals down to the base, resulting in 5 to 6 measurement points depending on the height of the tree. At each of these points diameter was measured. These were labelled 'Stem-Diameter' 1-6, with Stem Diameter 1 being the highest point on the main stem. In addition to these, diameter at breast height (DBH- standard New Zealand measurement of 1.4 m above ground) was measured. Two perpendicular measurements were made and the average between the two recorded. Diameter was measured to 0.5 mm accuracy.

- *Crown diameter:* two roughly perpendicular transects were selected through the crown. Each was selected to be as horizontal as possible. The selected transects did not necessarily include the widest points of the crown. Labelled red tape was used to mark the branches at the end of each axis and straight-line distance between each point was measured. This tape was visible in the images such that comparisons could be made accurately.

- *Crown depth:* The distance from the ground to the base of the first major branch was measured and this value was subtracted from the tree height to derive crown depth.

Figure 3.2: Red tape was used to mark the measurement locations for the linear metrics. The extremities of the remaining branches were often very thin (1-2 mm diameter).

3.2.5 Model Reconstruction in PhotoScan

Models were made on a University of Canterbury computer (64-bit and equipped with 2.8GHz Intel Core i7-4770 processor and 16 GB RAM). The workflow for the model production was done in accordance with the Agisoft tutorial. The first step was to upload the photos into the software. This was done in groups of sequential photos termed 'chunks' - each circular path of photos was uploaded as an individual chunk. The second step was image alignment (referred to alignment of 'cameras' in PhotoScan) wherein the position and orientation from which each image was taken was calculated to produce a sparse point cloud. The point cloud optimisation settings were left as the default values (camera = 10 pixels, marker accuracy = 0.001 m, marker placement = 0.1 pixels), alignment accuracy was set to 'high' and pair pre-selection set to 'generic'. Camera calibration data is automatically extracted from the EXIF data of the images.

For alignment to work correctly, the images in each chunk had to be arranged in chronological order. This allowed the software to utilise the overlap between sequential photos and recognise keypoints across multiple images. Once all the chunks had been individually aligned, they were aligned with each other and then merged into a single chunk, to produce one sparse point cloud model.

Sometimes due to the background noise in the image being too visually similar to the tree, the software could not consistently differentiate the tree from the background and therefore automatic alignment of images did not work correctly. The software also struggled to align photos when the primary background lacked texture or keypoints (e.g. clear blue sky) from which to detect movement between photopoints. These situations required some manual processing work to correctly align the images; this was done with point markers and image masking. Point markers act as tie points so the exact location of a specific feature in a photo, e.g. a particular branch or a knot in the tree trunk, can be manually selected in each photo. For best results they must be manually placed in each image they appear in. Several markers were sometimes required to properly align all the photos. Masking involves manually plotting a line around the relevant parts of the image to filter out the noise and irrelevant elements in each image. When aligning images, the software ignores everything within the masked area.

A helpful feature in PhotoScan is that the locations of the estimated camera positions are displayed in the point cloud space, allowing an easy visually assessment of whether alignment has worked correctly (Fig. 3.4). Once each individual chunk had been properly aligned, they were aligned with each other and merged to make a single chunk and sparse point cloud model. The point cloud was cropped to include only the relevant elements. Following the development of the sparse point clouds, the dense point cloud models were generated, each of which typically contains several million points (Fig. 3.3). Depth filtering was set to 'mild' as this is best suited for surfaces with numerous small details. Each dense point cloud model took 5-6 hours to develop at 'high' quality setting.

Figure 3.3: The four stages of model generation: top left) the original photo; top right) the sparse point cloud model following SfM photo alignment; bottom left) the dense point cloud following MVS; bottom right) mesh model. Each point in the model represents a pixel in the original photo. Dense cloud models contain several million points.

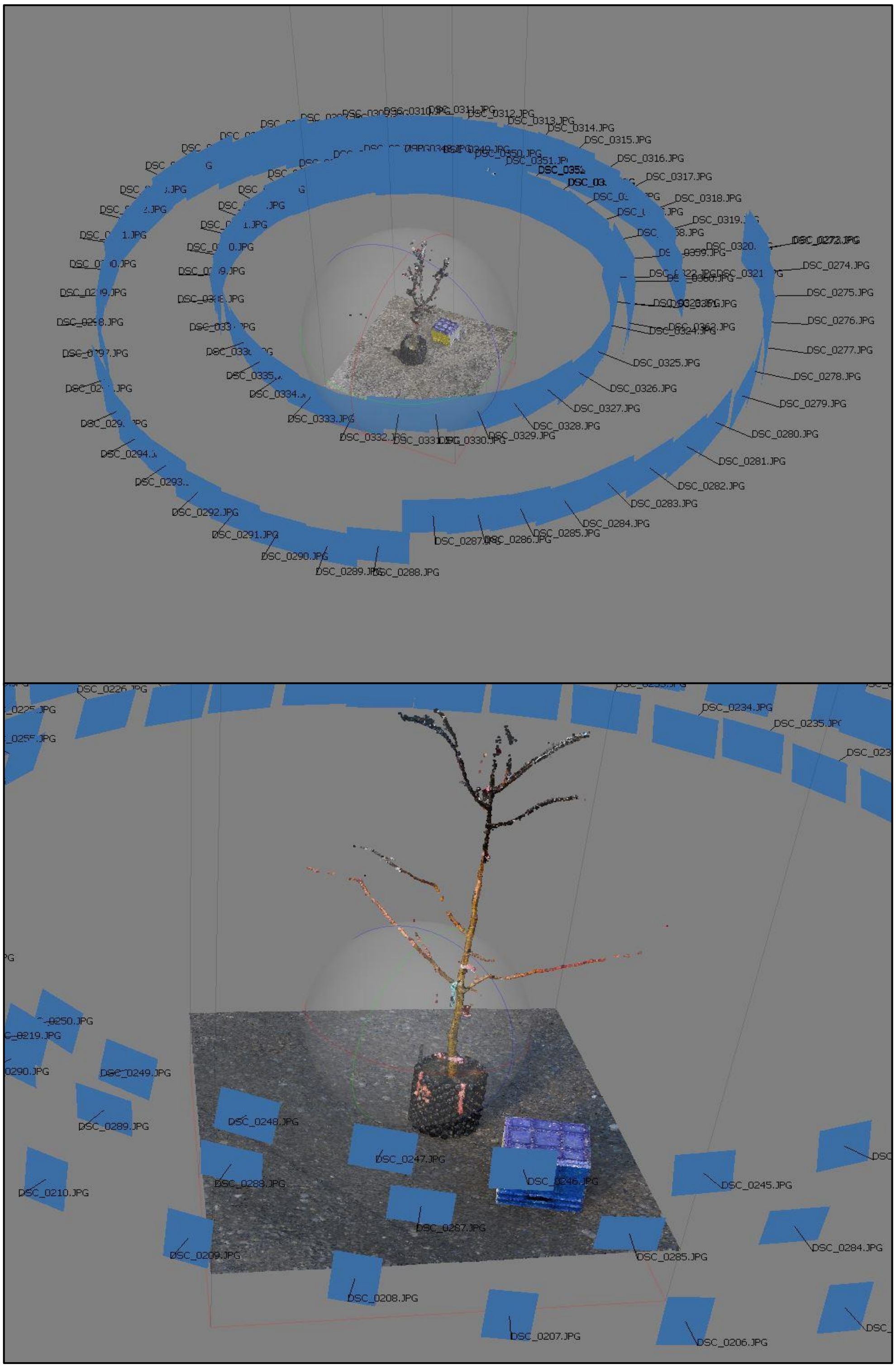

Figure 3.4: The blue squares indicate the location of the cameras. The distribution of these squares in PhotoScan allows quick determination of whether or not the images are aligned. The arrangement of the squares shows the circular paths taken for photography.

3.2.6 Model Spatial Scale

Models in PhotoScan do not have any spatial scale or geographic position. These had to be assigned to them manually through calibration with an object of known size in each model. A cube-shaped plastic box (35.5 x 32 x 29 cm) was positioned on the ground next to each tree as it was being photographed (which can be seen in Fig. 3.1) which allowed easy application of an arbitrary co-ordinate system to the model in order to give it a spatial scale for measurements to be made. In the model, point markers were placed on each corner of the cube and each was assigned an X-Y-Z co-ordinate in the ground control section, based on its physical dimensions. The position of each point marker was adjusted to minimise the spatial error of each of their respective model-space co-ordinates (which are shown in the ground control section). Each of the cube's five visible faces was painted a different colour to help with camera positioning during the alignment process.

The portability and simple geometric shape of the box meant it provided a very easy tool with which to provide a scale to the models. Ground truth data were entered into their corresponding scale bars and compared to the distance that the scale bar estimated – which was displayed as an error value in metres between actual and estimated distance.

3.2.7 Linear Measurement in PhotoScan

To make linear measurements in the model, point markers were placed on the locations of the model where the red tape was visible and 'scale bars' were created between appropriate point markers to measure the distance between them (Fig. 3.5). For the stem diameter measurements, two perpendicular transects were measured through the stem and average of the two recorded. Crown spread was divided into two sections; true crown spread (TCS) and visible crown spread (VCS). TCS was measured from the red tape, which represented the true extremities of the selected branches. VCS was necessary because sometimes the entire length of the selected branches leading to the red tape were not modelled. This was due to an insufficient number of points in the dense point cloud, which was a consequence of branch slenderness. VCS measured crown spread from the ends of the branches where the model ended, i.e. from the ends of the visible branches. If neither the tape nor any branches were captured then no data was recorded, though this did not occur often.

3.2.8 Volume Measurement of Nursery Trees

Using xylometry in the field for commercial forestry is simply not feasible due to the impracticalities involved, namely the huge amount of time, equipment and labour it would require. Large trees would have to be felled and cut into small sections in order to be immersed in tanks – which are not portable anyway. It is also not really necessary except for research where exactness is important. Volume does not exactly correspond to mass either, the latter being dependent on the density of the wood and the tree must be divided into different material components to produce a biomass estimate. Laboratory environments offer the most accurate way to measure tree volume, as equipment can be arranged in a manner that assures precision. However, laboratory analysis is only a realistic option if the space is available and if the tree can be transported there from the field. Small trees can be measured in a laboratory environment with relative ease compared to large mature trees.

Figure 3.5: Scale bars can be created between two point markers to measure the linear distance between them. In the above example, the scale bars are measuring height and crown spread.

The volumes of the 30 nursery trees were measured following the generation of the mesh surface models. The volumes of the nursery trees were determined using xylometry. The trees were transported to the School of Forestry workshop at the University of Canterbury and chopped into smaller sections (10-20 cm) with secateurs; this ensured that no woody biomass was lost, as would occur if a saw had been used. The resulting tree sections were secured in bundles with plastic cable ties (Fig. 3.6). The main stem and remaining branches of each tree were bundled separately so they could be measured separately. The bundles were left immersed in water for 24 hours in order to saturate them and eliminate the possibility of water absorption during the volume measurement which could potentially reduce the volume output. A 20 L plastic tub was filled with water and placed on a set of scales that provided accuracy to 0.01 g (Fig. 3.6). Each bundle was immersed in the tub and held just below the water surface with metal rods, and the increase in weight recorded. The tare weight was reset to zero between each measurement to account for water lost through removing the bundle. The volume of the cable ties and immersed sections of the metal rods were also accounted for. A wooden block of known volume was also measured to calibrate the method.

Figure 3.6: To measure their volume, each of the nursery trees were cut into smaller sections and held in bundles (left). These were then immersed in a water tank positioned on a set of scales (right) to measure the change in weight and thus their volume.

3.2.9 Volume Measurement in PhotoScan

The volume of each nursery tree model was measured in PhotoScan Professional. Before the volume could be measured, a 'watertight' polygonal 'mesh' surface had to be generated, which was based on the dense cloud points (Fig. 3.7). Interpolation was set to 'disabled' for this step. In parts of the tree where the stem or branches were only partly captured in the dense cloud model, the subsequent mesh generation created planes of mesh across the points, rather than an enclosed cylindrical shape, leaving many holes and gaps. These gaps and holes needed to be closed with the 'close holes' tool in PhotoScan in order to produce a 'watertight' model for which volume could be measured. However, this tool sometimes incorrectly linked branches together, creating a mesh plane that spanned the space between branches. To eliminate this problem, each individual branch was segmented and measured on its own and the sum of all branches calculated at the end. The irrelevant elements in each model were removed (i.e. the pot and ground surface around it). As well as total volume, the tree was subdivided into main stem and remaining branches and the volume for each was measured separately. Volume was recorded to 0.001 L (1 ml) resolution.

Figure 3.7: A mesh surface model must first be generated in PhotoScan before the volume of the model can be calculated.

3.2.10 Statistical Analysis

All data was analysed in R Studio statistical package, v. 0.98.1028 (R Studio Inc., 2013). Basic statistics were calculated for each tree metric (mean, maximum, minimum and SD). The accuracy of tree metrics were evaluated using root mean square error (RMSE) and bias, as defined in equations (1) and (2);

Equation (1)

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}}$$

Equation (2)

$$\text{Bias} = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)}{n}$$

Where n is the number of estimates, y_i is the value estimated by SfM-MVS and $\hat{y}_i$ is the ground truth value.

A linear regression analysis was also conducted between the measured values and model-estimated values to obtain R^2 values for each of the tree metrics. This was to provide additional statistics to align and allow a more direct comparison with previous literature. In order to ensure that linear regression models were appropriate for each of the datasets each of the models were appraised to check they met the critical assumptions. These include homoscedasticity of the variance and normality of the error distribution. All datasets met these assumptions which indicated that linear models were appropriate.

3.3 Results

The SfM-MVS values estimated for each metric were evaluated against the corresponding ground truth values and the RMSE and bias were calculated. Development of SfM-MVS nursery tree models was successful, with all 30 tree models having sufficiently high point cloud densities to visualise the tree and allow the 2D and 3D metrics to be easily measured. Each dense point cloud model was comprised of several million points (including the pot). Examples of the point cloud models at different stages of development were presented in Fig. 3.3.

3.3.1 Volume

The mean, standard deviation, maximum and minimum values for the ground truth and SfM-MVS-estimated data are presented in Table 3.1 and the RMSE and bias statistics are presented in Table 3.2. Volume estimates were able to be made for all 30 tree models. As well as measuring the total volume, each tree was divided into two sub-sections for volume measurement: 1) the main stem and 2) the remaining branches. The stem volume of each tree was estimated far more accurately than the remaining branch volumes; stem volumes was estimated with an RMSE of 0.174 L (12.3%) and bias of -0.115 L (-8.2%). The ground truth stem volume values correlated strongly with the SfM-MVS estimated values, with an adjusted R^2 value of 0.969 (Fig. 3.8). Remaining branch volume estimation had an RMSE of 0.195 L (47.5%) and bias of -0.139 L (-33.8%). The linear relationship for the remaining branches was not so strong, with an adjusted R^2 value of 0.77 (Fig. 3.8). The strong bias present, particularly for the remaining branches shows a tendency for SfM-MVS to significantly underestimate volume. Total volume was estimated with an RMSE of 0.195 L (10.7%) and bias of -0.254 L (-14%).The main stem accounted for 78% of the total tree volumes on average, which reduced the influence remaining branch volume estimation had on total volume. Estimated values for total volume correlated strongly with true values, with an adjusted R^2 value of 0.953 (Fig. 3.8).

Table 3.1 A comparison of descriptive statistics for tree volume in litres (L) determined via SfM-MVS and ground truth techniques.

Ground Truth Data (L)	Mean	SD	Max	Min
Stem Volume	1.409	0.730	3.234	0.550
Remaining Branches Volume	0.411	0.286	1.217	0.094
Total Volume	1.819	0.964	3.734	0.740
Modelled Data (L)				
Stem Volume	1.293	0.746	3.240	0.437
Remaining Branches Volume	0.272	0.224	1.006	0.052
Total Volume	1.565	0.909	3.506	0.640

Table 3.2 The relative and absolute RMSE and bias statistics for SfM-MVS volume estimates.

	n	Bias (L)	Bias (%)	RMSE (L)	RMSE (%)
Stem Volume	30	-0.115	-8.2	0.174	12.3
Remaining Branches Volume	30	-0.139	-33.8	0.195	47.5
Total Volume	30	-0.254	-13.9	0.328	18.1

3.3.2 Height and Crown

The mean, standard deviation, maximum and minimum for the ground truth and SfM-MVS-estimated data are presented in Table 3.3 and the RMSE and bias statistics are presented in Table 3.4. Point cloud densities were sufficient to enable the heights of all 30 trees to be estimated. Height was estimated with an RMSE of 7.8 cm (2.6%) and a bias of -6.1 cm (2.1%). The negative bias shows that SfM-MVS had a tendency to slightly overestimate tree heights. The linear regression results indicate that SfM-MVS estimated tree height accurately, with a very strong linear relationship present between the measured and estimated height values that is almost close to unity (R^2=0.988, Fig. 3.9). Crown depth was estimated with a high level of accuracy, with RMSE of 6.5 cm (2.4%) and bias of -5.4 cm (-1.9%). Regression analysis of crown depth estimates show they were correlated strongly with true values, with an R^2 value of 0.986 (Fig. 3.9).

Point cloud densities were sufficiently high to enable visible crown spread measurements at 54 of 60 model measurement locations and true crown spread measurements at 56 of 60 model measurement locations. Sparseness or complete absence of points prevented measurements being made at the remainder of measurement locations. TCS was estimated with RMSE 23.3 cm (20.4%) and bias of -10.3 cm (-9%). TCS was estimated with an RMSE of 16.6 cm (14.8%) and bias of -3.9 cm (-3.5%). Both VCS and TCS had positive bias, indicating that SfM-MVS had a tendency to underestimate them. VCS and TCS were both correlated reasonably well with ground truth values, with respective R^2 values of 0.874 and 0.782 (Fig. 3.10).

