B.Sc. Thesis, Faculty of Forest Sciences and Forest Ecology Georg-August-Universität Göttingen

Obtaining 3D Data from Trees: A Comparison of Photogrammetric Reconstruction and Digitization with a Magnetic Motion Tracker

Joel De Saint-Ours

21226907

Primary Assessor: Prof. Dr. Winfried Kurth

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Erzeugung von 3D-Daten für Bäume: Ein Vergleich von fotogrammetrischer Rekonstruktion und der Digitalisierung mit Hilfe eines Magnetic Motion Tracker (Magnetischer Bewegungsverfolger, MMT)

Zusammenfassung

Zwei kostengünstige Methoden zum Erhalt struktureller Daten von Bäumen sind das Magnetic Motion Tracking (MMT, dt. Magnetische Bewegungsverfolgung) und die auf Fotogrammetrie basierende Structure from Motion-Technik (SfM, dt. Struktur aus Bewegung). Ziel dieser Bachelorarbeit ist es, diese beiden Methoden danach zu bewerten, wie gut sie die strukturellen Eigenschaften beschreiben, und sie hinsichtlich ihrer Vor- und Nachteile zu vergleichen. Dazu wurden beide Methoden getestet anhand der Messung im Labor von einer kleinen Probe der Baumart *Pinus sylvestris*. Vier Kiefern verschiedener Größen im Alter von 3 - 6 Jahren wurden digitalisiert durch Messung signifikanter Punkte, die das jährliche Wachstum (Nodien) entlang einzelner Triebe anzeigen, um daraus XYZ-Koordinaten zu erhalten.

Für die Bewertung von MMT wurde das Polhemus FASTRAK Gerät verwendet. Damit wurde jedes Nodium manuell gemessen, indem der Stylus-Empfänger an die spezifischen Punkte gehalten, und eine Messung ausgelöst wurde, die dann automatisch in einer Tabelle mit den XYZ-Koordinaten aufgezeichnet wurde. Für SfM mussten für jeden Baum mehrere Fotoserien aufgenommen werden. Die Bilder wurden dann mit der Agisoft PhotoScan Professional Software bearbeitet, um eine Punktwolke des Baumes zu erstellen, auf der die Nodien digital markiert und gemessen und dann zur Extraktion der Koordinaten exportiert wurden. Die Ergebnisse konnten dann analysiert werden, unter Berücksichtigung von Faktoren wie Ergonomie, ökonomischen Überlegungen, Skalierbarkeit und Ausmaß menschlicher Fehler.

Beide Mess-Methoden liefern genaue Ergebnisse. Diese Arbeit beabsichtigt es nicht zu bestimmen, welche Methode genauer ist. Um jedoch das Ausmaß menschlicher Fehler im Gebrauch beider Techniken zu ermitteln, wurden die durch MMT erhaltenen XYZ-Koordinaten gegen die durch SfM erhaltenen aufgezeichnet, um zu sehen, ob und wie unterschiedlich die Ergebnisse waren. Es gab eine sehr hohe Korrelation, aber allgemein war eine Diskrepanz in den Ergebnissen der X-Koordinaten festzustellen.

Im Hinblick auf ergonomische und ökonomische Gesichtspunkte zeigten beide Methoden beachtliche Vor- und Nachteile. Während SfM optisch viel ansprechendere Modelle produziert, ist es für den Erhalt struktureller Daten weniger nützlich als MMT. MMT kann strukturelle Daten auf sehr einfache Weise sofort erstellen und zeigt jedoch eine stark vereinfachte Oberflächenform an. Damit können XYZ-Koordinaten direkt vom Stylus auf den Computer übertragen werden. Obwohl am Anfang der Messvorgang generell länger dauert als die Aufnahme der Fotoserien bei SfM, ist das Endergebnis einfacher zu bearbeiten. Darüber hinaus ist MMT besser für größere Bäume geeignet, bei denen SfM zu Problemen führt: Kleine Zweige an den Extremitäten sind schwer zu fotografieren, ohne von anderen verdeckt zu werden, so dass die Zuverlässigkeit ihrer Rekonstruktion in PhotoScan Professional beeinträchtigt wird. Dies wurde offensichtlich in der Schwierigkeit bei der Digitalisierung der komplexen Teile von Baum 11 und meinem Unvermögen, alles, was über Achsen mit Rang-Code der dritten Ordnung hinausgeht, genau zu betrachten und zu digitalisieren.

Die Ergebnisse zeigen, dass SfM und MMT – beides genaue Techniken, die 3D-Modelle von Bäumen und Baumteilen erzeugen können – wesentliche Vor- und Nachteile haben. MMT ist letztlich die bevorzugte Methode, da die Erzeugung von Strukturdaten einfacher ist und das Verfahren auf größere Bäume skaliert werden kann.

Abstract

Two low cost methods of obtaining structural data from trees are Magnetic Motion Tracking (MMT), and Structure from Motion (SfM), a photogrammetry-based technique. This thesis aims to evaluate these two methods, by assessing how well they describe the structural properties, and to compare their advantages and disadvantages. To do this, both methods were tested by measuring small samples of *Pinus sylvestris* in laboratory conditions. Four pine trees of various sizes, between the ages of 3 – 6 years, were digitized by measuring significant points that characterize annual growth (nodes) along individual shoots in order to obtain XYZ-coordinates.

The Polhemus FASTRAK device was used to evaluate MMT. This involved the manual measurement of each node by holding the stylus receiver to the specific points, actuating the stylus then automatically recorded the measurements, in particular the XYZ-coordinates, in a table. For SfM, several series of photographs for each tree needed to be taken. The images were then processed using the Agisoft PhotoScan Professional Software to create a point cloud of the tree, on which the nodes were digitally marked, measured, and exported for extraction of the coordinates. The results could then be analysed, taking into account factors such as ergonomy, economic considerations, scalability and the scope for human error involved in each method.

Both methods of measuring provide accurate results; this thesis does not aim to determine which method is more accurate. However, in order to evaluate the scope for human error in using each technique, the XYZ-coordinates obtained from MMT were plotted against those obtained using SfM, to see if and how different the results are. There is a very high correlation, however it was noted that there is in general a higher discrepancy in the results for the X-coordinates.