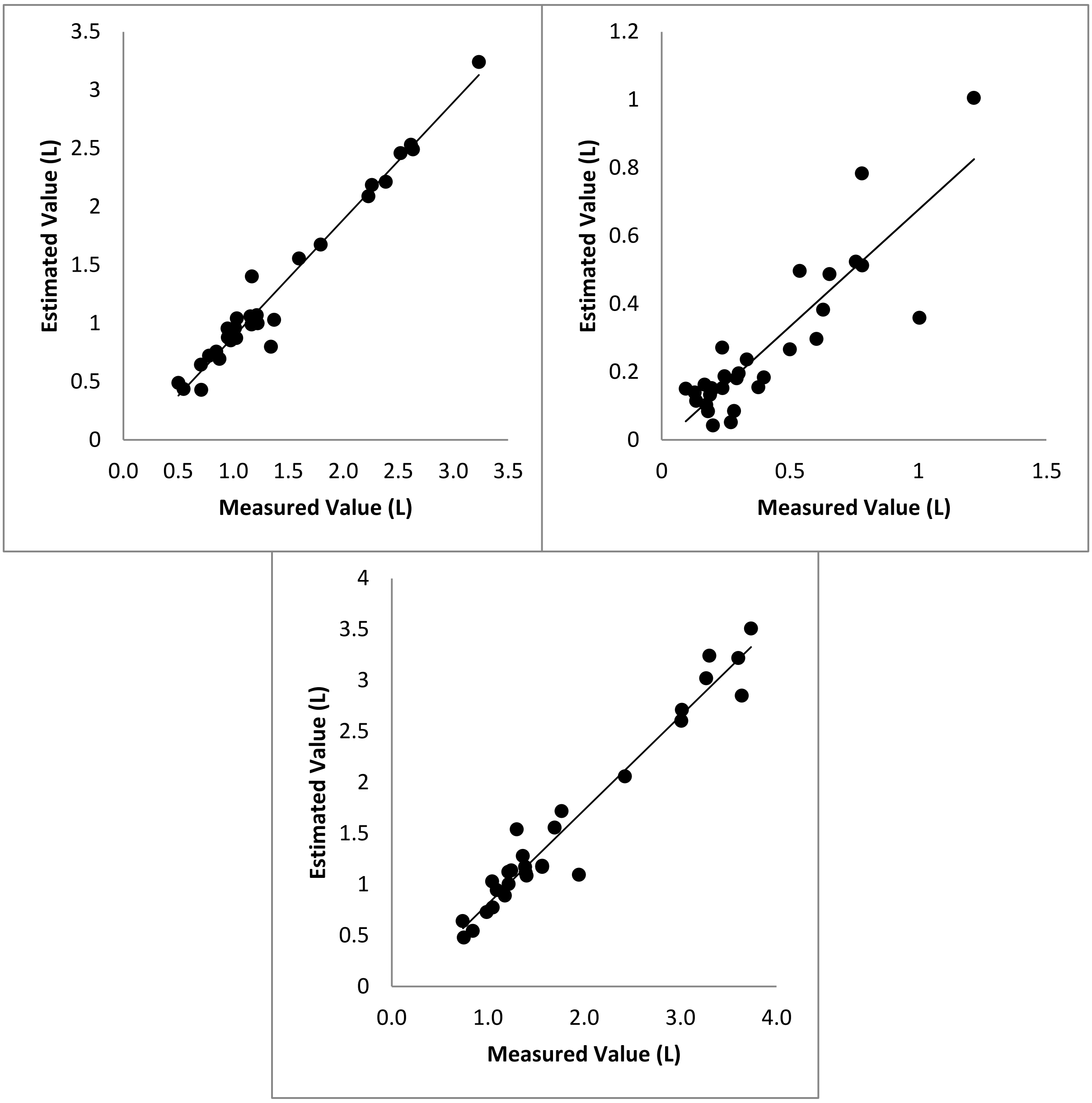

Figure 3.8: Regression analysis of SfM-MVS estimates of stem volume (top left, R^2=0.969), remaining branch volume (top right, adjusted R^2=0.77) and total volume (bottom, adjusted R^2=0.953) against ground truth values.

Table 3.3 A comparison of descriptive statistics for tree height and crown spread in metres (m) determined via SfM-MVS and ground truth techniques.

Ground Truth Data (m)	Mean	SD	Max	Min
Height	2.98	0.716	4.53	1.64
Crown Depth	2.30	0.571	3.24	1.28
Visible Crown Spread	1.12	0.450	3.06	0.58
True Crown Spread	1.14	0.446	3.06	0.52
Modelled Data (m)				
Height	3.04	0.731	4.61	1.70
Crown Depth	2.36	0.580	3.28	1.30
Visible Crown Spread	1.09	0.454	2.91	0.47
True Crown Spread	1.04	0.442	2.91	0.45

Table 3.4 The relative and absolute RMSE and bias statistics for SfM-MVS height and crown estimates.

	n	Bias (cm)	Bias (%)	RMSE (cm)	RMSE (%)
Height	30	6.1	2.1	7.8	2.6
Crown Depth	30	5.4	1.9	6.5	2.4
Visible Crown Spread	54	-10.7	-9.4	23.7	20.7
True Crown Spread	56	-3.9	- 3.5	16.6	14.8

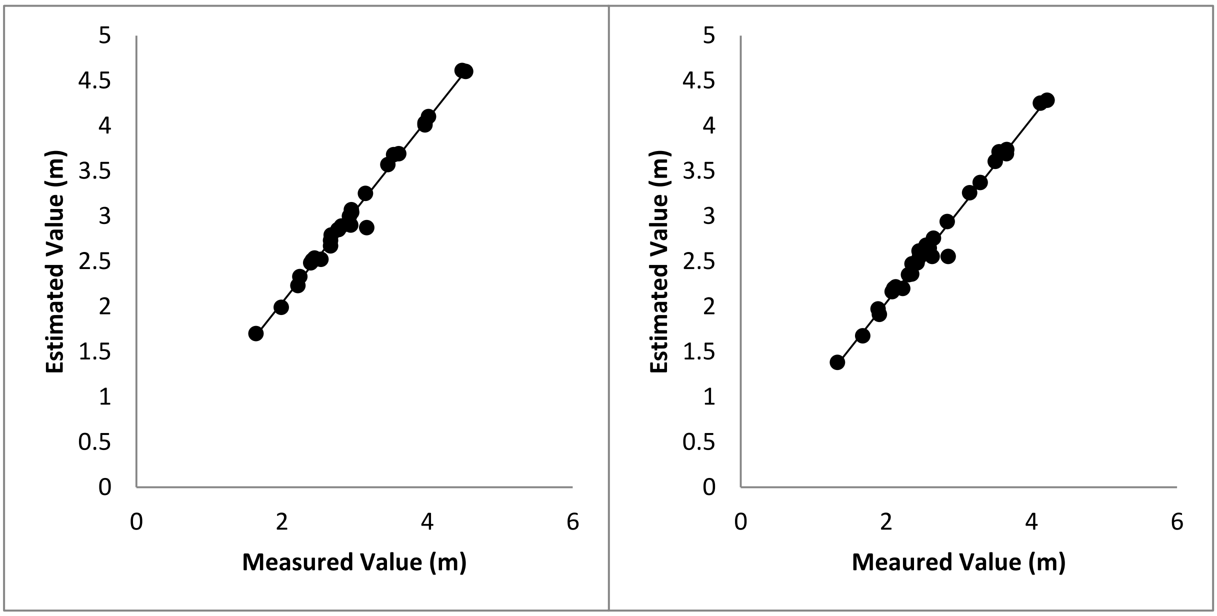

Figure 3.9: Regression analysis of SfM-MVS estimates of height (left, adjusted R^2=0.988) and crown depth (right, adjusted R^2=0.986) against ground truth values.

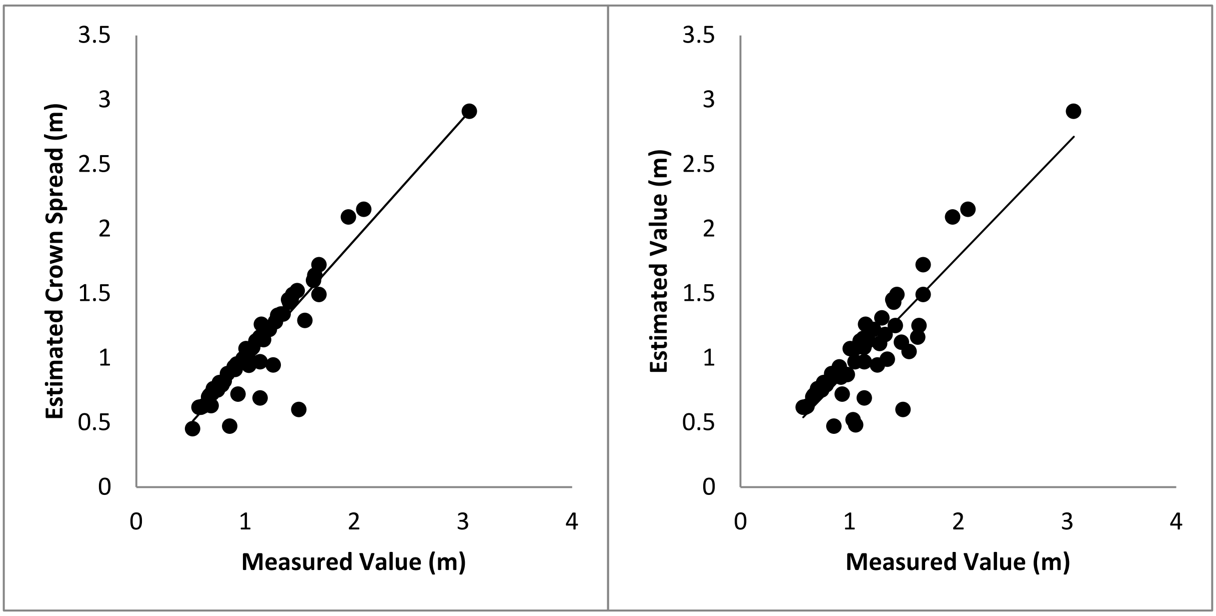

Figure 3.10: Regression analysis of SfM-MVS estimates of visible crown spread (left, adjusted R^2=0.874) and true crown spread (right, adjusted R^2=0.782) against ground truth values.

3.3.3 Stem Diameter

The mean, standard deviation, maximum and minimum values of stem diameters for the ground truth and SfM-MVS-estimated data are presented in Table 3.5 and the RMSE and bias statistics are presented in Table 3.6. The trees were reconstructed well enough for diameter estimates to be made at 166 of the 169 model measurement locations. The means for both the true stem diameters and the SfM-MVS modelled width were 17 mm. The combined stem diameters were estimated with RMSE of 1.9 mm (10.6%) and bias of 0.2 mm (1.2%). They correlated strongly with ground truth values (adjusted R^2=0.976, Fig. 3.11). The bias indicates stem diameters were slightly overestimated by SfM-MVS. The residual plot for the regression model (Fig. 3.12) shows that the absolute error remains reasonably consistent throughout the range of stem widths, meaning there does not appear to be a link between the slenderness of the stem and the ability of SfM-MVS to model it. However, in relative terms the greatest relative error is associated with the most slender parts of the stem (<5 mm) and decreases with increasing stem width. DBH was estimated to similar accuracy, with RMSE of 1.9 mm (10%) and bias of 4.3 mm (0.8%). The positive bias shows that SfM-MVS had a slight tendency to overestimate DBH. SfM-MVS estimates of DBH correlated quite strongly with ground truth values (adjusted R^2=0.905, Fig. 3.11).

Table 3.5 A comparison of descriptive statistics for stem diameters in metres (m) determined via SfM-MVS and ground truth techniques.

Ground Truth Data (mm)	Mean	SD	Max	Min
DBH	19	4.5	28	5
Combined Stem Diameters	17	12	48.5	1
Modelled Data (mm)				
DBH	18	5.5	29	5
Combined Stem Diameters	17	11.5	46	1.5

Table 3.6 The relative and absolute RMSE and bias statistics for SfM-MVS stem diameter estimates.

	n	Bias (mm)	Bias (%)	RMSE (mm)	RMSE (%)
DBH	30	-4.3	-0.8	1.9	9.9
Combined Stem Diameters	166	-0.2	-1.2	1.9	10.5

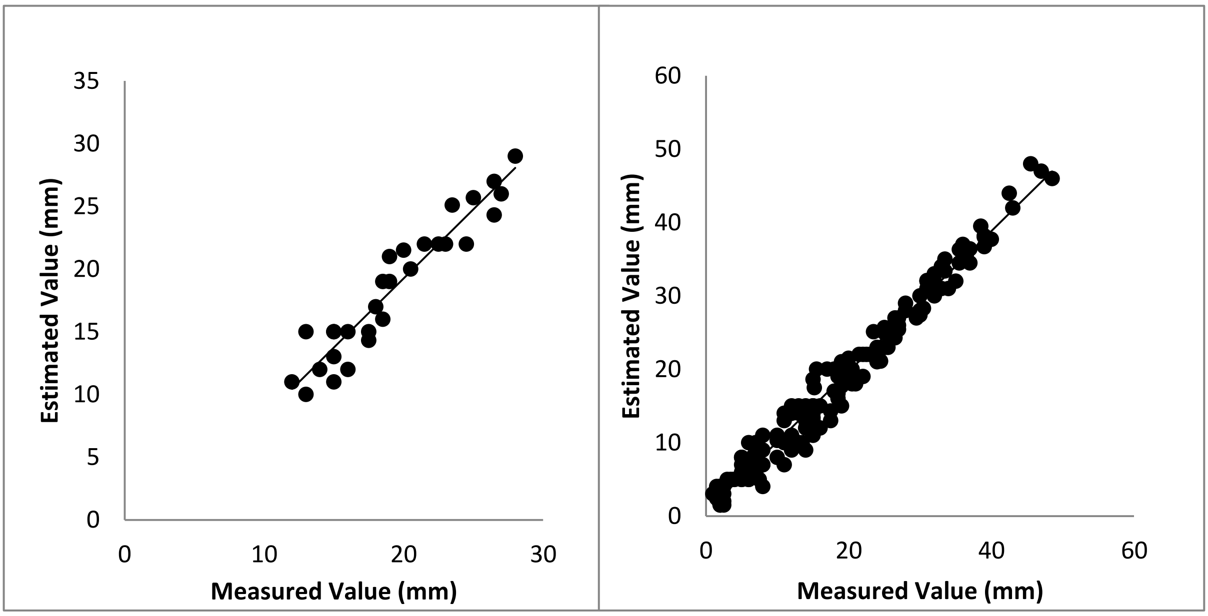

Figure 3.11: Regression analysis of SfM-MVS estimates of DBH (R^2=0.905, left) and combined stem diameters (R^2=0.976, right) against ground truth values**.**

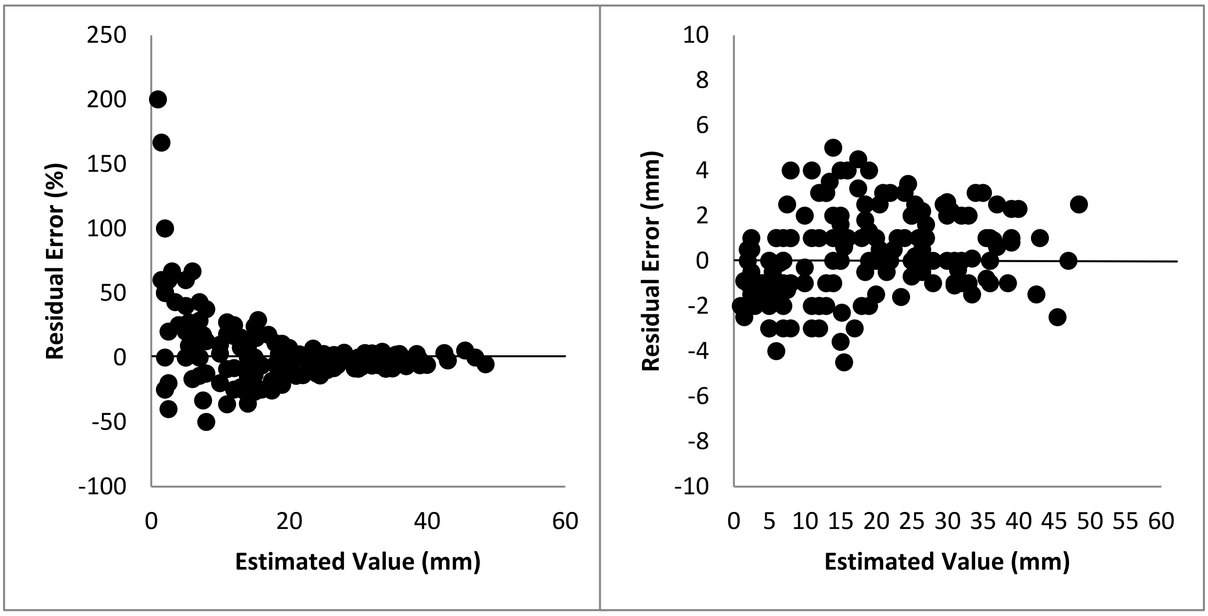

Figure 3.12: Residual plots for SfM-MVS estimates of combined stem diameter. Relative error is shown on the left, while absolute error is shown on the right**.**

3.4 Discussion

Linear (2D) and volumetric (3D) tree metrics are important for many forestry applications. Traditional dendrometry involves laborious field work which can be error-prone and time-consuming (Kankare *et al.*, 2013b). Remote sensing methods (e.g. LiDAR) have been employed and provide automated solutions, though logistical and economic considerations mean these are not always appropriate. Advances in computer vision coupled with digital camera technology has given rise to SfM-MVS, a relatively recent form of digital photogrammetry which offers the ability to reconstruct 3D models using collections of 2D digital imagery alone.

Due to the modernity of SfM-MVS very little research has been conducted in regard to its suitability as a tool for dendrometry. Thus the nursery tree component of this study tested the ability of SfM-MVS to produce spatially-accurate 3D models of trees in PhotoScan Professional (Agisoft LLC, 2012) from which 2D and 3D metrics could be estimated. Volumetric (main stem, remaining branches and total) and linear measurements (height, DBH, crown spread, crown depth) were made on each model and evaluated against ground truth data. The emphasis was on the volumetric estimates, as the ability to destructively sample the study trees allowed for very accurate ground truth volume measurements to be made using xylometry, the latter being a method that is seldom able to be carried out.

The results of the study show that the SfM-MVS can produce excellent quality reconstructions of trees which can be used to estimate most volume and linear tree metrics to a high degree of accuracy with little error or bias. Remaining branch volume and crown spread were estimated with a large amount of error though. The error present in the results does not appear to be a function of the size of the measurement being made, nor neither volume nor linear estimates.

3.4.1 SfM-MVS Volume Estimation

Stem volume and biomass of standing trees cannot be directly measured in the field and instead easily-measured linear metrics are used to allometrically estimate them. Generally volumetric information is sought for commercial forestry rather than ecological purposes (where biomass is a more useful parameter) due to the value of the resource involved (i.e. merchantable stem wood) and thus the vast majority of research has focused on large scale analysis with particular focus on stem wood. SfM-MVS models have the potential to be a useful tool in forestry for measuring 3D metrics such as stem volume and biomass. To the author's knowledge as of yet no terrestrial studies have tested the accuracy of SfM-MVS for volume mensuration, particularly for individual trees.

The results show that SfM-MVS was able to produce models with reasonable spatial accuracy, from which volumetric estimates could be derived. Each volume metric was underestimated. Stem volume was estimated reasonably accurately (RMSE 12.3% and bias -8.2%) and was strongly correlated with ground truth data (Adjusted R^2=0.97). Estimation of the volume of remaining branches was highly inaccurate with a large amount of error present and a strong tendency for underestimation (RMSE 47.5% and bias -33.7%) SfM-MVS estimates only had a moderate correlation with ground truth data (Adjusted R^2 0.77). Total volume was estimated moderately well (RMSE of 18.1%, bias of 13.9% and an Adjusted, R^2 of 0.95). The young trees displayed apical dominance and held the majority of their mass in their stems (78% on average). This meant overall accuracy of each tree volume was largely determined by the accuracy of the stem volume and the remaining branches did not have a large influence on total volume. The causal mechanism for poor estimation of volume, particularly for remaining branches is likely to be due to the nature of the image acquisition in the method including factors such as: 1) the image resolution being too low or conversely the images being taken from too far away from the tree to properly capture the smaller branches; 2) insufficient overlap between sequential images preventing recognition of reference features and subsequent alignment in PhotoScan; 3) shadowing on the tree surface leading to absence of points and failure to properly enclose 3D mesh surface

3.4.2 SfM-MVS Volume Estimation – Results in the context of previous research

With so little existing research on utilising SfM-MVS for tree mensuration it is difficult to directly compare the results with those found in other studies. Therefore it is appropriate to instead describe how SfM-MVS performs in relation to the other manual and remote sensing ground-based methods or methods that represent a form of photogrammetry.