In terms of ergonomy, and economic considerations, both methods had significant advantages and disadvantages. Whilst SfM produced much more visually appealing models, it was less useful and more cumbersome for gathering structural data than MMT. MMT can directly measure structural data in a straightforward way, though only recording a greatly simplified surface form. This allows XYZ-coordinates to be recorded straight from the stylus to the computer. Although the initial measurement process tends to take longer than photographing the tree for SfM, the end result is easier to work with. Furthermore, MMT is more suitable for larger trees as problems become apparent using SfM: Small twigs at the extremities are difficult to photograph without overlap from other branches, thus reducing the reliability of their reconstruction in PhotoScan. This was exemplified by the difficulty in digitizing the complex sections of Tree 11, and inability to accurately view and digitize anything beyond axes with rank code of the third order.

The results demonstrate that whilst both methods are accurate techniques which are capable of producing 3D models of trees and parts of trees, SfM and MMT both have significant advantages and disadvantages. MMT is ultimately the preferred method as obtaining structural data is straightforward and the method is scalable to larger trees.

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1. Introduction

1.1. Motivation

In commercial forestry as well as in scientific analysis and experimentation, it is often important to know precise structural data about trees. However, measuring trees is challenging as their shape and size rarely allow accurate manual measurements to be taken easily. Thus, several different methods have been developed to allow accurate structural data to be obtained. These include highly specialized non-contact techniques such as LiDAR (light detection and ranging), and contact 3D scanners such as an articulated arm coordinate measuring machine (CMM). These methods, however, require significant expertise as well as expensive proprietary technology. As such, other technologies are becoming more widely used; two accessible techniques of measuring trees are magnetic motion tracking (MMT) and the photogrammetry-based Structure from Motion (SfM) method. These are becoming more widely used, and greater understanding of their advantages and disadvantages would allow for them to be further utilized, including by non-experts who may need to obtain precise information about trees.

1.2. Problem statement

What are the comparative advantages and disadvantages of photogrammetry (using SfM), and MMT as methods for obtaining structural and surface data from trees? How well do the methods measure and describe said data?

1.3. Aim of the work

The thesis aims to provide a comprehensive overview of how photogrammetry and MMT are capable of describing the structural and surface properties of trees, and to outline the process of digitization using each technique. In order to do this, I discuss the two methods in the context of taking measurements of small samples of *Pinus sylvestris* in laboratory conditions. Based on the experiment, the paper aims to evaluate the two methods of obtaining data for use in forestry and related disciplines. It further aims to assess their advantages and disadvantages, particularly in terms of ergonomy, economic considerations, scalability, and the scope for human error. The paper focuses on measurement of structural data and aims to determine which method allows for the best description of the tree's structural arrangement.

1.4. Introduction to the methodological approach

In order to analyse and compare the two methods, 4 pine trees of various size were digitized by measuring significant points characterizing annual growth (nodes) along individual shoots and comparing the XYZ-coordinates obtained though the individual techniques.

For MMT, this involved the manual measurement of each node by holding the stylus receiver to the specific points, which was then automatically recorded in a table containing the XYZ-coordinates. SfM first required taking several series of photographs for each tree, and then processing them using the Agisoft PhotoScan Professional Software to create a point cloud of the tree. The nodes were then digitally marked and measured on the model, before being exported for extraction of the coordinates.

The results obtained were plotted against each other on graphs, to allow for a comparison of results in the X-, Y-, and Z- axes and an assessment of the accuracy of the techniques.

1.5. Structure of the thesis

The paper is divided into five sections. The current section introduces the work, whilst Section 2 provides a brief overview of the technologies, how they function, and their appearance in academic literature related to the topic. The case study and results are set out in Section 3, and the conclusions and critical reflections make up Sections 4 and 5 respectively.

2. Overview of the two methods

There are many different methods of obtaining data from an object for its reconstruction as a digital 3D model. These methods may be used for a variety of reasons: for example, to gain a better understanding of the object through 3D visual representation than would be possible from other methods such as 2D images, or for creating a digital replica of the object in its current state for further analysis because conventional methods do not allow for the desired measurements to be taken.

2.1. Acquisition of 3D data using different technologies

Structural data considers how features of the object relate to one another. In the case of a tree, it provides an overview of the architecture, layout, and appearance. Surface data, on the other hand, is obtained directly from the exterior of the tree, and is more concerned with visual detail and surface form (Surový et al., 2016).

As this thesis aims to determine which methodology allows for the best description of tree structure, two methods of generating 3D digital copies of objects for structural analysis will be compared. The following sections provide an overview of how MMT and SfM generate the necessary data, and how these technologies have been adapted for modelling trees and parts of trees, even though they were not developed specifically for use in forestry.

2.1.1. 3D data from magnetic motion tracking

Magnetic motion tracking is a form of contact 3D digitizing, meaning that one records either XYZ or polar coordinates of points on the object. This form of digitization is mainly used for virtual reality or in biomedical applications (Danjon & Reubens, 2008). Having used different contact 3D digitizers, Moulia and Sinoquet (1993) determined that the most accurate device was a magnetic motion tracker made by Polhemus, and since then there have been several studies carried out solely with the Polhemus FASTRAK device (e.g. Danjon & Reubens, 2008; Surový et al., 2011; Yoshimoto et al., 2014).

The Polhemus FASTRAK consists of a transmitter that emits an electromagnetic field with a radius of up to 3m (with the long-range transmitter accessory) and a System Electronics Unit (SEU), which houses its own CPU and other hardware needed to calculate the position and orientation of up to four small receiving nodes, which are then connected to a computer (Polhemus, 2012). An individual point measurement is made when pressing the button on the receiver, the FASTRAK then records the position of the point through XYZ-coordinates, as well as its azimuth, elevation and roll, this is known as 6 Degrees-of-Freedom (6DOF) (Danjon & Reubens, 2008).

The Polhemus FASTRAK records all measurements with 6DOF, and includes real-time self-calibration (Polhemus, 2012). Therefore, all measurements are absolute instead of relative, so one does not need any sort of manual scale calibration to calculate dimensions from the resulting points (Polhemus, 2012).

Since a magnetic field can penetrate most materials, and therefore does not require line of sight between receiver and field emitter, using a MMT device enables taking measurements in sections that would be hidden or 'invisible' to other methods of acquiring 3D data, such as LiDAR or photogrammetry, without needing to reposition the device (Yoshimoto et al., 2014). However, being electromagnetic, MMT is sensitive to metal, and large metallic objects in the near vicinity can cause distortion of the field, falsifying measurements, or cause other negative effects to the system (Polhemus, 2012).

There are several ways of recording and processing the data received from the FASTRAK, from its various uses in other fields such as neuroscience and biomechanics to digitising tree stem surface as done by Yoshimoto et al. (2014) and reconstructing crown growth over individual years (Surový et al., 2011). In forestry, these methods can be classified as recording either surface data or structural data.

Structural data methodology is characterized by measurements with the FASTRAK made along branches, with a point digitized at each new shoot formation, and the surface of the resulting segment represented as a straight, uniform cylinder, to gain an understanding of the crown growth represented by the structure of the tree (Surový et al., 2011). Danjon & Reubens (2008) employed a similar technique, measuring at appropriate positions, such as change in direction, instead of growth markers, for analysis of the 3D architecture of root systems. Yoshimoto et al. (2014), on the other hand, recorded surface data by measuring vertical and horizontal sets of points on the surface of the tree stem, to then reconstruct a mesh from those points using an approach of 0-1 integer programming, maximising the amount of triangle peaks while minimizing the total surface area. This was done to create a 3D model of the stem form as accurately as possible, so that it is not necessary to rely on classical assumptions of stem shape to estimate different parameters.

2.1.2. 3D data from photogrammetry-based method

Merriam-Webster (2017) defines photogrammetry as “the science of making reliable measurements by the use of photographs”. The source for and complexity of measurements can range anywhere from a simple 2D measurement of distance between two points on a single photograph with a known scale, to determining the exact position of points, relative to the camera, in two or more images containing the same points (Bemis et al., 2014). This matching of points is the basis of obtaining data from photographs to be then processed into 3D models. However, there are different approaches which generate distinct types of models.

Stereo photogrammetry uses overlapping 2D images from two different (preferably parallel) views. It determines the 3D position of the known reference points by triangulating the intersection of the line of sight, between the camera and the point of reference, for the two different views, based on the motion parallax principle (White et al., 2013). This is done in much the same way that human visual perception of depth works (White et al., 2013). The approach is suitable for modelling terrain, forest canopies and other large scale objects, as well as for using those models to monitor change over time (e.g. Lisein et al., 2013, Vastaranta et al., 2013), but is not ideal for creating an independent 3D copy of an individual object.

An approach better suited for this kind of 3D modelling is Structure from Motion (SfM) in combination with Multi-View Stereo (MVS) (Morgenroth & Gomez, 2014).

2.1.2.1. Photogrammetry – Structure from Motion

It is possible to align many overlapping images and match the same object(s) in them, due to a breakthrough in computer vision with the algorithm SIFT (scale-invariant feature transform), which can detect feature points in images that are unaffected by scaling, translation, and rotation (Lowe, D. 2004). SIFT has been further improved by the algorithm SURF (speeded up robust features), which “relies on integral images for image convolutions” (Bay et al., 2008). When used in conjunction with SfM and MVS theoretically any camera can be used to digitally reconstruct an object (Surový et al., 2016).

SfM uses the assumption that “the object in a 3D scene is located on a vector between the image of the object in the camera and the object itself” to calculate the positions and orientations of the object and camera, based on the differential positions of the features matched by the previously mentioned algorithms (Morgenroth & Gomez (2014), citing Fisher et al. (2005), Quan (2010), and Szelski (2010)), resulting in a point cloud similar to those from LiDAR, but with a much higher density of points, up to a factor of 10 times more (Morgenroth & Gomez, 2014).

SfM, unlike traditional stereophotogrammetry, does not need control points or specific camera calibration to be able to create a model, as the generated point cloud has no absolute geographic position or scale. If one wants to glean information from the model that is more than just relative to other points, there are several methods to apply a real-world scale to the model, from something as simple as including an object of known dimensions in the images, to using measurements of known dimensions on the object (i.e. height of specific points) to calibrate the scale for the model, to deriving it from the position of the cameras (Morgenroth & Gomez, 2014).

MVS is a technique used to reconstruct a 3D mesh from the point cloud obtained through SfM, and on to which the texture from the RGB images can be mapped, forming a unified object from which other metrics, such as volume, can be determined (Morgenroth & Gomez, 2014; Surový et al., 2016).

2.2. Accuracy and application of the two technologies

Dendrometry is traditionally fraught with errors, either because of practical limitations, such as an inability to reach the intended points for measurement, or because necessary calculations for the estimation of metrics are based on the assumption that all the input data has been measured without error (Morgenroth & Gomez, 2014). Therefore, it is hard to assess the accuracy of new methods, especially when the accuracy of the technology is so closely coupled with the way the technology has been applied to derive the desired measurements.

2.2.1. Magnetic motion tracking

The Manufacturer of the Polhemus FASTRAK cites a Root Mean Square Error (RMSE) of 0.03 inches (0.762 mm) and an even better resolution, claiming the device to be the most precise magnetic motion tracker available (Polhemus, 2012). As such, the information from the device is assumed to be correct. However, Danjon & Reubens (2008), citing Moulia & Sinoquet (1993), note that errors using this technology do not usually come from the device, but from its implementation. Since the Polhemus FASTRAK has been used by Surový et al. (2016) as a baseline to test the accuracy of the reconstruction of trees, and by Danjon & Reubens (2008), to assess root systems, it can be assumed that the use of the FASTRAK is suitable for the digitisation of trees and parts of trees. To ensure accuracy through a similar implementation, the same Fastrak Digitizer software as that used by Yoshimoto et al. (2014), Surový et al. (2011), and Surový et al. (2016) will be employed in this thesis.

2.2.2. Photogrammetry – Structure from Motion

Morgenroth & Gomez (2014), in a proof of concept paper, used Agisoft PhotoScan Professional to digitize and reconstruct a 3D model of three trees of different species and size and in different environments, and concluded that tree height estimates had an error of 2.59% while stem diameter estimates had an error of 3.7%, easily meeting their requirement for reliability. They did however note that strong shadows affect the process, and that features not captured by enough pixels would not be reconstructed accurately, but would appear as something closer to noise in the point cloud, or result in an incomplete mesh reconstruction. There are several further studies which similarly conclude that results obtained through SfM meet required standards: White et al. (2013) mention that the accuracy of the resulting point cloud is comparable to that obtained through laser scanning, whilst Surový et al. (2016) calculated an RMSE of

1.87cm for the circumference at breast height (1.3m) for fully grown trees, in comparison to traditional field measurements. It was also determined that error is increased at the top and bottom of the object, because this usually coincides with lower visibility, and less overlap between images. It was also determined that as expected, the error value decreases with the number of images capturing the point, and discovered that there is a significant decrease of error with every extra image between 5 and 8, after which adding move views would not increase accuracy. Because of its wide use in studies, and the accuracy achieved with it, PhotoScan Professional will be used for the application of SfM in this thesis.