3.4.2.1 Results in the context of previous research - Allometric Stem Taper Models

In the interest of practicality and cost, stem volumes in commercial forestry are based on allometric stem taper models that take into account only a few easily-measured linear tree metrics. These are ultimately designed to describe stem diameter and taper as a function of height. Many taper models of varying complexity have been suggested in previous research and given the value of timber in commercial forestry there is a large body of research looking at the applicability of these models to volume estimation of well-known tree species in different growing regions (Fraver *et al*., 2007). As xylometry is known to provide the most accurate measure of volume, it has been used by the likes of Filho *et al*. (2000) and Özçelik *et al*. (2008) to validate estimates made with some of these commonly used formulae.

Using Smalian's formula Filho *et al*. (2000) produced error of 11% for stem logs 6 m in length and concluded that the latter, as well as Huber's formula were the best performers of those tested and can be confidently applied to stems of varying species, age and growing regions up to 6 m in length. However, they did note that error increased with diameter size of the stem and when the diameter at the top of the stem was large. These findings are somewhat contradicted by Özçelik *et al*. (2008), who concluded that Smalian's and Huber's formulae produce error that are unacceptable for stem volume estimation of Cilician fir and Brutian pine, with biases of up to 20% reported. Smalian's formula was shown to overestimate stem wood volume for a 6 metre length by up to 16%. Fraver *et al*. (2007) also recommended that Smalian's formula be avoided, after they found bias of 12% in measuring the volumes of Norway spruce, Scots Pine and downy birch trees. Smalian's formula they recommended against its use unless the stem can be divided into sections – the latter method is obviously not possible with standing trees. Wiant *et al*. (2002) reported the centroid formula as being the most accurate with minimal error (<6%) for the 11 tree species tested. They also reported error as high as 30% for some of the other taper models.

Comparison with the existing body of literature shows that the accuracy of SfM-MVS sits roughly in line with some allometric formulae but performs much better than some. The results of each study highlight the respective strengths of the different formulae with respect to the particular tree species or stem length to which they are most suited. What also must be considered is that the dimensions of the stems were measured following felling, which means they are probably not truly reflective of their likely performance in the field on standing trees, which are far more challenging to measure. While some of formulae tested may have provided relatively accurate volume estimates, part of the existing challenge is obtaining measurements from parts of the tree that are not physically accessible (e.g. upper stem diameter) as these metrics are thought to be the largest contributor to volume error (Wiant *et al*., 2002; Berger *et al*., 2014)

The major advantage SfM-MVS has over stem taper models is that it is species-independent, as it allows individual trees to be completely analysed in the PhotoScan image space and eliminates the risk of applying inappropriate taper models and the assumption that the tree fits a pre-determined shape based on its species or growing location. This is critical as stem forms within the same species have been shown to vary greatly even at plot scale; both Rojo *et al*. (2005) and Li and Weiskittel (2010) reported that the error in these formulae can vary substantially over geographic regions due to the differences in growing conditions. The development of taper models for all species in different growing regions is totally impractical and it at least some error is unavoidable

3.4.2.2 Results in the context of previous research - Terrestrial Photogrammetry

Remote sensing methods have been utilised to fill this niche, due to the ability of certain instruments to provide information on physically inaccessible parts of the tree. Terrestrial photogrammetry Clark *et al*. (2000) used a commercially-available digital camera to individually estimate the heights, stem diameters and stem volume of red oak trees before validating the results with destructive sampling. The diameters obtained through the captured imagery were used in Smalian's formula. Dean (2003) used photography and commercial digitising software packages for automated volume calculation. Stem volume were underestimated by an average of only 0.5%, though the deficit resulting from non-circular cross-sections of the buttresses were known for the study trees and for trees where this deficit is unknown, stem volumes could be overestimated by as much as 10%. This is one of few studies where branch volume has been estimated as well as the stem; the former being underestimated by an average of 4%. The results of these studies sit in line with the results produced by SfM-MVS, both in terms of overall accuracy and the tendency for underestimation.

3.4.2.4 Results in the context of previous research - Terrestrial Laser Scanning

With so little existing research using terrestrial photogrammetry or SfM-MVS for stem volume estimation, TLS offers perhaps the most relevant method for comparison as it is the only other ground-based method with which 3D models can be produced. Some examples of these are displayed in Table 2.3

Numerous studies have used TLS to estimate volume and biomass, though few of these have utilised destructive sampling to validate TLS output. Hopkinson *et al*. (2004) were among the first use TLS for volume estimation. The volumes of trees in two forest plots were analysed. Error of 7% was reported in both total tree and merchantable stem volume estimations though this was calculated through comparison to allometric estimations. Dassot *et al*. (2012) managed to estimate stem volume to within 10% trees consisting of eight different species and different size classes (ranging from 15-94 cm DBH) and evaluated the output with destructive sampling. Like this study, the accuracy of remaining branch volume was low, with almost half the trees being estimated between ±10-30% of the manual volume estimation. Despite the large amount of error present these estimates were considered to be excellent. Kankare *et al*. (2013b) used TLS to estimate the stem volume and total volume of individual Scots pine and Norway spruce, before felling them to measure validate TLS estimation with laboratory measurement. Stem volume was estimated with RMSE 15.3% (bias 0.7%) while the whole tree volume was estimate with RMSE 16.7% (bias -2.7%). The results produced by Dassot *et al*. (2012) and Kankare *et al*. (2013b) were both considered to be highly accurate. Kankare *et al*. (2013b) also reported poor estimation of the biomass of the remaining living and dead branches, with the respective RMSEs for living and dead branches of pine trees being 23.4% and 31.1%. Liang *et al*. (2014a) used destructive sampling to measure the stem curve and volume of pine and spruce trees. TLS was able to achieve some of the most accurate TLS results so far, with an RMSE of 9.5% and bias of -5.9%.

These results show that SfM-MVS performs well relative to other commonly used methods, both remote sensing and manual. The RMSE of 12.3% achieved for stem volume using SfM-MVS is slightly less accurate than what was achieved in most other studies using photogrammetry or TLS, though it appears to be a more accurate method than digital stereo imaging (DSI) and a far more reliable method than allometric taper models, which vary greatly between the stem forms of different species. The findings of previous studies for volume estimation are relatively consistent with the results in this study and show similarities with a tendency for overall underestimation and poor accuracy in estimation of remaining branch volume.

3.4.3 SfM-MVS Linear Estimation

Linear tree metrics form the basis of allometric volume and biomass equations used in traditional dendrometry and are therefore essential to forest inventory. Error can easily occur in traditional dendrometry, especially when measuring aspects of the tree higher off the ground (Elzinga *et al*., 2005; Liang *et al*., 2014a). As the key linear metrics of height and DBH are relied upon for allometric stem taper models, small error in their measurement can have large consequences for volume estimation. Much research has examined the ability of TLS and photogrammetry to accurately retrieve linear metrics of standing trees, the most common of which are height and DBH, however, like volume, estimation of linear tree metrics has barely been touched with SfM-MVS; the only studies being those by Morgenroth and Gomez (2014) and Liang *et al*. (2014b).

3.4.4 SfM-MVS Linear Estimation – Results in the Context of Previous Research

The results show that higher accuracy was achieved in estimations of linear metrics than in estimations of volume. The most accurate of these were the height (RMSE 2.6% and bias 2.1%) and crown depth (RMSE 2.4% and bias 1.9%), both of which correlated very well with ground truth data, with respective adjusted R^2 values of 0.996 and 0.998.

3.4.4.1 Results in the Context of Previous Research - Height and Crown

In the only other SfM-MVS study to date (to the author's knowledge) that estimates tree height, Morgenroth and Gomez (2014) reported an error of <10 cm (3%) for their three study trees. Retrieval of tree heights using TLS has been relatively successful, with many studies producing accuracies within 2 m (<10%) of the true height, though very few have produced as little error as the RMSE 2.6% in this study. The positive bias (2.1%) is somewhat of an anomaly as the majority of height estimations in previous literature have seen a negative bias, with occlusion of tree tops in study plots being an issue. Table 2.1 (Chapter Two) provides examples of the height accuracy achieved with TLS in previous literature. Eitel *et al*. (2013) produced some of the most accurate results of all TLS studies to date with conifer height estimates reported to correlate perfectly with true values (R^2=1) and an RMSE of <1 cm. The latter are among the most accurate estimated by TLS. The accepted limit for lidar height estimation in forest literature is $R^2 \geq 0.8$ (Dandois & Ellis, 2013). Hopkinson *et al*. (2004) underestimated the heights of red pine and sugar maple by roughly 7% which was due to occlusion of the top tips of trees. Likewise, Maas *et al*. (2008) reported an underestimation of 0.64 m for the heights of plots dominated by spruce trees. Moorthy *et al*. (2011) was able to estimate the height of ∼4 m high olive trees to within RMSE 0.21 m while Kankare *et al*. (2013b) reported an accuracy of 8% for estimating the heights of Scots pine and Norway spruce.

Crown spread was not estimated so well, with visible crown spread (VCS) being estimated with RMSE 20.7% and bias -10.7%. TCS was estimated with higher error than expected (RMSE 14.8%) because in several cases the red tape did not register in the point cloud model, meaning the spread has to be measured from the furthest visible point on the branch it was attached to (as the VCS was measured). Where the red tape was present, there was virtually no error in the estimated spread. For comparison, using TLS Moorthy *et al*. (2011) reported strong correlations between TLS crown estimates and ground truth data with R^2 values of 0.97 and 0.96. Fernandez-Saria *et al*. (2013) reported a mean TLS crown estimate of 8.33 m compared with the ground truth mean of 7.91, a difference of 5%. Both of the latter two studies used trees in-leaf.

3.4.4.2 Results in the Context of Previous Research - DBH

DBH was estimated with RMSE of 1.9 mm (9.9%) and a bias of -0.8%. The model estimates correlated strongly with true values with an adjusted R^2 value of 0.91. The combined stem diameters were also underestimated and were slightly less accurate than DBH, with an RMSE of 1.9 mm (10.5%) and bias of -1.2%. These results are comparable with other research using SfM-MVS as well as other forms of remote sensing.

What is significant about the combined stem diameter results is that the residual error in the estimates is not influenced by the length of the measurement and the size of the tree has no bearing on the error in the model. Figure 3.12 shows how the absolute error remains consistent throughout the range of stem widths. In relative terms the error was far greater in the most slender parts of the stem (1-2 mm), with the RMSE of 1.9 mm corresponding to the estimated value being up to 100% different to the measured value. For comparison, the same 1.9 mm error in thicker parts of the stem (e.g. >20 mm) has a corresponding error of <10%.

Using terrestrial SfM-MVS Morgenroth and Gomez (2014) measured the stem diameters of three individual trees. The models were reported to be spatially accurate and the 32 stem diameters measured were reported to have an R^2 value of 0.92 for a variation of only 1.7 mm, very similar to the 1.9 mm found this study. Like this study, the thinner branches were not represented well in the models. Also using SfM-MVS, Liang *et al*. (2014b) achieved DBH accuracy of RMSE 2.4-4.5 cm (6.6-12.1%) with respective biases of -1.7-5.4% in their study plots. This study utilised a method wherein photos were taken from the perimeter of the plot, rather than around the circumference of each individual tree. The results of previous SfM-MVS studies of linear tree metrics are summarised in Table 2.6.

DBH is probably the most commonly estimated metric in previous TLS research due to the ease with which it can be validated with ground-truth data. Its position close to the ground means visibility is generally not an issue, with occlusion usually coming from the stems of other surrounding trees and understory vegetation. This means it is typically the best-estimated of all tree metrics, and TLS accuracy has been improving over time. Table 2.2 (Chapter Two) provides examples of the DBH accuracy achieved with TLS in previous literature. Hopkinson *et al*. (2004) and Henning and Radtke (2006) both reported DBH estimates within ±10 mm of the true value while Maas *et al*. (2008) achieved a precision of 18 mm. Strahler *et al*. (2008) estimated DBH with moderate success (R^2=0.66) though this decreased with distance from the scanner, to R^2=0.335 at

20-30 m. Eitel *et al*. (2013) bettered this by achieving an R^2 value of 0.99 and RMSE of 22 mm. Both Kankare *et al*. (2013b) and Olofsson *et al*. (2014) reported a DBH accuracy of RMSE 7.1% and a tendency for slight underestimation with respective biases of -3.4% and -1.8%. for Scots pine trees though error in estimation of deciduous trees (including outliers) was far greater at 75 mm (34.1%) which included a large overestimation (bias 11.5%). Liang *et al*. (2014a) reported DBH estimation of Scots pines with RMSE of 8 mm (4.2%) and a bias of 6 mm.

3.4.5 Interpretation of SfM-MVS Estimations

The results of this study have shown that SfM-MVS can be used to estimate stem volume, height and DBH to a level of accuracy that is at least equal to other methods currently used. However, reconstruction of slender branches and parts of the stem were not very successful and aforementioned precautions will need to be taken in the method to ensure that images acquired are suitable for facilitating adequate model reconstruction. This is particularly relevant when measures of crown spread are to be derived.

3.4.5.1 Visualisation of Tree Models

As a digital photogrammetry technique, SfM-MVS differs fundamentally from allometric taper models in the fact that it is computer-based, allowing the entire tree model to be visualised in PhotoScan. This is the main point of difference for any method utilising image-based point cloud reconstruction and using SfM-MVS effectively removes the need for error-prone allometric stem taper models that are currently relied upon for volume and biomass estimation. The RGB attributes of point cloud points make it very easy to identify different components of the model (i.e. leaves, branches, irrelevant noise), far easier than laser scanning point clouds (Fig. 3.12).

One of the issues faced by allometric formulae is the difficulty in obtaining stem dimensions from inaccessible parts of the tree that are high off the ground using traditional dendrometry. Measurement of upper stem diameter has been shown to be important for accurate volume estimation of tall standing trees (Wiant *et al*., 2002; Berger *et al*., 2014) and only remote sensing instruments are capable of providing this. SfM-MVS removes the need for any field measurements to be taken whatsoever, as through the inclusion of an object of known size in imagery (e.g. a ruler) to apply spatial scale to the model, the entire tree can be visualised and analysed. The dimensions of any part of the reconstructed tree can be selected, segmented and individually analysed.

Provided it is captured in the imagery, the linear distance can be calculated between any two points present in the model allowing diameter measurements to be taken anywhere along the visible height of the stem. This is a massive advantage to applications requiring volume or biomass not just of the stem, but of other parts of the tree that are virtually impossible to estimate with high accuracy using traditional dendrometry. It also allows abnormalities or unrecognised variations in stem shape to be considered that would otherwise be neglected. Volume is a measure of space whereas biomass is a measure of weight. Obviously only volume can be estimated in PhotoScan, so if biomass is required then the volume will need to be converted.

Figure 3.12: SfM-MVS models in PhotoScan can be reconstructed to extremely high quality, to provide life-like visualisation of trees**.**

3.4.5.2 Volume vs. Linear Metric Estimates

Estimating linear tree metrics using SfM-MVS is more straight-forward than estimating volume. As discussed in the preceding sections, there are a range of external parameters that can negatively affect the quality of models. Accurate estimation of volume is very dependent on the tree being reconstructed to the best possible quality in order not to omit any part of the tree, thus reducing the volume estimate. Imagery will ideally be captured from the full 360° circumference of the tree so as not to miss any branches or irregularities in stem form that could influence the result.

By comparison, linear estimates are relatively straight-forward, as they can require only two points to be present in the point cloud, i.e. two points to place point markers on, between which a scale bar can be positioned to measure the linear distance. They are less reliant on well-formed models, and everything between the two point markers can more or less be ignored. Linear metrics do not necessarily require imagery from the entire circumference of the tree, though this may have implications on model quality (which will be discussed further in Chapter Five).

Noise can be problematic for volume estimation as any irrelevant points will influence the mesh surface generation and exaggerate the volume estimate. Noise was not so much of an issue for linear measurements as it could be ignored when placing point markers (thanks to the RBG attributes of the point cloud).

The volume measurements made for each model in PhotoScan can be with a high level of certainty as the process for doing so is very straight-forward. Therefore it can be assumed that minimal error will be associated with this part of the process. An overestimation of volume could only be caused by irrelevant elements being wrongly included as part of the tree or incorrect assignment of scale to the model. An overestimation of stem volume is arguably more consequential than an underestimation, as whether a tree is felled or not is determined by its estimated size and felling an undersized tree is as a result of an incorrect estimation will obviously kill the tree.

3.4.5.3 Application of SfM-MVS to larger trees

The small size of the study trees (mean height: 2.98 m; mean DBH: 19 mm) must be considered when comparing the results to the findings of other research and the applicability of SfM-MVS to mature trees (although applicability to larger trees will be examined in Chapter Four: Landscape Trees). Virtually all other aforementioned research focuses on mature trees (usually >10 m in height with DBH >20 cm) where the volumes concerned are in the order of cubic metres, rather than litres. The majority of these studies have been in managed forest plots where trees are often densely planted for the purpose of testing their respective methods in the actual conditions they may be applied in.

The ability to modify field settings in this study (in terms of being able to reposition the potted trees) created somewhat artificial conditions from which better models could be produced than otherwise. This did, however, allow the destructive sampling using xylometry to be carried out. Young trees were necessary for this study because their small size enabled them to be destructively sampled with relative ease. They could be quickly cut into sections and transported to the workshop for volume mensuration.

Other literature did not have this luxury, hence many faced the problem of occlusion and being able to locate the position of stems within a plot is enough of an issue for it to be the focus of several studies (e.g. Liang *et al*., 2012, Moskal & Zheng, 2012). Unfortunately this was an element that could not be helped, as finance and time constraints meant that using mature trees was beyond the scope of the study. Further testing of mature trees, especially species commonly used in commercial forestry is certainly required before SfM-MVS can be verified as a reliable method for volume estimation.

The method also aimed to find a balance between accuracy and practicality; generation of SfM-MVS models reconstruction is very computationally-intensive and the speed at which models can be produced is dependent on the processing power, memory and the type of graphic card of the computer used. Given the number of models required for this study and the computers available, it was important not to include too many images for each model as this would slow the model output to an impractical rate. The greater the number of images used per model, the greater the time required to reconstruct the model. Likewise, the quality settings were reflective of maintaining a manageable method. In practice, the SfM-MVS process will not face the same restrictions.

3.5 Conclusion

This research has shown that SfM-MVS is capable of reconstructing 3D point cloud models with high spatial accuracy. Accurate estimates of volumetric (3D) and linear (2D) metrics were able to be obtained. Volume estimates were at least as accurate as the estimates produced by other remote sensing methods in previous literature and in many cases it was significantly more accurate than allometric equations used for field estimation. The results mean that for purposes where the stem volume is of primary interest, SfM-MVS provides a sound method that can be relied upon to produce accurate results. Height and DBH were estimated with very high accuracy and crown diameter could be estimated with relatively good accuracy, though the greatest challenge faced is reconstruction of the slimmest stems and branches. The nursery trees provided a scenario where field settings could be optimised to support better model generation, i.e. the ability to relocate the trees meant occlusion was not an issue and the potential for background noise could be reduced. It is not necessarily reflective of real field settings where conditions cannot be modified. The ability to carry out destructive sampling with xylometry meant volume estimates could be evaluated against true volume data. SfM-MVS is in its infancy as a method of forest mensuration and there are certainly many ways that its capabilities could yet be tested. Its ability to produce accurate estimate of standard metrics on tall, mature trees will be addressed in Chapter Four.