2.3. Summary of the two approaches

The two techniques use very different combinations of technologies, and each have unique advantages and disadvantages to arrive at the same result. While MMT utilizes specific hardware to determine points in a magnetic field, SfM can use the images from any conventional camera, but needs very advanced software to match the same points. However, one can use both techniques to digitize objects, more specifically trees, and reconstruct an accurate digital copy of the desired object in a 3-dimensional space.

3. Case study: Obtaining 3D data from *Pinus sylvestris*

To evaluate the process of digitization with the two different technologies, I have conducted a case study digitizing 4 pine trees between the ages of 3 – 6 years old, using both MMT and SfM photogrammetry. Digitization of these trees provides insight and understanding of the technique and methodology, allowing observations to be made on the ergonomic and economic aspects of each technique, as well as providing a comparison to each other.

As mentioned in Section 2.2, there have been studies with sufficient scope and scale to determine that the accuracy of both methods surpasses that of traditional techniques. However, the data sets collected from both digitisation techniques will be compared to each other to determine any differences caused by human error.

3.1. Plant Material

Pine trees provide excellent visual markers for annual growth (Surový *et al.* 2010). Thus, the study focuses on pine trees. These were provided by Dr. Lukáš Bílek[1] for Mr. Christopher Bahr[2], who was digitizing young pine trees using the Polhemus FASTRAK to create a functional-structural plant model (FSPM) for pine trees (*Pinus sylvestris*) based on work by Kurth (1994). As Mr. Bahr was working with structural data, I was able do the digitizing for him, to learn the process, while he would be able to use the data for his FSPM. Mr. Bahr had already digitized seven trees for his model, determining the methodology and notation of these samples. Therefore, my own comparison consists of trees 8, 9, 10, and 11.

Trees 8-10 were sourced from the edge of a forest stand at 50°33'33.248"N, 14°43'42.015"E. Unfortunately, no further information to the conditions in the stand could be obtained, as that section of forest was not managed by Dr. Bílek.

For Tree 11, I requested an older tree to see if increased tree size causes any limitations or difficulties during digitisation. Owing to the different age of Tree 11 it was sourced from a different stand located at 50°11'58.580"N, 12°47'33.646"E near the city of Loket. The Czech Forest Ecosystem Classification of the stand is 5M (*Abieto-Fagetum oligotrophicum*), meaning that it is a Fir-Beech forest with very poor nutrient supply (Viewegh et al., 2003). The stand has a wavy exposition, and is very strongly differentiated, with trees from the 1st to 6th age groups, even though the stand is 25 years old, and average tree heights for the different species ranging from 6 – 15 m. Tree 11 was a young tree regenerator near the border of the older stand.

3.2. Methodology

Because this comparison is also intended to provide a short introduction to 3D digitization and modelling, I provide a thorough explanation of my methodology, with each of the techniques and explanations as to why certain decisions regarding the method were made.

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[1] Ing. Lukáš Bílek, Ph.D., Department of Silviculture, Faculty of Forestry and Wood Sciences, Czech University of Life Sciences, Prague.

[2] Mr. Christopher Bahr, Student of M.Sc. Forest Sciences and Forest Ecology, Georg-August-University Göttingen.

3.2.1. Magnetic motion tracking

As I am digitizing structural data, I employed a similar method for digitizing the pine trees as that which was used by Surový et al. (2011) to digitize the crown of stone pines. This method was itself based on work done by Danjon & Reubens (2008), when digitizing woody root systems.

For digitization, I used the newest Polhemus FASTRAK magnetic motion tracker, coupled with the '4" (TX4) Extended Range transmitter', which has an ideal operating range of 0.30 – 2.13 m, and a single 3" Stylus, which according to Polhemus is designed to "allow access to those hard to reach places" (Polhemus, 2012). Both the transmitter and stylus have a very long wire, therefore the SEU can be placed somewhat further away from the object to be digitized, while still allowing for a great deal of free movement. So that I could digitize the pines without needing to reposition them, and to prevent any kind of interference by large metal objects, the transmitter was positioned high above the lab table, so that the entire pine would fit within the field. Each individual pine was attached to a wooden arm, using zip-ties around the stem, again to avoid bringing metal into the magnetic field.

Before I could begin with any digitization I needed to remove pine needles from the points which I intended to measure, as they were dense enough that even with the stylus I would not be able to reach the point without disturbing the tree, causing error in the measurement, as the point to measure would have been moved. This was relatively time consuming, as each individual needle needed to be hand-plucked from the start and end of each shoot, to ensure that only the needles were removed, that no twigs were broken off, and that the structure of the tree was otherwise undamaged. While plucking the needles, the tree was moved a lot, and therefore needed to be allowed to settle to ensure that the points to be digitized remained stationary.

The FASTRAK was then connected to my laptop via USB, and the data recorded using the Fastrak Digitizer 1.0 software developed by FORMATH Group (2013), using the FASTRAK API, specifically for the 3D digitization of trees instead of the proprietary software provided by Polhemus, as this is better suited to digitizing and reconstructing trees. The data was recorded in the Cylinders Grid of the Fastrak Digitizer 1.0 Software, using the Stylus Polling mode, where each press of the Stylus button records a new point, automatically recording the XYZ coordinates. The software then automatically creates a cylinder connecting each subsequent point measured, until a new set of cylinders is started manually.

The points to be digitized on the pine tree are based on the work done by Sinoquet et al. (1997) and the topology coding laid out therein. Shoot description in terms of axis (A1) being the entire shoot, and segments (S_n) being the internodes of annual growth, is maintained. However, the coding for a growth unit (U_n) is unnecessary, as that is simply signified by the last segment on the shoot, as shown in Figure 1 below.

Because of the distinctive way in which pine trees grow, with a very dominant apical shoot, each tree was digitized one shoot at a time, starting from the bottom of the stem and completing the digitisation along the axis, with each new node being a point to be measured, and the cylinders created by the software being the internodes. The parts of a pine tree defined as node and internode are clarified in Figure 2 below.