Chapter Four

Constraints of the SfM-MVS Method

4.1 Introduction

With remote sensing methods, the time required for producing estimates of tree size and form can be reduced in two specific areas; 1) collection of data and; 2) data processing. This applies for the SfM-MVS method, where the duration can be reduced through collecting less data (taking fewer photos). The added benefit of using fewer images for model reconstruction is that less computational power required meaning models are generated faster. As always there is a balance between the quality of the estimates derived from the data and the effort and cost required to obtain the data. As a general rule, better quality models offer the ability to extract more information and these require more images and more time to develop, although this is only true to a point; if sufficient number of keypoints are able to be identified from an existing photoset, additional images will be of little benefit but will greatly increase the processing time. Therein lays the challenge of implementing a method that is as efficient as possible in terms of identifying the minimum amount of work required to produce a result that is of adequate accuracy for the specific application.

Traditional dendrometry is known to be time and labour intensive, not only for commercial forest inventories but also for urban forest inventories (Fernández-Sarría *et al*., 2013). Widely used forms of remote sensing like ALS and digital stereo imaging (DSI) have proved themselves to be cost-efficient in analysis over large spatial scales (Holopainen *et al*., 2013) though ground-truth mensuration of standing trees is still fundamental for reference data and for scaling up plot-size measurements to whole forests (West, 2009). Such tools are simply unaffordable and impractical for applications where the study area may be down to individual-tree scale.

Data processing can be as time-consuming as data collection. Traditional field techniques aside, current TLS scans can take two hours (West, 2009; Dassot *et al*., 2011) and if the data is inadequate the additional time required for recollection can be costly. The expertise required to operate TLS systems is also one of the limiting factors in its use (Liang *et al*., 2014b), so the time required for training must also be considered. Dassot *et al*. (2012) describe that repeated TLS surveys would require a balance to be found between data quality and scanning time.

The mobility of a hand-held camera means that it is perfectly suited to rapid acquisition of data, although it is only recent advances in computer vision image matching techniques and the development of SfM-MVS software for facilitating the extraction 3D geometry from 2D digital imagery that have made the technique useful for life sciences. The simplicity of SfM-MVS makes it such an attractive method for low budget analysis and for users with no expertise in forest mensuration or instruments. User-friendly software packages like PhotoScan Professional remove much of the technicalities and it does not require a great deal of expertise of training to use. Despite this it has been shown to reconstruct 3D models of high spatial accuracy and at a fraction of the cost of laser scanning.

4.1.1 Research Aim

The landscape tree component of this research examines some of the limitations of the SfM-MVS method. The emphasis here is on the method, with the main purpose being to find out how the number of images used for model generation affects the accuracy of the estimated metrics. The objectives are to determine; 1) the minimum number of images required to reconstruct a model that is spatially accurate; 2) how the minimum number of images compares to the accuracy of a 'full' photoset and; 3) whether tree size affects estimation accuracy. The nursery tree component of the research, reported in Chapter Three, has shown that spatially-accurate models can be generated from photosets consisting of 150-180 images. This chapter focuses on only the 2D metrics of landscape trees as there was no way to validate the volume estimated by SfM-MVS with ground truth data as we could not destructively sample trees on public land. As such only height and DBH were modelled with SfM-MVS and validated with ground-truth data.

4.2 Method

4.2.1 Overall Approach

In most respects the method for model reconstruction of landscape trees was much the same as it was for the nursery trees. The main differences were that multiple models were made for each tree and that the method of image acquisition was more regimented. In total 35 trees were modelled. Traditional field mensuration techniques were used to collect ground truth data immediately following photography, in order to validate the model estimates.

4.2.2 Study Area

The trees selected for the study were found in public parks and reserves in Christchurch and Nelson, New Zealand. The geographic co-ordinates for each tree can be found in the appendix. These trees were as isolated as possible from surrounding trees and buildings in order to allow continuous series of photos to be captured from all perspectives around the circumference of each tree. The trees targeted for the study were in-leaf though no size or species was preferred (Fig. 4.1). Photography began in late spring (Nov, 2014) and ended in summer (Dec, 2014).

Figure 4.1: Examples of some of the trees used in the landscape tree study.

4.2.3 Image Acquisition

Where possible, the photography technique for landscape trees was much the same as it was for the nursery trees although the location of the trees relative to their surroundings meant obtaining a continuous series of photos around the entire circumference of some trees was difficult in some cases. Photos were taken along a circular path around each tree, with the tree at the centre of the circle. 90 photos of each tree were taken, with photopoints being distributed as uniformly as possible around the circle. The distance from which to photograph the tree was determined by the minimum distance at which the entire tree could fit into the image frame. The radius of each circle was measured with a measuring tape to be as consistent as possible.

Stand-alone trees were sought, though nearby trees, buildings, private property or roads provided obstacles that meant complete coverage of the tree from a continuous circle wasn't possible in some cases. These obstacles obscured the view of the tree or prevented access to certain angles around the tree. The trees that were selected were so because they presented less of these difficulties and were in a location that allowed imagery to be collected from at least 75% of their circumference. The images were ensured to be convergent toward the centre of each tree as this allows better reconstruction of complex surfaces with varying face orientations (Bemis *et al.*, 2014).

The number of photos for each circle meant that significant overlap was achieved between sequential pairs of photos. Photos were captured with an un-calibrated, hand-held, commercially-available digital SLR camera (Nikon D5000 with Nikon AF-S NIKKOR 35 mm lens). The focal length of the camera was set to 18 mm (wide-angle) and automatic focusing was used. Photographs were portrait in orientation with the bottom of the image frame aligned parallel with the ground and images were saved in medium quality (4288 x 2848 pixels, 300 dpi) JPEG format. The PhotoScan user manual (Agisoft LLC, 2012) describes the optimum camera settings; these include setting the ISO to be as low as possible to prevent additional noise being captured; aperture should be set sufficiently high to obtain a high depth of field and retain sharpness of imagery while preventing blurriness.

Wind presented a challenge to photography, particularly for small trees as the smaller leaves and branches were more easily moved. To avoid the potential for difficulties in model reconstruction through too much movement, photography was not undertaken during wind strong enough to cause significant movement.

4.2.4 Ground Truth Mensuration

Immediately following photography, ground truth data was collected using traditional dendrometry techniques. The stand-alone position of the trees allowed for straight-forward mensuration of metrics as space, line-of sight and access were not issues. The following metrics were measured

- *Tree height:* Trees <7 m in height were measured with a telescopic height pole to 0.01 m accuracy, while trees >7 m in height were measured with a Vertex III hypsometer to 0.1 m accuracy. The transponder was positioned at breast height (1.4 m).

- *Stem diameter (DBH):* measured 1.4 m above the ground with a diameter tape, to 0.5 cm accuracy.

An elastic band was stretched around the tree to mark the point on the stem where the DBH was measured. Markers were positioned on the tree stem to identify the location where the measured crown axes crossed.

4.2.5 Model Reconstruction in PhotoScan

The workflow for reconstruction of landscape trees was much the same as the workflow for nursery trees, as described in Chapter Three. Each tree model contained a single chunk as only one circle of photos was used. The point cloud optimise settings were left as the default values (camera = 10 pixels, marker accuracy = 0.001 m, marker placement = 0.1 pixels), image alignment accuracy was set to 'high' and pair pre-selection set to 'generic pair pre-selection' as the images were uploaded in chronological order. Following this, the dense point cloud model was generated at 'high' quality and the mesh model was generated with 'interpolation disabled'.

In order to determine the minimum number of images that could be used, several different models were made for each tree. The number of images made available for each respective model was progressively reduced to examine how this affected the number of point cloud points and the accuracy of the estimated linear metrics. A model was generated with the complete photoset (90 images) of each tree. A sparse point cloud can only be reconstructed if the SfM step is successful and images are well aligned. Therefore, the MVS step to produce the dense point cloud was only taken if the image alignment was successful. After some initial trials to see how few photos may be required for total alignment, the starting number of images was set at 50. This was progressively reduced by five images at a time until the point where the images could no longer be aligned. The resulting photoset was termed the 'minimum photoset'. Images were thinned evenly. No point markers were placed to help with image alignment.

4.2.6 Applying Scale to the Model

The coloured box, described in Chapter Three was used for scale for most of the smaller trees (≤5 m) though for some of the larger trees it was too far away to be captured well in the imagery. Instead, telescopic surveying rulers were extended to 2 m and positioned next to the tree (Fig. 4.4). Point markers were placed on the modelled version of these and the co-ordinates for each were entered in the ground control panel in PhotoScan to apply a spatial scale to the model. To ensure that the scale remained the same throughout the models, the point markers for scale were positioned on the model made from the total photoset and these were retained as the number of images was thinned. The position of each point marker was confirmed in each of the images to retrospectively improve the image alignment.

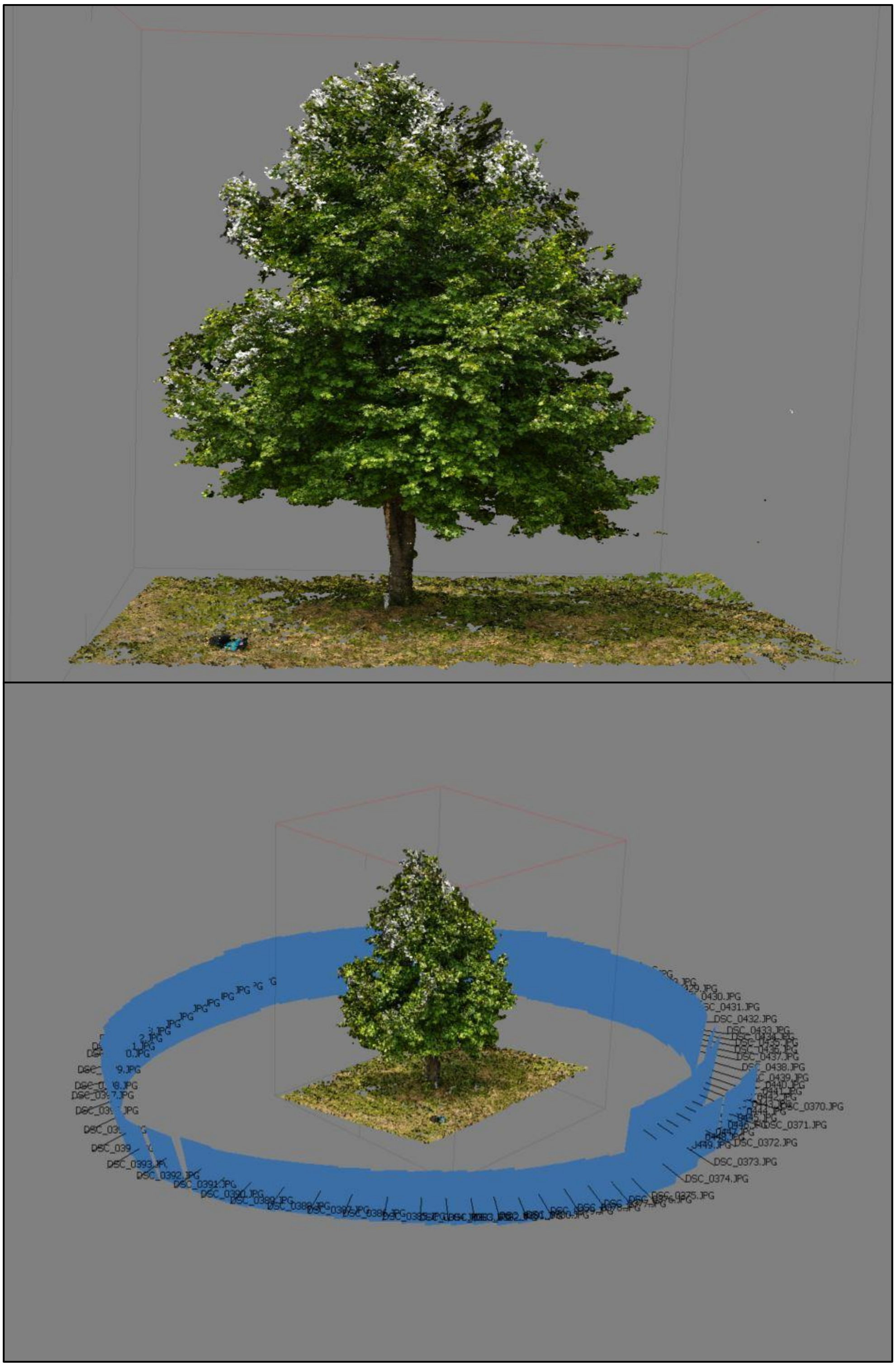

Figure 4.2: Examples of the landscape trees dense point cloud models. The blue squares show the locations from which the photos were captured.

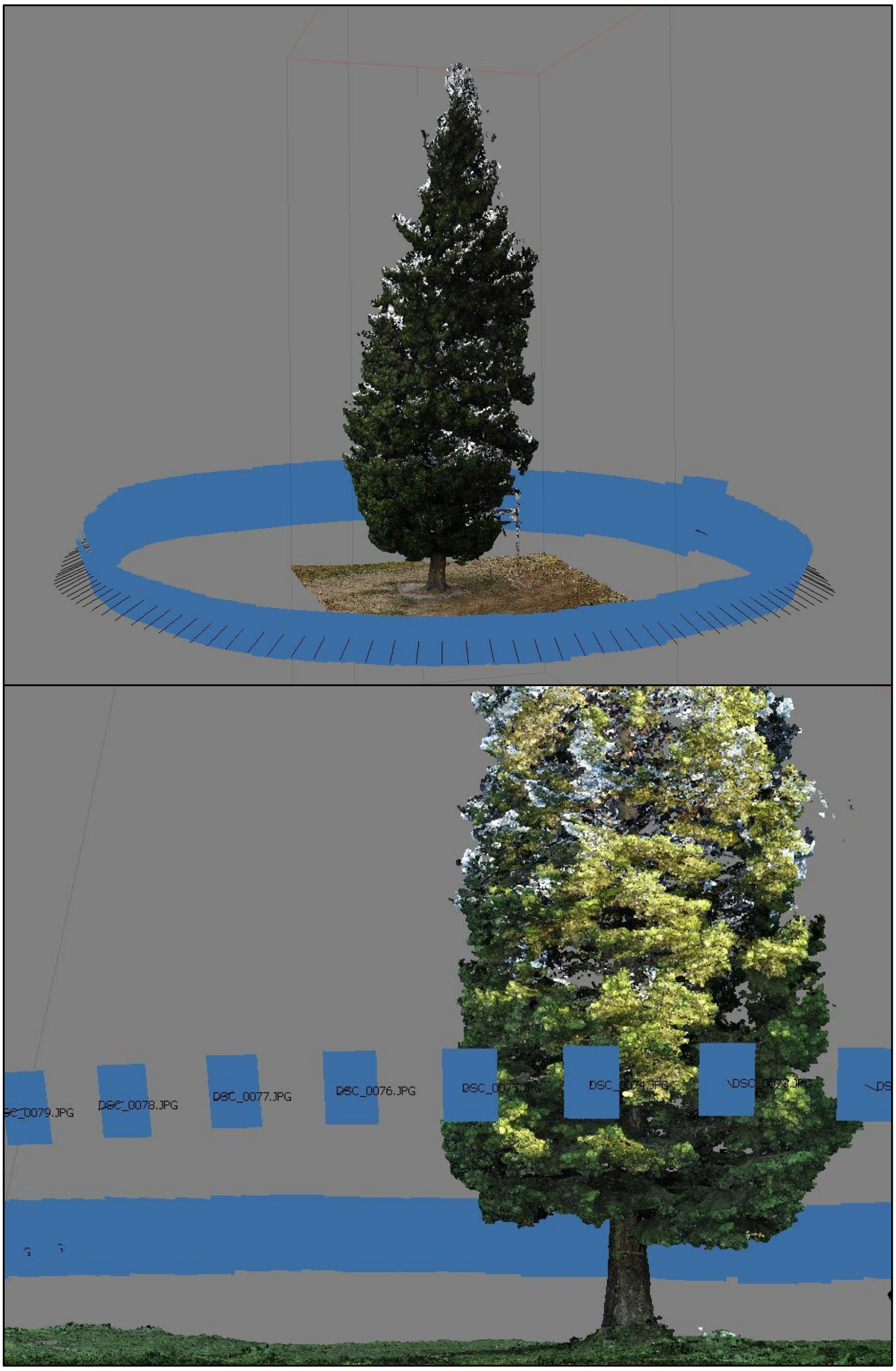

Figure 4.3: Examples of the landscape trees dense point cloud models. The blue squares show the locations from which the photos were captured.

Figure 4.4: The telescopic surveying poles provided useful scaling devices for the models.

4.2.7 Linear Measurement in PhotoScan

To make linear measurements in the model point markers were placed on the appropriate locations on the model and scale bars were created to measure the distance between them. Height was measured from the ground to the highest visible part of the tree. For the DBH measurements, two perpendicular transects were measured through the stem and average of the two recorded. The minimum number of photos required for 100% image alignment was recorded, as was the total running time for generation of the mesh model (including sparse and dense point cloud generation).

4.2.8 Statistical Analysis

All data was analysed in R Studio statistical package, v. 0.98.1028 (R Studio Inc., 2013). Basic statistics were calculated for each tree metric (mean, maximum, minimum and SD). The accuracy of tree metrics were evaluated using root mean square error (RMSE) and bias, as defined in equations (1) and (2);

Equation (1)

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}}$$

Equation (2)

$$\text{Bias} = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)}{n}$$

Where n is the number of estimates, y_i is the value estimated by SfM-MVS and $\hat{y}_i$ is the ground truth value. Relative RMSE and bias were calculated by dividing each of the latter by the mean of the ground truth values.

4.3 Results

The SfM-MVS values estimated for both the full photoset and the minimum photoset were evaluated against the corresponding ground truth values. Reconstruction of all 35 landscape tree models was successful, with each having sufficiently high point cloud densities to visualise the tree and allow height and DBH to be measured. Each dense point cloud model was comprised of several million points. Examples of the reconstructed dense point cloud models are presented in Figs. 4.2 and 4.3. The mean, standard deviation, maximum and minimum for the ground truth and SfM-MVS-estimated data are presented in Table 4.1.

Table 4.1: The mean, SD, max and min for the ground truth data, the SfM-MVS estimates from the complete photoset and minimum photosets.

Ground Truth Data	n	Mean	SD	Max	Min
Height (m)	35	8.57	4.87	24.2	3.61
DBH (cm)	35	28.5	26.15	142.2	7.3
Complete Photoset					
Height (m)	35	8.84	4.89	24.3	3.64
DBH (cm)	35	28.5	25.69	139	7.6
Minimum Photoset					
Height (m)	35	8.4	4.91	24.5	3.44
DBH (cm)	35	27.7	25.66	139	6.2

4.3.1 Minimum Image Requirements

The minimum number of images required for alignment and the associated error for height and DBH for each are displayed in Tables 4.2 and 4.3. The minimum number of images required for 100% image alignment ranged between 20 and 50, with 30 images being the most common number (12 of the 35 trees). There does not appear to be any correlation between the minimum number of images required for alignment and the accuracy of each associated estimate for either height or DBH, with each having respective adjusted R^2 values of 0.001 and 0.09 (Fig. 4.5). There also appears to be no correlation between the height of the tree and the minimum number of images required for alignment (Table 4.4), with an adjusted R^2 value of 0.004 (Fig. 4.6).