Once the whole length of the shoot had been fully digitized, a new set of cylinders could be started. The process was then repeated for the first shoot branching off from the stem, and continued with the digitization of each subsequent shoot branching off moving clockwise, and proceeded to the next whorl along the stem until the whole tree was digitized.

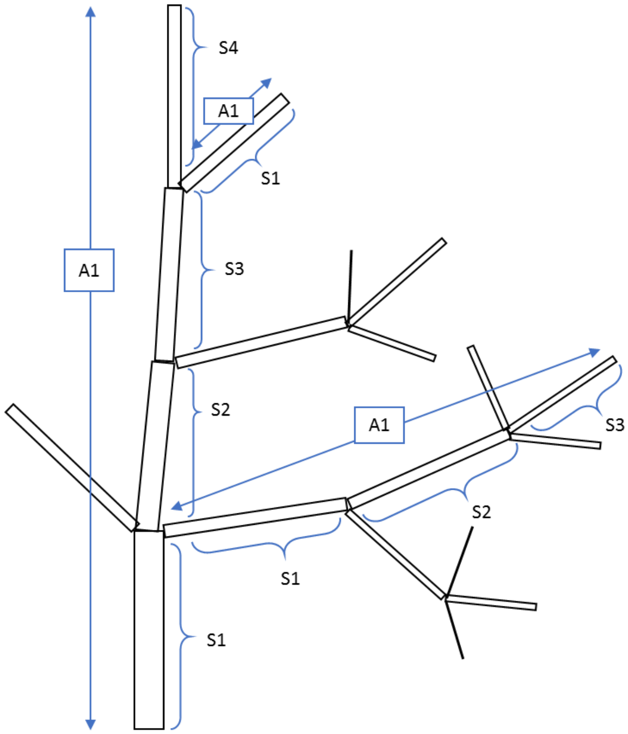

Figure 1. Illustration of a Pine tree detailing the breakdown of axes and segments.

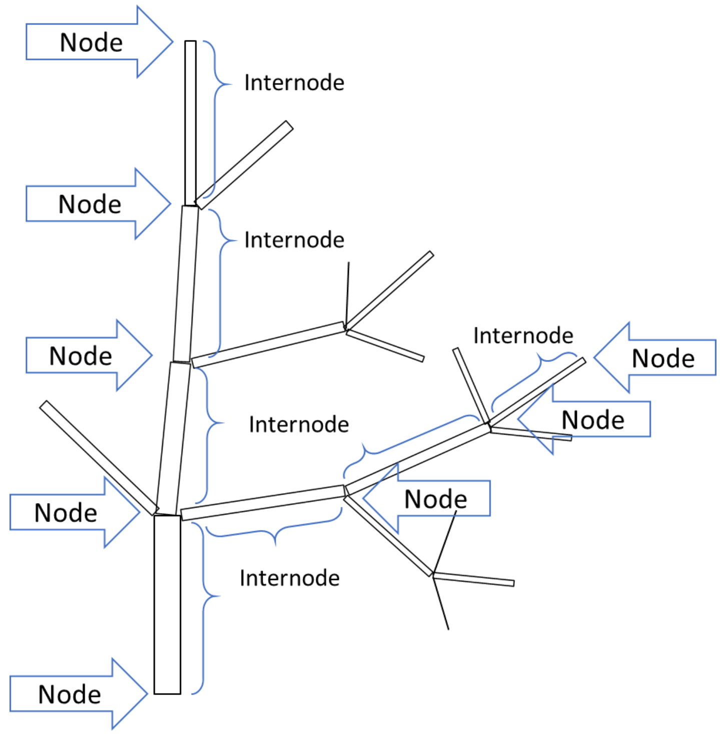

Figure 2. Illustration clarifying nodes and internodes on a pine tree.

This results in a different order for the points to be measured, as shown in Figure 3 below, giving each shoot/axis a rank. Because of this, the topological coding used by Sinoquet et al., (1997) needed to be modified to represent the rank and position from which the shoot branches off. This was done by assigning two further codes to each axis: the rank (r_n) of the branch, and the level (l_n) of the whorl from which it grows.

To clarify: the stem of the tree is the first axis to be measured, giving it the rank r1. The first shoot branching off from the stem is given the rank r1r1, to signify it is no longer on the primary axis, but has branched off once, as well as the code l1, showing that it grew out of the first whorl of the stem. The second shoot branching off from the stem is given the rank r1r2 and level code l1, continuing to the n^{th} shoot/branch on the n^{th} node having the rank r1rn. In each new branching off, a new layer of rank and level is added.

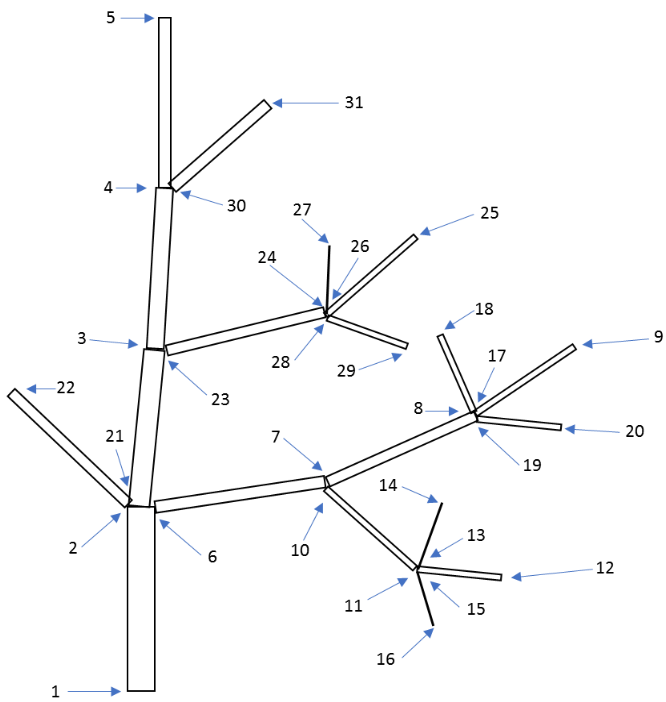

Figure 3. Illustration of a young pine, showing the order in which to measure the individual points with the FASTRAK.