Table 4.2: The number of images required for image alignment and the % error associated with the height estimates of each.

# of images	n	Mean (%)	Max (%)	Min (%)
50	2	11.1	20.6	1.5
40	3	12.4	24.2	1.1
35	7	3.7	7.1	1.2
30	12	3.9	9.5	0.7
25	8	4.2	7.9	0.3
20	3	17.6	26.4	2

Table 4.3: The number of images required for image alignment and the % error associated with the DBH estimates of each.

# of images	n	Mean (%)	Max (%)	Min (%)
50	2	2.7	4.6	0.9
40	3	4.3	7.7	0
35	7	7.7	24.4	0
30	12	7.1	22.6	0
25	8	3.3	7.7	0
20	3	5.1	8.1	1.9

Table 4.4 The number of images required for image alignment and the mean height (m) associated with each size photoset.

# of images	n	Mean (m)	Max (m)	Min (m)
50	2	6.1	6.9	5.2
40	3	9.9	13.5	5.6
35	7	11.4	24.2	3.8
30	12	9.4	19.7	3.61
25	8	6.3	12.5	3.95
20	3	7.1	11.6	4.5

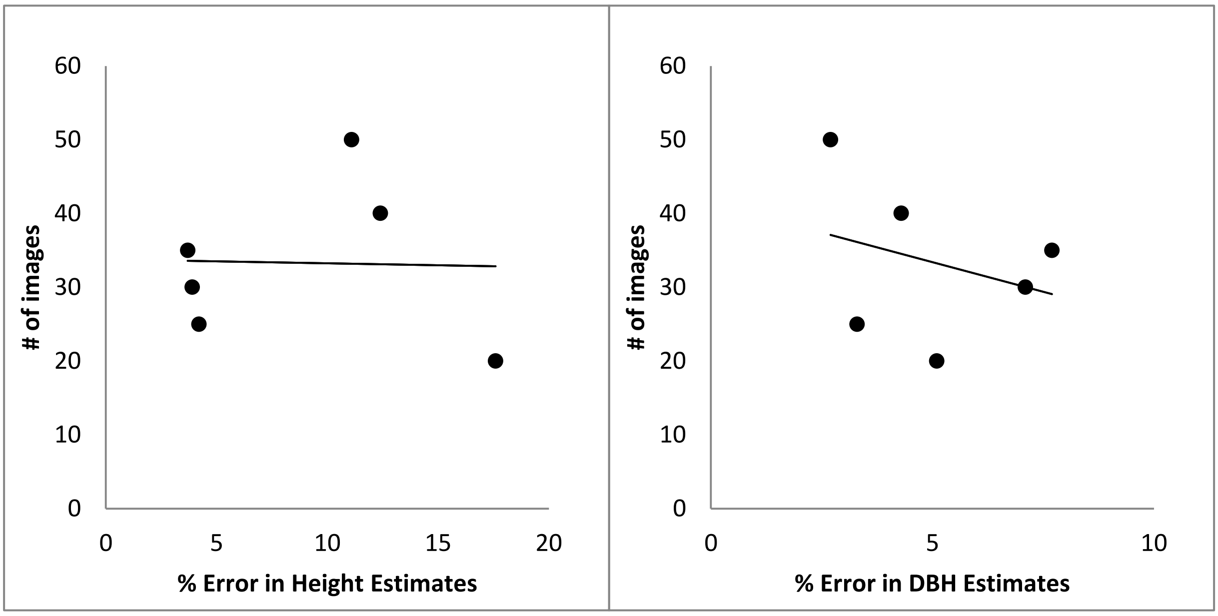

Figure 4.5: Regression analysis between the size of the minimum photoset and the mean height error (left, adjusted R^2=0.001) and DBH error (right, adjusted R^2=0.09) in SfM-MVS estimates.

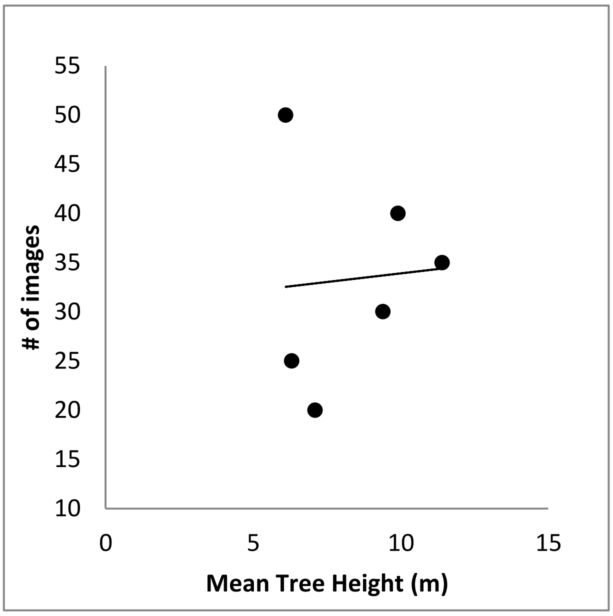

Figure 4.6: Regression analysis between the size of the minimum photoset required for image alignment and the mean tree height for each respective minimum photoset size (adjusted R^2=0.005).

4.3.2 Height

RMSE and bias for the height estimates of complete and minimum photosets are shown in Table 4.3. Each of the SfM-MVS models reconstructed from the complete photosets produced very accurate height estimates, with an RMSE of 0.53 m (6.2%). The positive bias of 0.32 m (0.37%) indicates a slight tendency for SfM-MVS to overestimate height. The SfM-MVS models reconstructed with the minimum photosets were not as accurate as the complete photosets estimates, with an RMSE of 0.79 m (9.3%) and a negative bias of -0.16 m (-1.8%), indicating a very slight tendency for SfM-MVS to underestimate height. The respective adjusted R^2 values for the complete and minimum photoset estimates are 0.991 and 0.973, indicating very strong correlations with ground truth values for both (Fig. 4.7).

4.3.3 DBH

RMSE and bias for the DBH estimates of complete and minimum photosets are shown in Table 4.4. Each of the SfM-MVS models reconstructed from the complete photosets produced very accurate DBH estimates with RMSE of 1.6 cm (5.6%). There was no bias for the complete photoset. The model reconstructed from the minimum photoset produced a very accurate DBH estimate too, with RMSE 2.1 cm (7.4%). The bias for DBH in the minimum photoset model was -0.8 cm (-2.8%), indicating a very slight tendency for SfM-MVS to underestimate it. The respective adjusted. R^2 values for the complete and minimum photoset estimates are 0.996 and 0.994, indicating near-perfect correlations with ground truth values for both (Fig. 4.8).

Table 4.4: RMSE and bias statistics for height and DBH estimates for the complete and minimum photosets.

Height (m)	n	Bias	Bias (%)	RMSE	RMSE (%)
Complete	35	0.32	3.7	0.53	6.2
Minimum	35	-0.15	-1.7	0.79	9.3
DBH (cm)					
Complete	35	0	0	1.6	5.6
Minimum	35	-0.8	-2.8	2.1	7.4

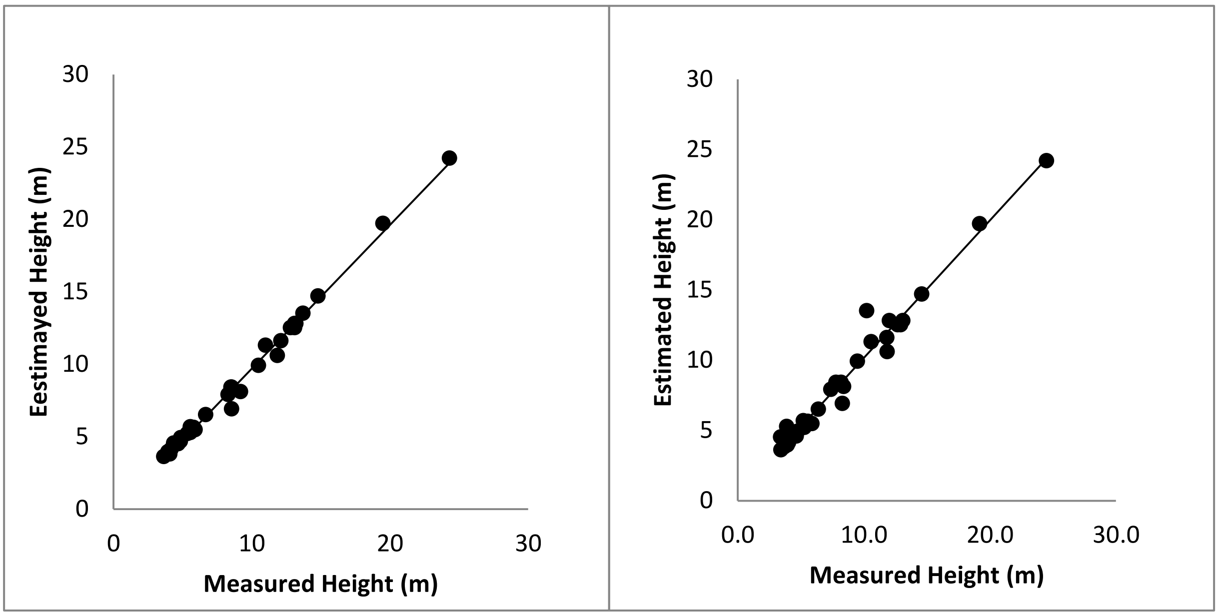

Figure 4.7: Regression between ground truth height values and SfM-MVS height estimates for the complete photoset (left, adjusted R^2=0.993) and the minimum photoset (right, adjusted R^2=0.975).

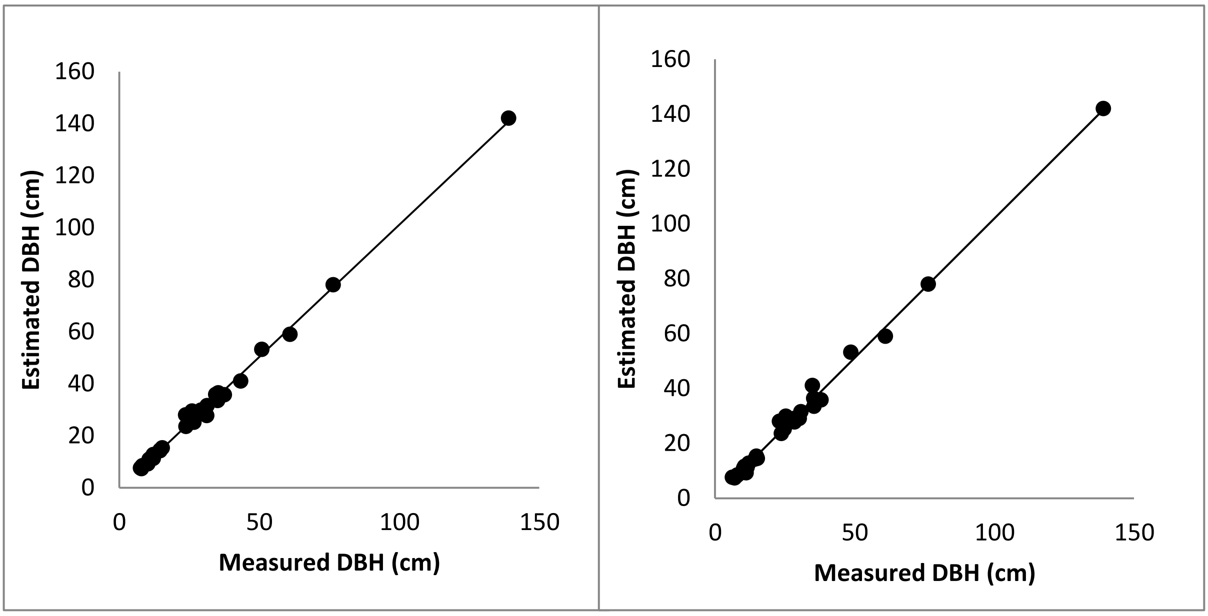

Figure 4.8: Regression between ground truth DBH values and SfM-MVS DBH estimates for the complete photoset (left, adjusted R^2=0.996) and the minimum photoset (right, adjusted R^2=0.994).

4.3.4 Time Requirements

Images could be acquired at an extremely rapid rate; as a general rule photos could be taken at a rate of one per five or less seconds, depending on the distance between each photopoint (which was determined by the size of the tree). Complete photosets of 90 images generally took 8-10 minutes to collect meaning a photoset of 30 images took only 2-3 minutes. The respective sizes of a complete and minimum photoset are 530MB and 150 MB. The time taken for each model to be reconstructed was primarily determined by the size of the photoset, the resolution of the imagery and the quality settings used. This included the three steps of image alignment to reconstruct the sparse cloud model (SfM stage), then the dense cloud model (MVS stage), and finally the mesh surface model. A general indication of the time required for model reconstruction using different sized photosets is shown in Table 4.6. For the complete photosets this was between 2 and 3 hours, though from start to finish, a mesh tree model from a 30-image photoset could be produced in under 30 minutes. The settings described in section 4.2.5 were kept the same for each model reconstruction.

Table 4.6: The approximate times required for model reconstruction using different size photosets on a high-end desktop computer (all values in minutes, all quality settings on 'high').

# of images	Image alignment (SfM)	Dense cloud reconstruction (MVS)	Mesh surface (extrapolation disabled)
180	60	240	20
90	30	120	10
60	15	40	5
30	5	10	2

4.4 Discussion

The time, effort and cost required for traditional dendrometry is a well-known issue as well as their reliance on allometric relationships which are known to be flawed (Kankare *et al*., 2013b). Remote sensing methods like laser scanning are capable of producing highly accurate estimates of tree metrics over scales ranging from thousands of hectares to individual trees. However, their applicability to low budget and small-scale tasks is greatly limited by the high cost of equipment and the expertise required operating them.

This research examined the minimum requirements, in terms of image availability, for SfM-MVS to reconstruct spatially-accurate 3D models from which height and DBH could be accurately estimated. The 35 study trees used represent a wide range of sizes, shapes and species. Beginning with a complete photoset of 90 images taken from uniformly-distributed photopoints around the circumference of each tree, the number of images made available for model reconstruction was progressively reduced to identify the minimum number of images that could still be 100% aligned with SfM in PhotoScan Professional. Point markers and masking were not used to aid model reconstruction. Height and DBH were measured on the models reconstructed from both the complete and minimum photosets and these values were compared with each other and the ground truth data, which were collected with traditional dendrometry.

Complete photosets of the study trees were able to be reconstructed with high spatial-accuracy and each provided excellent visual representations of the study trees. Following manual editing to remove the background noise and irrelevant elements each dense cloud model comprised of 1-2 million points. Though every single one of the study trees were reconstructed well, noise was present at varying degrees in all and actually increased significantly when fewer images were used.

The minimum size of photoset required to achieve 100% image alignment and allow model reconstruction ranged between 25 and 50 among the 35 study trees. Below this number of photos there appears to be insufficient overlap between successive images for them to align correctly. The number of images required for alignment did not have an effect on the accuracy (a shown in Tables 4.2 and 4.3) with the error in the estimates produced in models made with 50 images very similar to the error in those made with 20 images. The respective R^2 values of 0.001 and 0.09 for height and DBH show there is no correlation between the minimum number of images required for alignment and the accuracy that can be achieved in the height and DBH estimates on the subsequent model. Likewise, there is no correlation between tree height and the minimum number of images required for alignment, as shown by the adjusted R^2 of 0.008.

The height estimates were very accurate for the complete photoset models were accurate (RMSE 6.2%, bias 3.7%). Somewhat surprisingly, the height estimates in the minimum photoset models were not significantly less accurate than the complete photoset estimates, with an RMSE of 9.3% (only 3.1% more). The same trend occurs in the DBH estimates, with the RMSE of 7.4% for the minimum photoset only 1.8% greater than the complete photoset (which was RMSE 5.6%). For both height and DBH there were many cases of the estimated value being the same in both the complete and minimum photoset models.

The height of the complete models tended to be slightly overestimated, with a bias of 3.7%. This trend is reversed in the minimum photoset models, where height was underestimated, though not by a great amount (-1.7%). There was no bias in the complete photoset estimates of DBH, though in the minimum photoset models DBH was slightly underestimated (-2.8%). The respective R^2 values of 0.001 and 0.01 for height and DBH shows there is no apparent correlation between tree height or stem diameter and accuracy of estimations.

This was one of the considerations discussed in Chapter three, however, the relatively small sample size must be considered. The heights of taller trees (>15 m) were generally estimated with less accuracy than small trees (<5 m) though only very slightly. This may have been partly due to the switch in measurement instrument from the height pole to the hypsometer above 7 m trees, which reduced the measurement resolution from 0.01 m to 0.1 m.

4.4.1 Results in the Context of Previous Research

The accuracy of complete photoset height and DBH estimates are very similar to those of the nursery trees. The accuracy of SfM-MVS relative to other methods and research has already been discussed in Chapter Three and the explanation for these landscape tree results is very similar, however, the results of Chapter Four have shown that accuracy of 2D estimates appears to be independent of tree height.

Here the emphasis of the research is on identifying the minimum number of images required to produce spatially-accurate models, as well as the time and required to acquire the images and produce models. To the best of the author's knowledge there is no other research of this nature yet published, and with such little existing research utilising SfM-MVS at all, especially for dendrometry, it is difficult to directly compare the results of this study with others. Many studies do not list the time required for data collection or processing.

4.4.2 Results in the Context of Previous Research –Time Requirements

The method of image acquisition for this study is based on that of Morgenroth and Gomez (2014). The latter study found success using only 32 images taken around the circumference of each of their study trees. The reported results are very similar to the results of this study, with error of

2.6% for height and 3.7% for DBH, though at only three trees their study size was very small and for one of their study trees only the stem was photographed. Large RAW images (>12 MB) were used for this study and as so few images were used each tree model took only a matter of minutes to develop start to finish. The other SfM-MVS forestry study by Liang *et al*. (2014b) involved acquiring images of an entire plot (of 278 stems/ha density), rather than individual trees. In total 973 images (of 5472 x 3648 pixel resolution) were acquired over a 43 minute period and model reconstruction in PhotoScan took 32 hours on a high-end desktop computer.

For their geomorphological study, Westoby *et al*. (2012) reported an image acquisition time of approximately 2 hours for 889 images and total SfM-MVS processing time for dense cloud reconstruction of 23.5 hours. They also describe that the total SfM-MVS processing time for a typical photoset of 400-600 (2272 x 1740 pixel resolution) can range from 7 to 56 hours on a mid-range computer. For comparison, the time required for their supplementary TLS data acquisition took two and a half times longer at 5 hours. Likewise, James and Robson (2012) reported their data acquisition time for SfM-MVS being <10% that of TLS for a photoset 210 images in size.

Some of the time gains achieved in the data acquisition stage of SfM-MVS are offset by the long processing times (Westoby *et al*., 2012). At only 1-2 hours, the time required for processing each of the landscape trees in this study was comparatively rapid to the time reported in some other studies. James and Robson (2012) encountered lengthy processing times of 10-12 hours, which were actually 10 times longer than the associated TLS processing times. Dandois and Ellis (2013) reported a processing time of 2-5 days It must be noted that the latter two studies were using SfM-MVS to produce surface models, rather than models of enclosed, stand-alone objects.

Comparison with TLS puts into perspective just how rapidly images can be acquired. For instance, Henning and Radtke (2006) reported scanning times of up to 45 min. Dassot *et al*. (2012) described the manpower and time required to carry out TLS data acquisition, point cloud processing and destructive sampling in their study. TLS scanning required two people for only an hour, though the processing work required on the point cloud was dependent on the complexity of the tree and ranged from 30 min to 4 hours for one person. Like SfM-MVS, TLS point clouds take longer to reconstruct if higher resolution (high laser pulse density) scans have been acquired.

4.4.3 Interpretation of SfM-MVS Estimates

The success of model reconstructions can be partly explained by various aspects of the method and this will be discussed in Chapter Five. Many of these aspects are the same as what were encountered in the nursery tree research, though as the research aim for the landscape trees was different, the method differed slightly, and so too did the aspect that have affected the results. The most important of these is the fact that volume was not a metric of interest, meaning that accuracy of height and DBH did not necessarily hinge on each tree being reconstructed in high detail.

4.4.4 Interpretation of Results - Number of Images Required

The minimum number of images required for SfM model reconstruction is determined by the number of keypoints that can be identified in multiple overlapping images in order to align them (image alignment). The SfM algorithms used in PhotoScan are robust to the orientation of images, though they are sensitive to insufficient overlap (Gienko & Terry, 2014). For a stand-alone enclosed object, around which imagery is acquired from uniformly-spaced photopoints along a circular path, sufficient overlap between images to achieve alignment depends on the distance between photopoints not being too large. For a given tree circumference (in terms of distance), more images will mean greater overlap between each successive image. As the photoset is progressively reduced in size, the distance between each photopoint will be greater and the overlap between images will decrease to the point where it is insufficient to identify keypoints across multiple images (Snavely *et al*., 2010). At this point the software will be unable to estimate the correct location and orientation from which each images was captured.

There does not appear to be any correlation between the number of images required for alignment and the error in the associated estimates, i.e. estimates in models that required 50 images to align were not any more accurate than the estimates of models that took only 20 images to align. Likewise there is no correlation between tree height and the number of images required for alignment. This leads to the idea that success of alignment is primarily determined by external parameters (e.g. the background scene, lighting, texture of the tree surface – these will be discussed in more depth in Chapter Five).

While the results are indicative of the lower limit of images necessary for total image alignment (20-50 images), using this few images should be avoided if possible, especially if more detailed analysis of tree structure is required. It is important to remember that image alignment involves only the SfM stage to produce a sparse point cloud. Whilst reliant on success of the SfM stage for calculating basic scene geometry, the succeeding MVS stage that produces the dense point cloud is equally important for reconstructing the target object to a quality that allows measurement to be made.

Successful image alignment does not always mean a high quality dense cloud will be reconstructed. It is clear that reconstruction using photosets containing such few images would most likely be insufficient to estimate anything other than height and DBH. The stem will remain relatively densely populated with points (Fig. 4.9), because it offers a large, relatively simple surface on keypoints can be easily identified. However, high quality reconstruction of the crown or trees with complex branch architecture cannot be expected using 20-30 images. The majority of the crown was completely absent of points in the minimum photoset models. The crown is often represented by complex surfaces with varying face orientations (Bemis *et al.*, 2014). The more complex a surface is, the more keypoints are required to reconstruct it properly (Gienko & Terry, 2014). Complete photosets (90 images) were reconstructed well and contained high point density in their crowns, though the point density reduced quickly with fewer and fewer images made available. Linear metrics are less vulnerable to error than 3D metrics as only two points need be present in the point cloud to measure them; whatever lies between the two points does not come into consideration.

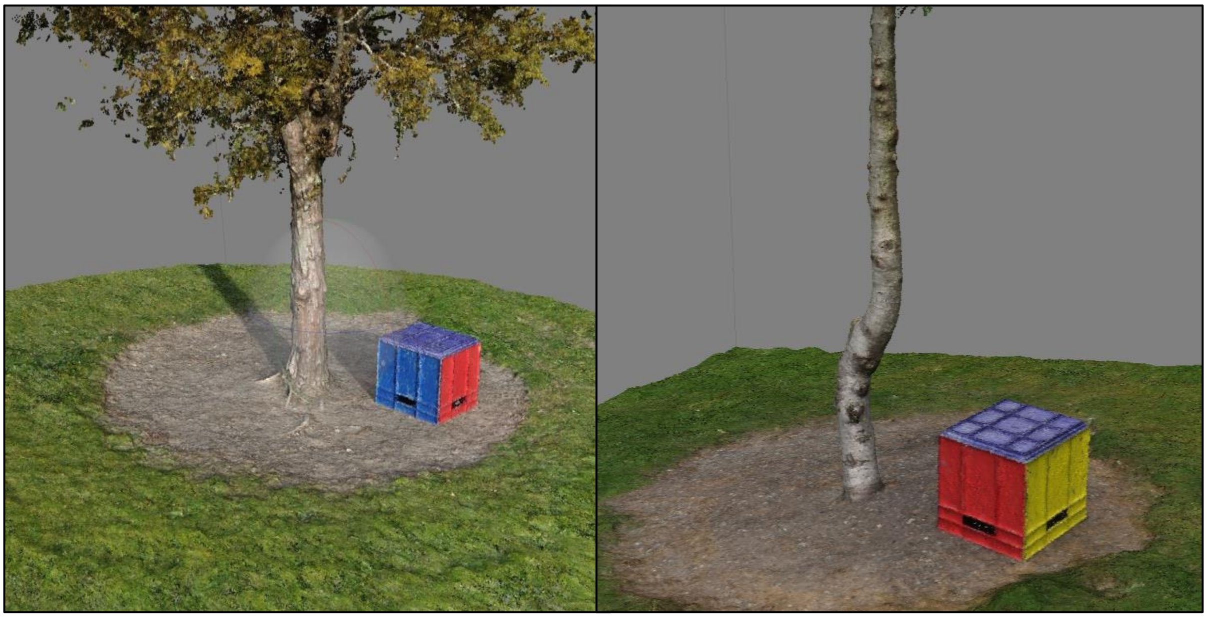

Figure 4.9: Trees stems were able to be reconstructed very well with very high point cloud densities present. The above two examples are dense point clouds reconstructed from complete photosets. Note the box for scale.

If a tree is easily accessed or time is limited then taking only 30 photos should be adequate for models to be reconstructed to a quality where estimates of height and DBH can confidently assumed to contain ~10% error. Though If the tree of interest is difficult to access or there is no chance of retaking the photos then it would certainly be better to take too many than too few photos as those surplus to requirement can always be discarded or not uploaded for model reconstruction. The additional time required to taking 90 photos over 30 is 10-15 minutes which is not overly significant if the study size is small, though this may add up if the many trees need to be modelled. Models reconstructed using complete photosets of 90+ images can confidently be expected to produce error in height and DBH estimates no greater than 5%.

While it may be assumed that 'bigger is better' in terms of the size of the photoset, there is a point where the quality of reconstructed model cannot be improved any further. At this point, additional images will be of no extra value and will only act to slow the processing time. An interesting feature of the nursery tree models was that some of the best models were made using only a portion of the photoset. Bemis *et al*. (2014) found that the best quality models could be produced using only 51 of the 100-large photoset.

4.4.5 Interpretation of Results - Image Resolution and Quality Settings

It was postulated that SfM-MVS accuracy would be greater for shorter trees, as greater proximity of the camera to any given object will result in greater pixel density. This could lead to the height estimates for shorter trees being more accurate than for taller trees. James and Robson (2012) describe the ratio between estimate precision and distance from of the photopoint from the target object as ~1:1000, which means where 1 mm precision is sought, the images should be captured from photopoints 1 m away. For this research, as so few images were made available in the minimum photosets, capturing the images from a distance in which the whole tree could fit within the image frame (with an 18 mm focal length) was the only way to ensure that the entire tree was captured evenly. In other words, images were taken closer to the tree for smaller trees and hence had greater pixel density. This meant the method did contain some bias towards smaller trees, which could ultimately affect the estimation accuracy.

For a given image resolution, the real-life distance that each image pixel represents is entirely dependent on how far away the object is from the camera. If the same or roughly the same number of photos are to taken of each tree no matter what its size, with the aim to fit the entire tree within one image frame (either portrait or landscape in orientation), there will be inconsistencies in resolution and detail in which each tree is photographed. Trees that had preferential growth in one particular direction (i.e. tall and narrow or short and wide) were an issue as the photos had to be taken from further back in order to accommodate them within the image frame. Therefore the detail they could be reconstructed in was reduced with this method

To reduce this bias, the number of images taken could be determined by the form of the tree, i.e. more images taken of large or expansive trees (as with the nursery trees). In practice there does not have to be a limit to the number of photos taken of each tree, and the size of the photoset that can be realistically used to reconstruct a model is restricted only by the computational power available and the quality settings desired for the model. Images can be acquired from very close range or with a longer focal length to capture the tree in as high resolution as possible if necessary, though the resulting larger photoset can be expected to require very lengthy processing times; Bemis *et al*. (2014) state that for every two-fold increase in the number of images, the processing time will increase four-fold.

The processing time for a model will also depend on the resolution of the imagery. Higher resolution imagery (either through a higher quality camera or larger focal length) will certainly allow better reconstruction of target trees, however, as Westoby *et al*. (2012) state, if images are captured at ultra-high resolution (>12 MP) they will almost certainly need to be down-sized or else processing times will be extremely long. The complexity of texture in the imagery will also be a strong determinant of the processing time; this will partly depend on the nature of the target object and the background scene. It is also likely that if 'ultra-high' quality was used in the dense cloud reconstruction, the accuracy of SfM-MVS estimates would have improved as Agisoft claims that model quality approximately doubles with each step up in quality.

4.5 Conclusion

This research has investigated some of the methodological limitations of SfM-MVS. The aim of this research was to determine the minimum number images required for image alignment, which is the first step of model reconstruction (SfM) and without which a complete model (with MVS) cannot be generated. The results show that good quality SfM-MVS models with high spatial accuracy can be reconstructed from as few as 20-50 images. The models are of sufficient quality to obtain accurate estimates of height and DBH. The minimum number of images required for alignment does not appear to affect the accuracy of the associated linear metrics and likewise, the height of the tree appears to have no bearing of the minimum number of images required for image alignment. If higher quality models are desired then more imagery may be required, though this will require further research. Aspects of the methodology and external parameters which may affect model quality will be discussed in Chapter Five.

Chapter Five

Discussion and Conclusions

5.1 Influences on SfM-MVS Model Reconstruction

The results of the model estimates, particularly volume, are directly related to the ability of SfM-MVS to model the entirety of the tree. The volume estimates provide an absolute indication of exactly how much of each tree had (or had not) been captured in the model. The complexity and sheer number of branches meant it was not always obvious if anything had been missed through visual assessment of the model or the results of linear metrics. With the assumption that spatial scale has been applied to the model accurately, error in the volume estimations can be pinned solely to the inability of SfM-MVS to properly model the entirety of the tree. The high accuracy of the linear metrics validates the models as realistic reconstructions scale-wise, so any error was caused simply by SfM-MVS failing to reconstruct parts of the tree, therefore excluding these parts from being accounted for in volume estimation.

Structure-from-motion has a unique set of parameters that affect the outcome of model reconstruction. As described by Bemis *et al*. (2014) and Gienko and Terry (2014) these parameters can be categorised as the following;

- The conditions of image acquisition;
- The character of the target object and background scene;
- The functionalities of PhotoScan and the properties of the camera.

The influence that each of these parameters has on the success of model reconstruction will be further discussed in the succeeding sections.

5.1.1 Conditions of Image Acquisition - Image Resolution

As PhotoScan uses pixel arrangement in the acquired imagery to recognise keypoints, the better represented a particular object is with pixels in the images, the more likely it is to be reconstructed successfully. Therefore if it fails to appear in the model, it is most likely due to either: 1) the camera being too far from the object, or the focal length being too long for it to be represented by sufficient pixels, or; 2) inadequate overlap or convergence of perspectives between successive images causing failure to recognise keypoints in multiple images

The photography technique was based on that used by Morgenroth and Gomez (2014) but was refined prior to its use on the study trees. The technique was relatively consistent for each tree, though the number of images varied slightly depending on the size and shape of the tree; rather than maintaining absolute consistency in the method used for each tree, the emphasis was on ensuring the imagery was conducive to producing the best possible model for each individual tree.

Poor point cloud representation and subsequent lack of success in estimating the volume of the remaining branches is simply due to the photos being taken from too far away given the slenderness of these branches. The diameters of the remaining branches were not measured but through visual assessment alone the vast majority registered under 5 mm for much of their respective lengths. This is reflective of the difficulty Kankare *et al*. (2013b) and Morgenroth and Gomez (2014) encountered when measuring the slender upper stem diameters and remaining branches of their study trees. Liang *et al*. (2014b) also reported a correlation between the quality of the point cloud model and distance the imagery was acquired from, i.e. trees were reconstructed with less quality the further away the imagery was taken.

Poor point cloud representation was not limited to the remaining branches. On trees where the stem tapered to less than 10 mm diameter it was often represented by insufficient points to form a fully enclosed cylindrical shape in the mesh model. Aside from uppermost 10%, the stem of each of the nursery tree models was represented very well for the majority of its height. The most obvious reason for this is that it is the thickest part of the tree and therefore offers the most surface area of any part of the tree to be captured in the imagery. This is highlighted by the results of the five *Juglans regia* trees, which on their own were found to have an RMSE of 5% for stem volume (compared with the overall RMSE of 12.3%) and also had the five largest DBH values (mean 26 mm compared with the overall mean of 19 mm).

The other reason for the success of stem reconstruction is the simplicity of its shape; it is a vertical, nearly straight feature and as it forms the centre of the tree, it appeared in the centre of each of the images and appearing relatively consistent from each angle. As Gienko and Terry (2014) demonstrate, the more geometrically-basic the target object is, the fewer keypoints are needed for 3D reconstruction. Though objects with large surface areas are generally modelled better, it is important that they have sufficient texture or else they will not be modelled well (James & Robson, 2012).

5.1.2 Conditions of Image Acquisition - Ambient Lighting and Weather

The weather also has a large effect on the quality of imagery. Diffuse lighting is best in order to reduce shadows and also prevent highly contrasted and over-exposed images from direct sunlight. Photography around reflective surfaces should also be avoided as they can negatively affect keypoint recognition (Bemis *et al*., 2014). Clouds passing overhead may also pose a problem they may cause change in brightness and cast shadows over the scene, which will change the appearance of certain features over the duration of photography. Photography should not be undertaken in windy conditions if it can be avoided as the wind will cause too much movement in leaves and small branches and reconstruction of the tree is likely to be unsuccessful due to the reduced number of reference features. Wind is likely to create more relative movement in small trees as their thinner branches are more easily disturbed.

Though the nursery trees were re-positioned at the nursery to reduce the impact of background noise, the natural lighting that occurred was an uncontrollable factor and proved to have a major influence on how well SfM-MVS estimated volume. Appropriate ambient lighting during photography is required for proper detection of features in the images during the model generation in PhotoScan (Gienko & Terry, 2014). Though diffuse lighting created by an overcast sky was preferred for photography, the weather was obviously an uncontrollable factor and some shadowing inevitably occurred on sunny days. This was exacerbated by the fact that photography was mainly undertaken through winter, meaning the sun followed a low angle across the sky.

Photographing against sunlight produced overexposed and high contrasted images. Shadowing had the effect of removing the ability to examine surface shape or texture, meaning automatic recognition of keypoints is not possible and prevented the shadowed side of the model from developing properly (Fig. 5.1). It also meant that features varied in their appearance from different perspectives around the trees, sometimes making image alignment difficult. This is an issue faced by Morgenroth and Gomez (2014), where excessive shadowing meant there were insufficient points in the dense point cloud meant the mesh surface could not be successfully generated.

To address the lighting issues, the camera settings could have been adjusted according to the conditions (e.g. adjusting the exposure, aperture), but in order to maintain consistency in the method and not incur the significant additional time that would be required due to the sheer number of photos that were taken, the same settings were used for every photo. It also reflected the intended simplistic nature of the SfM-MVS method; though knowledge of photography techniques is an obvious advantage, SfM-MVS should not require photography expertise to use. Though the use of SfM-MVS cannot be limited to times of optimum lighting, photography should not be carried out when lighting is unsuitable if this can be avoided.

Figure 5.1: Bright sunlight caused half of some models to be in shadow, reducing the surface detail (top images). Subsequently the dense cloud model (bottom left) is characterised by dark points and missing points. This is reflected in the subsequent mesh generation (bottom right), where the same stem fails to be enclosed in a complete cylinder.

5.1.3 Target Object and Background Scene

The type of object is important, i.e. whether it is an enclosed object or a flat surface, as are its surface characteristics (e.g. the texture and patterns) and shape (e.g. protrusions, hollows, irregularities). Trees are enclosed objects and often have complex surfaces and as such, to properly model them ideally involves imagery being acquired from 360° around the circumference of the tree.

5.1.4 Target Object - Study Tree Markers

The red tape that was used to mark the locations of the measurements points on the nursery trees proved to be a simple yet invaluable tool for making linear measurements in the model. The distinct red colour of the tape simplified the identification of measurement locations and without it many of the linear measurements would have been nearly impossible to make. The usefulness of the tape is particularly evident when measuring the crown spread, as showcased by the difference in error between true crown spread (TCS) and visible crown spread (VCS). Most importantly, TCS could not have been differentiated from VCS as a separate metric without the tape.

The greater error in VCS was caused solely by the inability of SfM-MVS to reconstruct the entire length of the branches that were selected for crown spread measurement. As previously mentioned, these branches were very slender at their extremities (<5 mm) and often the last 20-30 cm of the branches were not reconstructed at all in the model (Fig. 5.2), meaning the red points of the tape were positioned on their own in the image space, disconnected from the rest of the branch. Without red tape at their extremities, it would have been very difficult to ascertain whether the terminus of a branch in the model was truly the end or whether SfM-MVS had failed to reconstruct the remainder of the branch.

The tape took less than five minutes to apply per tree. In practice, it is unrealistic to think the tape method could be applied to trees in the field, as the accessibility issues that would be associated with placing tape on tall trees one of the fundamental reasons why remote sensing is utilised for tree mensuration. Without any markers to mark the extremities of the tree, the only way to ensure that the outer reaches have been captured is with careful analysis of the photos captured. It is also reassuring to know that the SfM-MVS models are more likely to underrepresent tree form than over represent it, and even if the outer branches fail to be reconstructed in the model their slenderness means their contribution to the overall volume is likely to be negligible.

Figure 5.2: Some of the slender branches failed to be reconstructed, leaving the red points of the red tape positioned on their own in the point cloud. The red tape was useful for seeing what portion of the branches failed to be reconstructed.