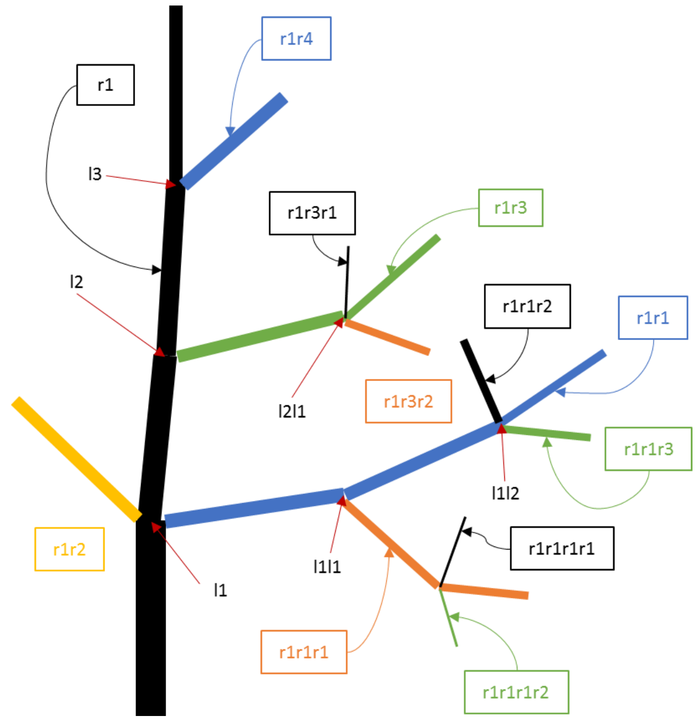

Figure 4. Illustration of the additional coding for rank and level.

e.g. a twig with the rank code r1r3r1r4 and the level code l1l1l2 means that it is the fourth shoot to be measured on the first shoot to branch off the third branch attached to the stem (r1). The level code denotes that the third branch attached to the stem (r1r3) branched off at the first whorl of the stem (l1), the first shoot on branch 3 (r1r3r1) branched off at the first whorl of that branch (l1l1), and the twig (r1r3r1r4) is attached to the second whorl on shoot r1r3r1.

A visual representation of the coding for rank of each axis as well as level of the individual nodes is shown in Figure 4 above.

3.2.2. Photogrammetry

Unlike MMT, photogrammetry is an automatic, non-contact method of digitisation. This means that it is usually better suited to obtaining surface data and determining volume (Danjon & Reubens, 2008). Therefore, a few additional steps are required to obtain the desired structural data.

As mentioned in section 2.1.2.1, any camera can theoretically be used to obtain measurements using photogrammetry. However, the detail and quality of the resulting model is affected by several choices relating to the camera and settings used. I used a Sony Alpha ILCE-5100 camera with an aperture set to f/8, a shutter speed set at 1/80 s, a prime lens with focal length of 50 mm, as suggested by Agisoft in the PhotoScan Professional user manual (2017), with the sensor set to record at 12 Megapixels (mpx), while using the automatic camera settings for all the other options.

The aperture determines the depth of focus. Because the limbs of a tree have a large spread, it is better to have a small aperture (a higher number) so that as much of the crown as possible is sharp and not blurred in the image. It is not only necessary to have sharp images so that PhotoScan can process them, but it also maximises the number of angles of capture for each point. However, a smaller aperture allows less light reach the camera sensor, resulting in a significantly darker image. Therefore, a compromise needs to be made. The choice of shutter speed is also important, as a slow shutter speed causes motion blur. While an extremely short exposure prevents such blur, it also reduces the amount of light hitting the sensor. It was therefore necessary to stabilise the camera with a tripod, allowing me to take photos with a smaller aperture and slower shutter speed. ISO is the last factor affecting exposure, a lower ISO usually means a finer quality, yet darker image, while a high ISO heightens the sensitivity of the sensor, resulting in a brighter photo, but more digital noise. The camera was set to control the ISO setting automatically, even though I was in a controlled environment with relatively uniform lighting, as there were changes due to the arrangement of branches.

The PhotoScan manual suggests taking photos at maximum resolution, however, instead of recording at the 24.3 mpx that the Sony ALPHA 5100 is capable of, I recorded the images at 12 mpx. This decision was a compromise between recording as much information as possible in each image, and keeping the file size of the images small enough to reduce the impact on the digital workflow of working with large image files. In addition, although approximately 2x more information is recorded, the difference to the end result of the model is not as large. Another advantage is the digital storage space that gets saved when taking hundreds of photos for each tree.

To try and ensure a high alignment of the images in Agisoft PhotoScan, while capturing each feature on each tree at least five times, a series of images consisted of images taken approximately every 20° at the same height over 360°. The aim is to have a series with the whole tree in the image, and then series repeated at different heights to capture a more close-up section of the different levels of each tree, essentially resulting in a sphere of camera angles. To help with consistency, markers from which an image