5.1.5 Background Scene - Surface Texture

Lack of surface texture created an issue that was encountered frequently with the tallest of the nursery trees. Parts of the sky were modelled around the trees and in the worst cases the entire upper halves of trees were shrouded in large amounts of blue and white points (Fig. 5.3). This was especially a problem for photosets collected on days where the sky appeared to be very homogenous in appearance, through being perfectly clear or having thick cloud cover. The reason these points were modelled is thought to be due to the fact that the lack of texture in these parts of the imagery meant no reference features could be identified and therefore depth could not be properly perceived (through the motion parallax principle) causing pieces of cloud and sky to be incorrectly modelled in and around the tree when in reality they are in the background.

This problem could be minimised by capturing as little of the sky in the imagery as possible, i.e. taking ensuring. This became difficult for the tallest and slenderest trees, as in order to properly represent the slender the stem and higher branches with enough pixels, the photos had to be taken from very close range (2-3 m). However, as the hand-held photographs were taken from ~1.7 m above the ground, photographing trees >3 m in height meant the camera had to be angled considerably upward, so capturing large portions of sky was often unavoidable.

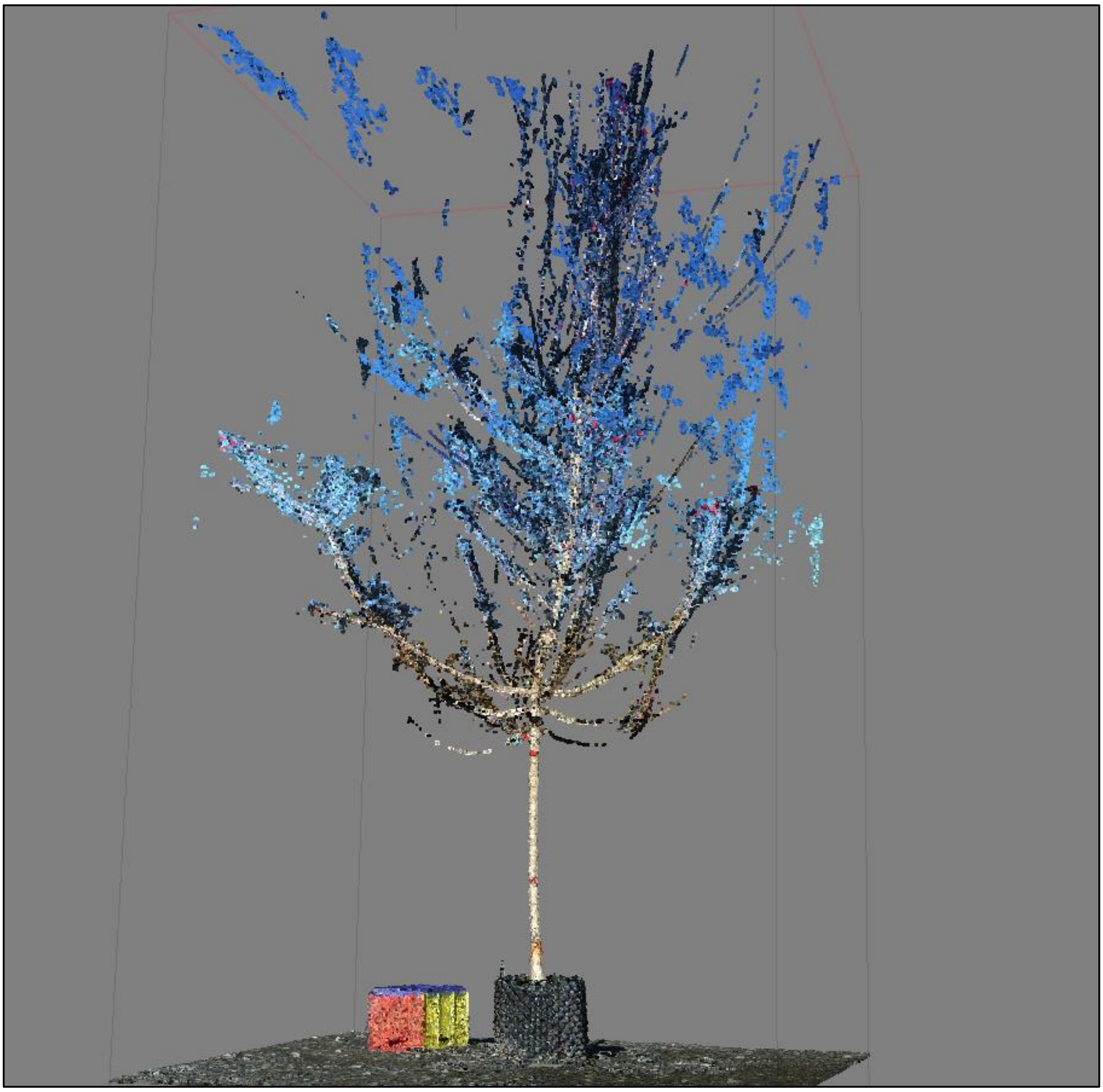

Figure 5.3: Blue and white noise points in the dense point cloud were an issue for several of the nursery tree models**.**

5.1.6 Functionalities of PhotoScan - Point Cloud Attributes

Perhaps what is fundamental to the ease of point marker placement in PhotoScan is that point cloud models are coloured. This allows easy visualisation of the tree and its components making it simpler to extract information than in laser scanning (Bemis *et al.*, 2014) and allowing easy identification of the tape (i.e. the red points). The absence of red colour on the tree and in the background meant that any red pixels in the images could only be from the tape.

The colour of the points also made it easy to determine which parts of the point cloud was irrelevant background noise. It was impossible to remove 100% of the noise as this would have been far too time consuming and the points were mostly inconsequential; they were often present as a single layer surrounding branches and removing them would have been difficult without also removing points representing the tree. The masking tool in PhotoScan allows selection of certain parts of the images to be ignored, though depending on the size of the photoset this may be an impractical task, and often the background noise can be removed quickly with relative ease anyway. The parts of the model where these points were the biggest problem were the most slender; at these points there were so few points of the actual tree captured that noise points significantly altered.

5.1.7 Functionalities of PhotoScan - Point Markers and Scale Bars

One of the difficulties with making measurements in the PhotoScan image space is that point markers may only be placed on points in the point cloud or on a mesh surface, not in empty space. Scale bars to measure height, crown depth and crown spread must be positioned as vertically as possible (perpendicular to the ground) or else they will not give a true measure. This requires a point marker to be positioned on the ground directly below the location of tallest point of the tree. However, if the necessary location on the ground for point marker placement is not represented by any points in the point cloud, point markers are not able to be placed. If this is the case, then a point marker must be placed on the nearest possible point or surface, which means the scale bar may not be vertical and therefore will not a true measure of the height. The highest point of the tree was seldom located directly in the centre of the crown. As was often the case, the location where the marker needed to be placed was represented by unremarkable piece of ground with no distinguishing features, making it difficult to identify the correct location to place the marker.

Point markers can be placed directly in the images which mean that they are able to be located in empty space in the image space, though it can be difficult to identify the correct location to place them in the imagery. Placing point markers directly in the imagery also becomes very impractical and time-consuming in large photosets because the point markers need to be placed in the same location in all photos.

This issue also justifies why crown spread was not included as one of the metrics of interest in Chapter Four. It became apparent following generation of the models that crown spread would be very difficult to measure. In ground truth measurements, crown spread was measured parallel to the ground. In models where the ground failed to be modelled, there were no points in the point cloud in the necessary location available for placement of point markers and placing them on the crown itself meant that the scale bar could not be parallel to the ground to replicate the ground truth measurement. In hindsight it would have been highly beneficial to place markers on the ground prior to photography to mark the locations where the point markers needed to placed, so they could be easily recognised in the images and in the model.

Point markers can be placed either in the images or on the model (following generation of mesh surface). In very small diameter measurements in the model, millimetre-scale differences in the placement of a point marker resulted in large relative error. The diameters at the highest point on the model stems were the most difficult to measure. On many of the nursery trees the highest portion of the stem was very slender, some being only 1.5-2 mm thick and were sometimes only represented by only a very sparse scattering of points in the point cloud model (Fig. 5.4). This made it difficult to identify the bounds of the stem, as at times it was hard to determine whether a particular point in the point cloud was part of the stem or was a thin layer of background noise. Liang *et al.* (2014b) experienced similar difficulty in measuring the distance between objects in the point cloud, as the point cloud was so sparse, presence of noise points or absence of any points.

To ensure correct placement of point makers one must be zoomed in to the model as closely as possible in order to be able to "click" on the single desired point in the point cloud. In PhotoScan the point cloud points remain the same size regardless of the amount of zoom. To accommodate any error in the point marker location, PhotoScan provides buffers which help with computing camera location.

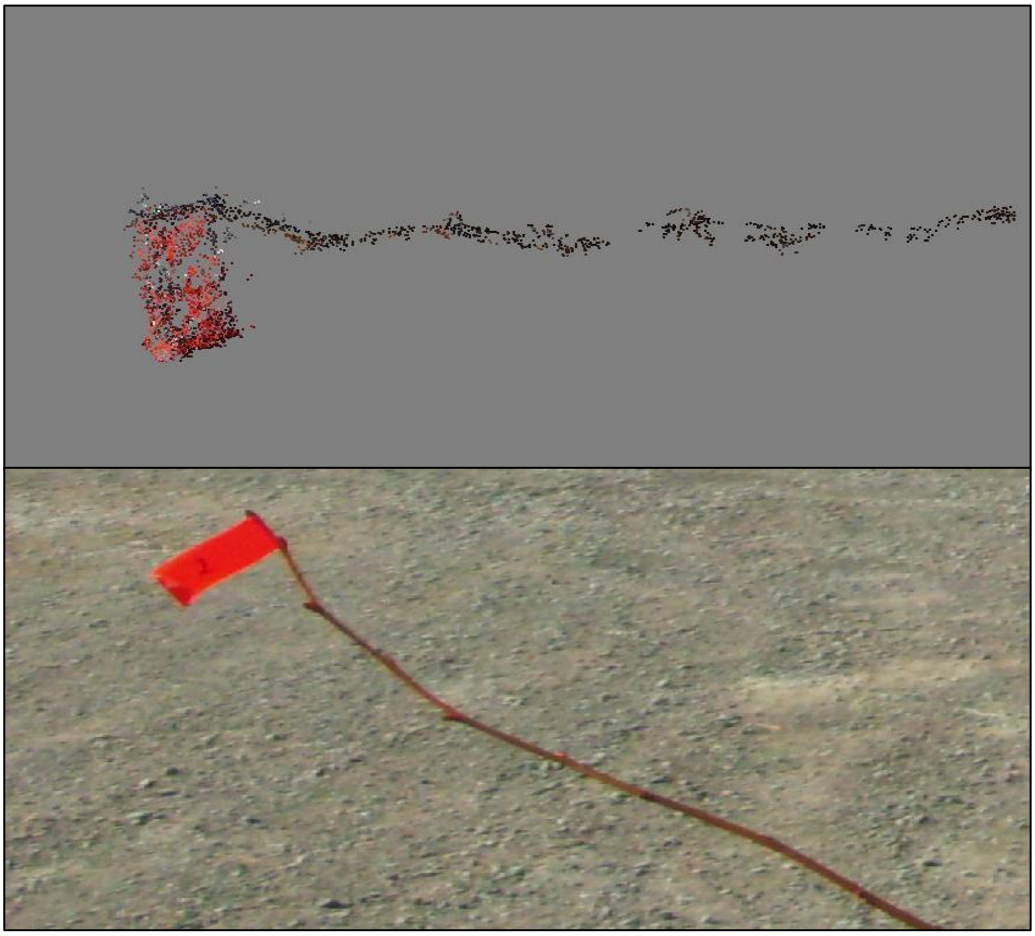

Figure 5.4: The tops of the stems and the slender branches of some of the nursery trees were represented by only a thin scattering of points.

5.1.8 Functionalities of PhotoScan - Mesh Surface Models

As well as an absence of points from failure to capture part of the stem or branches, low point cloud representation resulted in a failure to produce a mesh model with fully enclosed shapes, i.e. the cylindrical shapes of the branches. Poor images did not prevent the photos from aligning correctly, but it affected the generation of the mesh models which in turn reduced the volume output. Interpolation was 'disabled' for generation of the mesh model, as the 'enabled' option was tended to grossly exaggerate tree form and size and would have led to unrealistic volume measures. With interpolation disabled the mesh model was often incomplete, with holes and gaps that required closing in order to produce a 'watertight' model and produce a volume estimate.

The 'close gaps' tool filled in the openings but this tool does not consider tree form at all; where mesh cover of the stem was incomplete, the close gaps tool simply linked the two closest mesh pieces together, creating flat surfaces when realistically they are rounded or cylindrical in shape (Fig. 5.5). Though shadowing was certainly an issue for some models, comparison of the results produced by a heavily shadowed tree with those produced by a model with no shadowing shows that higher error is still present in those unaffected by shadowing. Photographs should be captured at an appropriate time of day (such as noon with the high-sun) and over a period no longer than 30 minutes, as the sun's azimuth as well as surface albedo will change enough to affect the model quality (Bemis *et al.,* 2014; Gienko & Terry, 2014).

Figure 5.5: In order to measure model volume, it must first be made 'watertight' by using the close holes tool in PhotoScan (pink area in the left image). This tool can sometimes incorrectly link parts of the tree (right image).

5.1.9 SfM-MVS Camera and Equipment Requirements

The strengths of SfM-MVS are the low cost of equipment the low expertise required to use the software as well as the speed at which data can be acquired and processed. There are multiple advantages of using SfM-MVS for mensuration of tree metrics over other methods, especially for low-budget and small-scale applications.

The only instrument required for SfM-MVS data acquisition is a digital camera. A high-end camera of the calibre used in this study (Nikon D5000) typically retails for $750-1000, though any form of digital camera will suffice provided the method is sound. Compact digital cameras can be purchased for under $100 and data can also be captured using mobile devices such as smartphones and tablets. Wide-angle lenses are preferable (James & Robson, 2012) though fish eye lenses should be avoided due to their large distortion.

Metric cameras are those made specifically for photogrammetric purposes and have high precision optics and mechanics (White *et al*., 2013), though low quality consumer grade (non-metric) digital cameras can be used for SfM. More advanced digital SLR cameras will provide better quality and higher resolution images, but the time required for processing will also increase. Non-metric cameras normally have distortions associated with their zoom lens which vary with focal length, although improvements in calibration methods have reduced the error caused by these (Dandois & Ellis, 2010; Westoby *et al*., 2012).

The mobility and versatility of the hand-held camera are what set it apart from all other instruments. The camera used for this study weighed 560 g, substantially less than the typical 14 kg weight of a TLS system; cameras will continue to be far lighter for the foreseeable future (Liang *et al*., 2014b). TLS systems also need to be positioned on tripods to ensure they remain still throughout the duration of each scan; movement will cause blurriness in the laser points. Images acquired for SfM-MVS can be taken from a hand-held camera with no need for a tripod. Images can be acquired extremely rapidly and there are no limits on the number of perspectives that can be captured; the location from which images can be acquired is limited only to those which can be accessed by foot, i.e. SfM-MVS can be used everywhere laser scanning can be used, and more. It can also be used on aerial platforms such as UAVs (e.g. studies by Dandois & Ellis, 2010; 2013), meaning it is not limited to terrestrial use.

Image acquisition with a camera for SfM-MVS can begin immediately with very little setup time, whereas TLS requires substantial setup time for each scan. The majority of TLS systems are static and have to remain in position through the duration of the scanning time; this means multiple scans are required to minimise the issue of occlusion. Undertaking multiple scans also requires positioning of control points in the field in order to merge the scans together in post-processing (Dassot *et al*., 2011). These factors have prevented TLS from being utilised operationally in commercial forest inventory, despite them currently being regarded as the best suited instrument for reconstructing models of tree stems (Liang *et al*., 2014a).

One of the major advantages of SfM-MVS is that models can be generated on site using a portable laptop, which enables rapid assessment of whether the acquired images are adequate for more precise processing at a later stage or whether photos need to be retaken (Gienko & Terry, 2014). That being said, the high computing requirements of the SfM-MVS process mean the laptop will have to be of sufficient processing power, or that the quality settings of the initial model runs are kept lower. The high computational demand means battery reserves can drop quickly, meaning back up may be necessary for long days in the field (Westoby *et al*., 2012; Gienko & Terry, 2014). If the amount of data captured is inadequate or of insufficient quality then it can be recaptured rapidly at virtually no cost, an option seldom feasible for costly laser scanning methods.

5.1.10 Scaling Device

Application of spatial scale to the model is critical for ensuring distance and volume estimates are accurate. It requires the location (in terms of X-Y-Z co-ordinates) of at least two points be known. This means an external object of known dimensions can positioned next to the target object (e.g. the box used for the nursery trees or the surveying poles used for the landscape trees). An external object is often easier in the sense it that it can be a simple geometric shape which allows point markers to be placed accurately, however, to save on carrying extra equipment, there is no reason why natural reference features could not be used rather than an external object (Liang *et al*., 2014b), e.g. marking known points on the stem. Easily-recognisable targets will need to be positioned in order to be well represented in the imagery.

5.1.11 SfM-MVS Software

PhotoScan Professional (Agisoft LLC, St. Petersburg, Russia) can be bought for as a standard licence for $3499 though an institutional licence as used in this study is only $649. PhotoScan couples SfM and MVS algorithms in one fully-automated, graphically-friendly interface and package. Open-source SfM software is also freely available, though it is often not as straight-forward to use. There is also the potential to export point cloud models into other software (e.g. Meshlab) for more advanced analysis.

5.2 Suitability of SfM-MVS for Different Trees

The results show that SfM-MVS can be used to accurately model trees of widely varying size in order to be obtain accurate estimations of linear metrics. The size and shape of the tree itself does not seem to have an effect on the ability of SfM-MVS to reconstruct it. However, the landscape study trees were preferentially selected due to their anticipated suitability for reconstruction with SfM-MVS, and the suitability of a given tree for reconstruction will ultimately be determined by other external parameters. These external parameters include:

- Surrounding environment;
- Crown Shape;
- Leaf Habit;

Each of these parameters influences the likelihood of successful reconstruction, though whether or not a tree is well-suited to SfM-MVS will depend on the objective of the mensuration. The surrounding environment of a target tree include several aspects; 1) the position of tree relative to surrounding features; 2) characteristics of the background scene and; 3) ambient lighting and weather. The effect each of these aspects can have on model reconstruction has already been partly discussed, though there are certain parameters that are specific to the landscape trees.

5.2.1 Suitability of SfM-MVS - Position of Tree

Trees that are isolated (stand-alone) from surrounding features can be reconstructed more accurately than those that are not. This is because imagery can be more easily captured from the entire circumference of the tree without occlusion being an issue. If part of the tree is not captured in the imagery then it obviously cannot be reconstructed. This is an important consideration for modelling trees that are asymmetrical or have preferential growth in one particular direction.

The optimum amount of open space between the tree and surrounding features required will depend on the size of the tree and specifications of the camera. Cameras with a wide-angle lens (short focal lengths) allow photographs to be taken from close-range whilst at the same time capturing a field of view large enough to capture the entire tree in one shot. Focal length is inversely proportional to field of view, so wide-angle lenses may be especially helpful when other trees or features restrict the amount of open space around the tree. Lack of open space around the tree may prevent the tree from being captured in one frame. In this situation several 'rows' of images may be required, i.e. photographing the bottom half of the tree and then the top half and loading them to PhotoScan as individual chunks. This is a perfectly acceptable technique, though care will need to be taken to ensure enough overlap between the upper and lower images rows for them to align with each other. The larger photoset will also require more processing time.