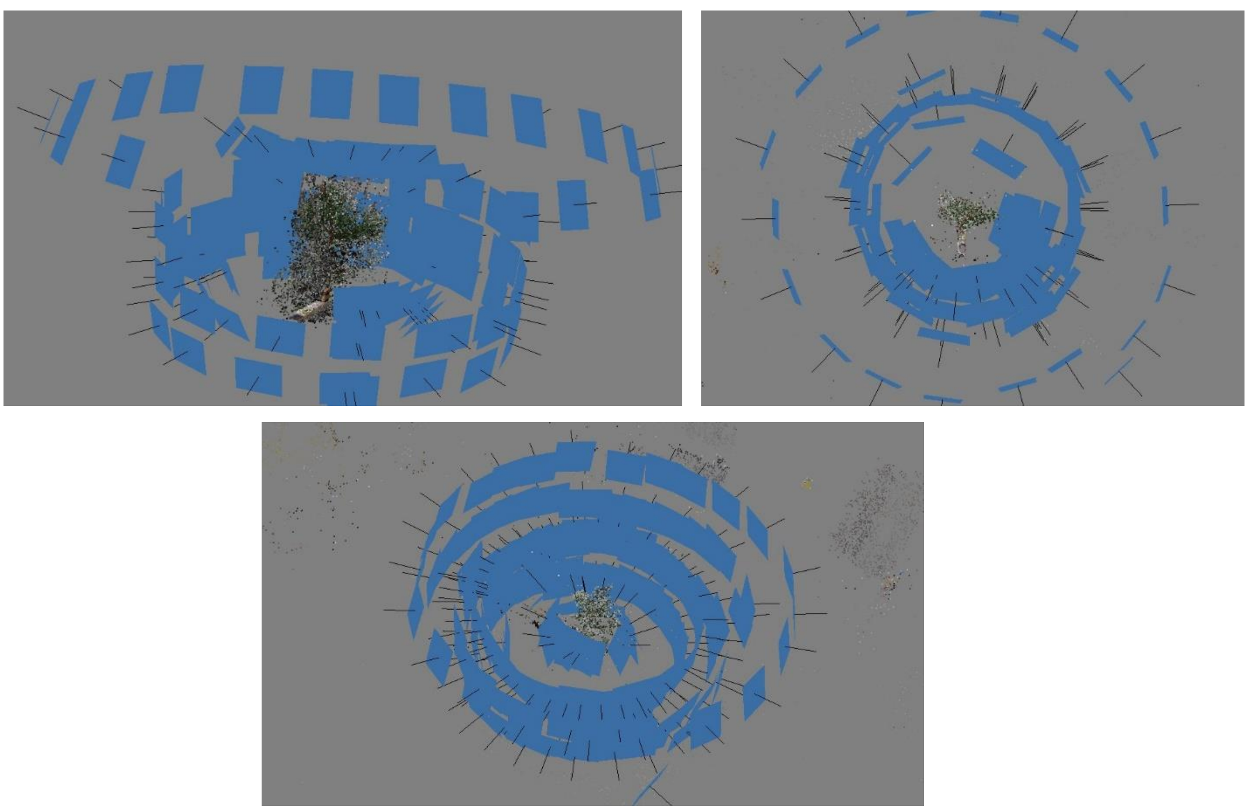

Figure 5. View capture from PhotoScan, showing the camera positions (blue squares) for each photo of Tree 10.

would be taken were placed on the floor at every 20°, as well as at the centre of the circle, where the tree would be positioned. Depending on the size and complexity of the crown architecture of each tree, this would result in approximately 100 – 300 photos per tree.

Figure 5 shows the resulting spatial distribution of the cameras, represented by blue squares, on Tree 10, giving an example of how a tree should be captured.

The captured images were then processed in PhotoScan by following the recommended work flow in the user manual. This consisted of loading the photos into the software and setting them to align at the highest accuracy settings the computer was capable of. Image pair preselection was turned off, as the dataset to be processed was still small enough to not make it a necessity. This meant that all points were matched across all possible images instead of from a subset of image pairs, resulting in better image matching. All other parameters were set as suggested by the software. As mentioned in section 2.1.2.1, a sparse point cloud is built from the points used to match the images. However, this sparse point cloud does not provide enough information from which to measure the desired structural data – see Figure 6.

Figure 6. Sparse point cloud of Tree 10 with needles (left) and without needles (right), generated from aligning and matching images.

Therefore, PhotoScan needs to build a dense point cloud, which produces a visually impressive representation of the tree. However, due in part to the complex shape of the tree crown, the dense point cloud is also very noise heavy. Once the noise has been cleaned, the dense point cloud provides enough visual detail to select points for measuring structural data. This difference is shown very clearly in Figure 7. Since it is now possible to zoom in and select specific structural points, further object reconstruction is unnecessary, especially since it would not improve visual detail, foregoing the use of MVS to generate a mesh model.

Figure 7. Dense point cloud of Tree 10 with(top) and without needles (bottom), immediately after being built, showing all the noise generated (left); and after manual clean-up (right).

Up until now the entire process was done twice for each tree, once with the needles attached, and once with all the needles removed. This was done to test the viability of reproducing the needles in PhotoScan, which could then be selected by colour and classified as needles, allowing for accurate biomass calculation, if so desired. However, even after having cleaned up as much noise as manageable, the dense point cloud is only able to give a general idea of the needles, as shown by the top-right image in Figure 7.

Figure 8 shows how the needles obscure the shoots, so as to make accurate point selection dubious. Therefore, any further processing and measuring was done using the dense point cloud of each tree without needles, which, as shown in the bottom right image of Figure 7, gives a much better understanding of the tree structure.

Figure 8. Close-up on the cleaned up dense point cloud of Tree 10, showing how the needles obscure the branches, preventing structural measurements.

To manually apply a scale to the point cloud, a marker needs to be placed on two points, of known distance to each other, and the distance between them, as well as the accuracy of this distance needs to be entered. These same two points need to be marked in at least two matched images so that PhotoScan can then use the matched points in those images to apply the scale to the rest of the model. The more images in which the same two points can be matched, the better and more accurately the scale can be applied to the whole model. In this case study, a protractor was included, and the 0 cm and 5 cm markers on the ruler used as points of reference.

To be able to compare the data from MMT with that obtained through SfM, both models need to be in the same position of the same coordinate system, otherwise the same points would have completely different coordinates. Therefore, it was necessary to manually assign reference coordinates to the point cloud. This is done by marking at least three reference points on the model, and then manually entering in X, Y, and Z coordinates. The reference coordinates used for each tree were taken from the measurement of r1r1 with the FASTRAK.

Then, because structural data was desired, the same points were measured with the same order and rank coding as those in the magnetic motion tracker. Using polylines to mark each axis, the individual points along the line marked the nodes. The polylines were labelled with the rank code of the corresponding axis, and saved in a shape layer titled 'Structural_Data'.

3.3. Data

Both methods generate visual reconstructions of each tree, as well as absolute numbers for the X, Y, and Z coordinates for each point.

3.3.1. Magnetic motion tracking

Exporting the data set containing coordinates into Excel for further analysis is very straight forward; the Fastrak Digitizer software gives the option to save the cylinders to XML. Excel can open the file as an XML table, but does generate its own schema based on the data. The data from Fastrak Digitizer also includes azimuth, elevation and roll as all points are recorded in 6DOF. Since this information is not relevant to structural data it can be removed. If so desired, the table formatting can be edited for better visual representation, and saved as a standard *.xlsx excel workbook. So that the data from all the trees is available in one file, the data set from each tree was saved on its own worksheet and all four worksheets saved in one workbook.