If occlusion or lack of accessibility prevents imagery of the entire tree circumference being captured, it does not necessarily mean an adequate model cannot be reconstructed. Imagery from as little as a quarter of the tree circumference may be sufficient for reconstruction where at least the basic tree metrics can be estimated. Relying on such a small portion of the tree will obviously be unsuitable for certain applications. However, if the stem is non-circular it likely that the accuracy of the subsequent SfM-MVS DBH estimate will be negatively affected. However, so long as the tallest part of the tree is captured in the images, a partial model could potentially offer an estimate of height and crown depth. Too little is known about the effects on model reconstruction of photographing less than 360° of the circumference of a tree; clearly this represents a field of further study. Miscalculation of non-circular stems has faced the same issue (e.g. Kankare *et al*., 2013b; Saarinen *et al*., 2014). There are also implications for asymmetrical crown growth and the implications of these will be discussed in succeeding sections.

5.2.2 Suitability of SfM-MVS - Excurrent Branch Growth

The shape of a tree has a large influence on method of image acquisition; some tree shapes are easier to model than others due to the simplicity of their shape. The two main types of branch habits are excurrent and decurrent and these will be the main determinant of overall crown shape.

Trees that are excurrent branch growth have a leader (the stem) that outgrows all lateral branches, resulting in a cone-shaped crown with a well-defined central stem (apical dominance) (Fig. 5.6). Conifers are typified by excurrent branch growth, the crowns of which usually taper at a rate that matches the stem, narrowing to the top and thus the tallest point is easily-identified. Conifers make up large portions of the species used in the world's commercial forest plantations, particular in the boreal forests of Canada, Russia and Scandinavia. For example, Scots pine make up 24% of all the forested area in Eurasia (Urban *et al*., 2014), while Norway Spruce is considered one of the most important commercial species in Europe (Urban *et al*., 2013) Excurrent form is preferred for commercial forestry as growth focused in the stem promotes higher timber yields.

Trees with excurrent branch growth are more likely to allow relatively straight-forward acquisition of linear metrics due to their often relatively symmetrical shape. They are also easy to acquire imagery for as their appearance is reasonably consistent in form from all perspectives, meaning the tree need not be visible for its entire circumference for an accurate assessment of its dimensions (e.g. height and DBH) to be made.

Figure 5.6: Two examples of trees that display excurrent branch growth.

5.2.3 Suitability of SfM-MVS - Decurrent Branch Growth

Trees with decurrent growth form have lateral branches which outgrow the original leader, often resulting in expansive hemispherical crown shapes (Fig. 5.7). It can be difficult to identify the tallest point of these trees, especially when viewed from only one perspective, as their often-rounded crowns reveal no distinct peak. When viewed from the ground some parts of the crown cannot be seen at all and it may be impossible to accurately estimate the height of the tree.

If there is preferential growth of the crown in a particular direction and the only available perspective (unaffected by occlusion) happens to be such that the tree appears larger than it actually is, the resulting model reconstruction will be an unrealistic portrayal of the tree. Therefore where possible, the tree should be photographed from as many perspectives as possible; that it is to say, around the full 360° circumference. It can be very difficult to estimate the total volume or biomass of trees with excurrent branch growth, as this requires estimation of multiple lateral branches, rather than the more straight-forward estimation of a single stem in excurrent growth type trees.

As well as the background scene, the surface of the tree itself may be poorly reconstructed if. The crowns of trees can be geometrically complex, and the homogeneity and repetition that can be present in their structure can make distinguishing between individual branches more difficult, particularly small branches. Other prominent objects in the background may be important for providing keypoints to help with image alignment. This may mean imagery captured further back from the tree may be necessary, in order to incorporate more of the background scene in the imagery.

Figure 5.7: Two examples of trees with decurrent branch growth. It can be difficult to locate the tallest point or examine the branch architecture of these trees.

5.2.4 Suitability of SfM-MVS - In-Leaf vs. Leafless

When 3D metrics are of interest (volume and biomass), an accurate estimate would be almost impossible to achieve on most evergreen trees or deciduous trees whilst in-leaf, as crown foliage and branches can obstruct the view of the stem and branch structure behind. Whereas the various forms of laser pulses are able to penetrate gaps between branches and leaves (Liang *et al*., 2014a), photographs cannot do so. In saying this, laser penetration is only effective to a point, and occlusion of the stem by the crown has been an on-going issue for TLS studies (e.g. Kankare *et al*., 2013b) and will most likely continue to be.

For trees with no leaves, SfM-MVS provides a good tool for biomass estimation, particularly for trees with decurrent branch growth. Estimation of biomass of decurrent growth type trees using allometric formulae is almost guaranteed to involve a significant amount of error due to the difficulty of estimating multiple, seldom-linear lateral branches. In leaf-off conditions the lateral branches of these trees can be easily reconstructed and segmented in the PhotoScan image space to be analysed on a branch-by-branch basis.

Trees with dense crowns may actually be reconstructed better than leafless trees as the foliage provides additional surface area from which to identify reference points to aid image alignment and also reconstruct lateral branches that may have been too small to be reconstructed otherwise (Fig. 5.8). When linear metrics are of concern, an in-leaf crown makes little difference and may actually help identify the extent of crown spread. The exception to this would be if additional stem diameter measurements on top of DBH are required. However, when 3D metrics are required, foliage may present an issue.

For trees that display dense crowns, some volume may be able to be calculated if: 1) the height to the live crown is sufficient to allow visibility of the stem for a reasonable portion of its height, or; 2) if the stem is visible through the crown intermittently throughout its height. In these situations, whilst the entire stem may not be able to be visualised in the PhotoScan image space, at the very least the diameters can be obtained from the visible portions of the stem. These would have otherwise been inaccessible, to create a better-informed allometric taper model or verify the existing localised or national models.

Though SfM-MVS models are limited by what can be captured in imagery, settings in PhotoScan offer the ability to change the characteristics of the mesh model surface that may help to remedy the lack of visibility. The settings for the mesh surface can be changed so that interpolation is either 'enabled', 'disabled' or 'extrapolated'. Enabling interpolation creates additional surface in a circular radius beyond the dense point cloud points, in a sense 'filling in [some of] the blanks'. With 'extrapolate' selected the anticipated surface based on the surrounding model is generated. Both of these will reduce the need for the 'close holes' tool. Texture can be added to better visualise the tree surface and aid the placement of point markers. If parts of the stem are occluded by foliage or branches, the interpolation algorithm within Agisoft PhotoScan may help to model the stem behind them. This has not been tested herein, so will require further research to test the feasibility and accuracy of this approach.

Figure 5.8: An example of the same tree in leaf on and leaf off conditions; the leaves can provide more surface area (and therefore keypoints) to better align the imagery in PhotoScan. However, the leaves also prevent much of the stem and many of the branches from being seen, and therefore they cannot be reconstructed**.**

5.3 Application of SfM-MVS to Commercial and Urban Forestry

Considering the suitability of different trees for reconstruction with SfM-MVS, it is a method that may be more appropriate for some applications than others. However, when considering its utility for different applications, the fundamental issue with all photogrammetric methods must be considered; the fact remains that 2D imagery of a particular scene does not provide any information on what lies beyond the immediate surface captured (White *et al*., 2013). The innate limitation has been realised in DSI, where in closed-canopy forests only canopy height models cannot be produced if the ground is not visible within close proximity (St-Onge *et al*., 2004). This is because the ground is needed as a reference surface from which to calculate the heights of adjacent trees and canopy. The consequence of this limitation will be discussed in the coming sections. Unless an object is visible in the imagery, it cannot be considered or measured in any way. Therefore the utility of SfM-MVS is limited depending on what the research objective is.

5.3.1 Applications of SfM-MVS - Commercial Forest Inventory

Given the huge land areas usually involved, analysis of commercial forest plantations relies mainly on application of instruments designed for large scale aerial analysis like ALS, DSI or aerial or satellite photogrammetry. Terrestrial SfM-MVS simply isn't capable of capturing information over the vast spatial area that the latter two methods can, however, validation with plot-scale ground truth data by way of traditional mensuration methods is still an essential part of the inventory process. The timber volume of a stand is calculated by extrapolating plot values, the calculation of the latter has heavy reliance on site-dependent allometric stem taper models as height, DBH and stem density are the all-important metrics (Watt & Donoghue, 2005). For example the Austrian national forest inventory takes into account only four metrics; height, DBH, height to live crown, and diameter at 3/10 of the tree height (Berger *et al*., 2014), while the Finnish national inventory uses species, height and stem diameter at 1.3 m and 6 m height (Liang *et al*., 2014a).

Stand-alone trees cannot be found in commercial plantations due to the density at which trees are planted and managed; this makes it virtually impossible to capture an entire tree in imagery without some form of occlusion from the stems and crowns of neighbouring trees or any understory growth that may be present. The heights of individual trees can be difficult to measure as they are often occluded by the crown and branches of the canopy of neighbouring trees (West, 2009). Occlusion has remained a consistent issue for TLS systems of forest resources, enough so for success stem location to be included as a parameter in its own right (e.g. Strahler *et al.,* 2008; Moskal & Zheng, 2012; Liang *et al*., 2014a). The lack of open space with which to work means the utility of SfM-MVS in commercial forests is limited, though the mobility of the camera means this may be able to be partly overcome through simply changing position.

SfM-MVS certainly offers a very accurate tool for measuring stem volume (as shown by the nursery tree results), so it may be of use for stem-only harvesting, though the conditions required for its use will depend on the conditions discussed in the preceding sections. If the stem is un-crowded by branching and is visible for a considerable portion of the tree's height and vegetation is sparse understory vegetation tree stems may be able to be modelled for a portion of their height. This will also depend on ambient lighting being sufficient, as dense canopies can create very dim lighting. Commercial forests may provide suitable conditions for SfM-MVS, as the trees often have simple structure and the understory is generally kept clear of vegetation (Maas *et al*., 2008). The suitability will of course depend on the type of forest and level of management; tropical forests and even some coniferous species (e.g. spruce) will not offer enough sub-canopy visibility due to the density of their lower branches and leaves (Liang *et al*., 2014b). Commercial trees are usually managed in such a way that lower stem branching (up to 6 m, but dependent on the species) is removed through pruning and trimming to promote high wood quality (e.g. knot free), which will enhance sub-canopy lighting and visibility. Whether the trees are evergreen or deciduous is also important because if they are deciduous then there will be times of the year when visibility will be greatly improved.

Perhaps in combination with ALS, SfM-MVS could be a potent tool. As Saarinen *et al.* (2014) notes, one especially interesting option is a combination of ALS and TLS data in which ALS can be used for measuring tree height and TLS is used for providing not only the accurate position of all trees but also detailed information about the quality of the tree stem. As TLS is similar in nature to SfM-MVS. The use of SfM-MVS for commercial forest inventory definitely requires further research.

5.3.2 Applications of SfM-MVS - Urban Forest Inventory and Ecosystem Services

The management of urban forests through maintaining up-to-date inventories is now becoming commonplace (Tanhuanpää *et al*., 2014) and maintaining records of individual tree metrics is useful for a number of reasons, such as allocation of resources for maintenance (e.g. pruning and watering), monitoring growth over time and identifying trees that pose hazards (due to things like decay or wind damage). The value of trees are recognised through local government protection In New Zealand; resource management plans prepared by local government bodies provide detailed lists of trees protected for their historical, ecological or recreational significance and catalogued with great detail. There are societies such as the New Zealand Notable Trees Trust whose Tree Register is dedicated to cataloguing and educating about significant trees and nationally-important trees. The number of trees in these registries often number in the hundreds, so cost of data acquisition is an important consideration.

As well as for management and maintenance purposes, there is an increasing body of research examining the contribution of urban forests and individual trees to ecosystem services, such as pollution reduction (e.g. Nowak, 2006), carbon sequestration (e.g. Nowak & Crane, 2002), storm water attenuation (e.g. Xiao & McPherson, 2011) and urban climate regulation (e.g. Chen *et al*., 2006). Understanding the value of urban forests allows urban planners to make more informed decisions regarding their management (Nowak *et al*., 2002). The 3D structure of trees is important for fields of research that require accurate dendrometry for proper calculation, e.g. the role a tree plays in reducing airborne pollution or acting as carbon sinks can only be precisely quantified with accurate measure of its biomass. There is also more likely to be a focus at an individual tree-scale.

Urban forest inventories typically contain standard metrics of height and DBH as well as location, however, whereas mensuration in commercial forestry is chiefly focused on timber volume (i.e. resource appraisal), urban tree inventories and analysis of ecosystem services generally include just as large an emphasis on qualitative information that help to describe tree health, which cannot be described by spatial metrics alone (Ostberg *et al*., 2013). Biomass is a more relevant metric than volume and there is known to be a lack of focus on the biomass of individual trees (Fernández-Sarría *et al*., 2013). Ecological studies also examine the tree in greater detail, with research into such things as stem breakage and bark thickness.

There is also interest in measuring the dimensions of the crown. Crown dimensions are essential for evaluation of radiation interception and evapotranspiration (Moorthy *et al*., 2011). Determining tee canopy cover is an increasingly popular metric, not just in a horizontal sense, but in also in a vertical sense (McPherson *et al*., 2011). The potential to use the residual biomass that results from pruning urban forests has been examined by Fernández-Sarría *et al.* (2013).

SfM-MVS is a method that is particularly suited to modelling individual trees in high detail. As the models are image-based, allowing high-resolution 3D visualisation of the tree, it is also suited to acquisition of qualitative data. The visual representation of a tree SfM-MVS can provide is better suited for assessment of ecological services than TLS. For estimates of biomass or crown dimensions, a model representing the entirety of the tree may be important meaning imagery from the entire 360° circumference of the tree is likely to be required to provide a realistic estimate.

Stand-alone trees are far more numerous in urban areas, allowing straight-forward acquisition of imagery from the entire tree circumference. Many urban trees are planted with the purpose of enhancing the surrounding urban environment by means of serving some or of function e.g. proving shade or standing out as natural 'features'. Many 'notable' trees are certainly in this category, with most being stand-alone due their protection status. Obstacles such as other trees, buildings and roads present a challenge when photographing the tree as they obscure the tree or prevent access, to capture imagery from certain perspectives. However, the trees often lend themselves to being suitable for analysis with SfM-MVS as their growth is often managed for practical purposes (e.g. pruning lower branches of the crown) such as allowing access for mowing as well as creating space and allowing greater light penetration and understory visibility.

Work by Holopainen *et al.* (2013) and Saarinen *et al.* (2014) had already examined the role TLS could play in managing urban forests. Given the road infrastructure already in place in urban environments, urban forests naturally lend themselves to being suitable for vehicle-based TLS, however, their use is mostly restricted to vehicle access ways, and a vast portion of urban trees will be unable to be accessed in this manner.

SfM-MVS is an ideal tool for repeated surveys and it can be undertaken on a frequent temporal basis to monitor growth or changes over time, as these can be carried out at virtually no cost. As Morgenroth and Gomez (2014) note, SfM-MVS is a method that can be used by anyone with very little training. It is also a method that can utilise crowd-sourcing for images, a method which could significantly increase the efficiency of image acquisition.

5.4 Conclusion

In summary, this research was undertaken to answer the research questions: 1) is SfM-MVS capable of reconstructing spatially-accurate 3D models from which 2D (linear) and 3D (volumetric) metrics can be estimated; 2) can SfM-MVS be used to model trees of a range of species and sizes, and; 3) how few images are required to reconstruct a model from which 2D metrics can be estimated. PhotoScan Professional

This thesis determined that SfM-MVS is capable of producing high quality 3D models of trees, from which 2D and 3D estimates can be accurately made from models reconstructed with images acquired in controlled field settings. The standard tree metrics of stem volume, height and stem diameter could be estimated to a degree of accuracy as least as high as other terrestrial remote sensing technologies and significantly higher than allometric taper models used in traditional field dendrometry. Slender branches were the most poorly modelled component of the study trees, though these were negligible in regard to the overall tree volume.

SfM-MVS is capable of reconstructing models of trees across a range of species and sizes. Height and DBH can be accurately estimated from models reconstructed from photosets containing as few as 20 images. Tree height appears to have no influence on the minimum number of images required to reconstruct it. Furthermore, the minimum number of images required to facilitate image alignment in PhotoScan appears to have no influence on the accuracy of the 2D metrics from the subsequent model. Therefore the quality and spatial-accuracy of SfM-MVS models is determined primarily by aspects of the methodology as well as external parameters.

Methodological considerations include such things as the number of images acquired, the resolution of that imagery, the quality of the camera and computing power available for model reconstruction. External parameters that will affect the quality of the models include such things as the position of the tree, the background scene, and lighting and weather. Stand-alone individual trees are likely to be the best candidates for SfM-MVS reconstruction as these provide the best opportunity for image acquisition around the full 360° circumference of the tree in order to estimate 3D metrics.

The accuracy of tree metric estimates SfM-MVS can achieve with respect to the cost of equipment and acquisition makes it a very attractive method for dendrometry over a small spatial scale when compared with traditional dendrometry and other terrestrial remote sensing technologies. It is a method that requires no specialised equipment or expertise to carry out, for both the photography and model reconstruction steps and can produce estimates of tree metrics

In conclusion, this thesis has successfully demonstrated the ability of SfM-MVS to produce spatially-accurate reconstructions of trees across a range of species and sizes, as well as outlined some of the factors that influence success of model reconstruction. The findings of this study will go a long way toward increasing the breadth and depth of knowledge around the use of SfM-MVS for tree mensuration.

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7.1 Appendix

Table 7.1: Geographic co-ordinates for each of the landscape study trees

41°17'6.50"S 173°14'36.21"E	41°20'51.60"S 173°12'10.49"E
41°17'7.12"S 173°14'35.06"E	41°20'36.51"S 173°12'26.46"E
41°18'26.59"S 173°13'53.78"E	41°20'4.07"S 173°12'21.96"E
41°18'27.11"S 173°13'53.38"E	41°19'49.23"S 173°12'42.62"E
41°19'45.25"S 173°12'49.97"E	41°24'27.27"S 173° 2'28.08"E
41°20'2.26"S 173°12'20.01"E	41°23'6.91"S 173° 9'31.93"E
41°28'48.50"S 172°52'37.94"E	41°17'5.94"S 173°14'38.23"E
41°28'48.71"S 172°52'38.56"E	41°24'28.29"S 173° 2'27.20"E
41°28'54.11"S 172°52'47.16"E	41°15'49.42"S 173° 8'40.94"E
41°28'55.07"S 173°48'51.58"E	43°29'56.50"S 172°39'18.74"E
41°28'55.17"S 172°52'52.66"E	41°20'4.63"S 173°11'23.51"E
41°28'55.32"S 172°52'49.37"E	41°19'16.77"S 173°15'8.00"E
41°28'55.68"S 172°52'49.20"E	43°29'56.28"S 172°39'16.39"E
41°28'55.72"S 172°52'49.32"E	41°28'48.54"S 172°52'38.55"E
41°28'56.61"S 173°48'52.72"E	43°29'53.60"S 172°39'19.85"E
43°32'10.33"S 172°36'59.47"E	43°31'9.17"S 172°35'32.13"E
43°32'4.84"S 172°36'53.88"E	