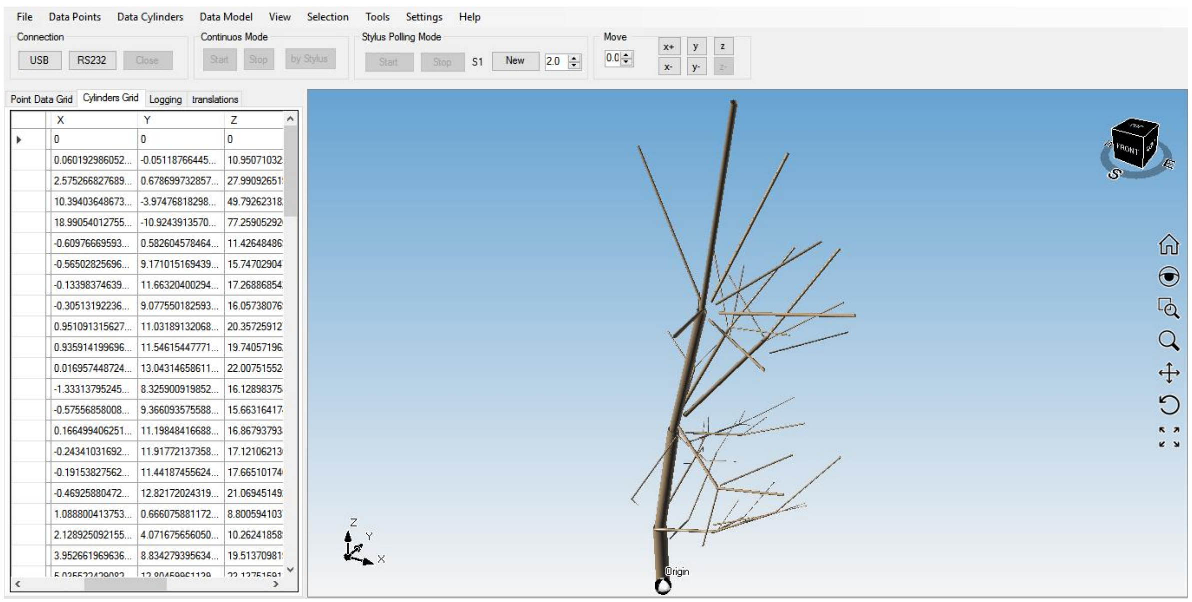

Figure 9. A Screenshot of the Fastrak Digitizer Software showing part of the data table, and the visual reconstruction of Tree 8 as digitised with the Polhemus FASTRAK magnetic motion tracker.

The visual data obtained is only visible in the Fastrak Digitizer software as shown in Figure 9. However, because of the versatile file extension, it is possible to open the file in a wide range of programs, although this does not guarantee that the data will be displayed in the same way, as different programs handle XML files in different ways.

3.3.2. Photogrammetry

For further analysis, the Structural_Data layer was exported as a shapefile (*.shp), so that the XYZ-coordinates of the nodes could be extracted using the attribute table in a GIS program like ArcGIS or QGIS, and saved as a comma-separated-values file (*.csv) to be opened in Microsoft Excel. As with the data obtained from MMT the tables generated were formatted for better representation, and saved in separate worksheets in the same workbook.

Unlike the MMT, the model created with PhotoScan, as well as individual parts of it, can be exported in numerous ways to be used with other programs, ranging from CAD to GIS software, depending on the model created. However, PhotoScan itself does present an appealing visual representation of the model, as shown in Figures 5-8, the end result of measuring the structural data with the polylines along each axis is shown in Figure 10.

Figure 10. View capture from PhotoScan showing the visual representation of Tree 8 as well as the polylines used to determine structural data.

As the data from both techniques have been tailored to contain the same type of data, their tables contain the same headings, an example of which can be seen in Table 1.

Table 1. Table with data for a Stem (axis r1) and the first shoot branching off (r1r1), showing an example of how topological notation, XYZ-Coordinates, as well as axis rank and level codes for the nodes are recorded.

FID	Topo	X (cm)	Y (cm)	Z (cm)	Axis Rank Code	Axis Level Code
1	A1/S1	0	0	0	r1	l0
2	/S2	0.06019	0.0511	10.9507	r1	
3	/S3	2.5752	0.6786	27.9909	r1	
4	/S4	10.3940	3.9747	49.7926	r1	
5	/S5	18.9905	-10.9243	77.2590	r1	
6	A1/S1	0.6097	0.5826	11.4264	r1r1	l1
7	/S2	0.5650	9.1710	15.7470	r1r1	
8	/S3	0.1339	11.6632	17.2688	r1r1	

3.4. Analysis

As mentioned in section 2.2, both techniques are accurate, therefore, any disparity between the data sets would have been caused almost entirely by human error. Because of the limited scope of the case study, no conclusions can be drawn as to which method is overall more accurate. However, to assess the difference in the data, the coordinates obtained for each tree from either method have been plotted against each other on a scatter graph, included in the Appendix section 7.1. Figures 11-13 show the XYZ-coordinates of both methods from Tree 8 plotted against each other.

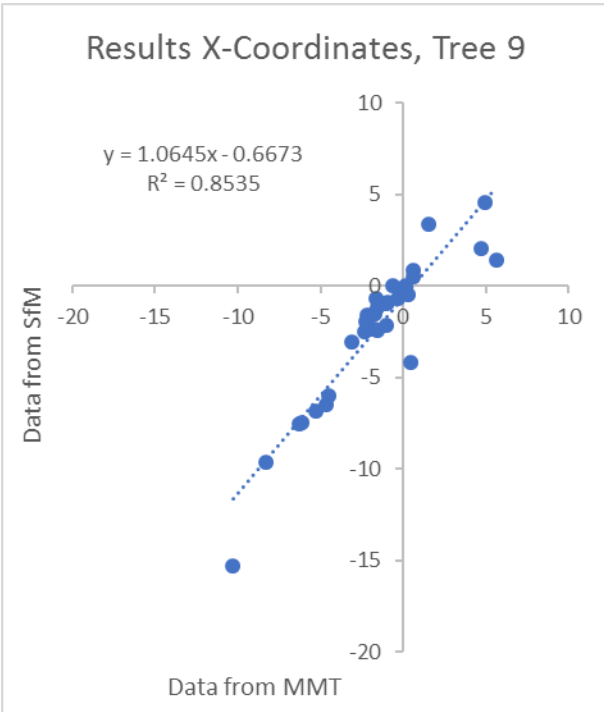

Figure 11. Graph showing X-coordinates measured for Tree 8 through MMT plotted against those obtained with SfM.

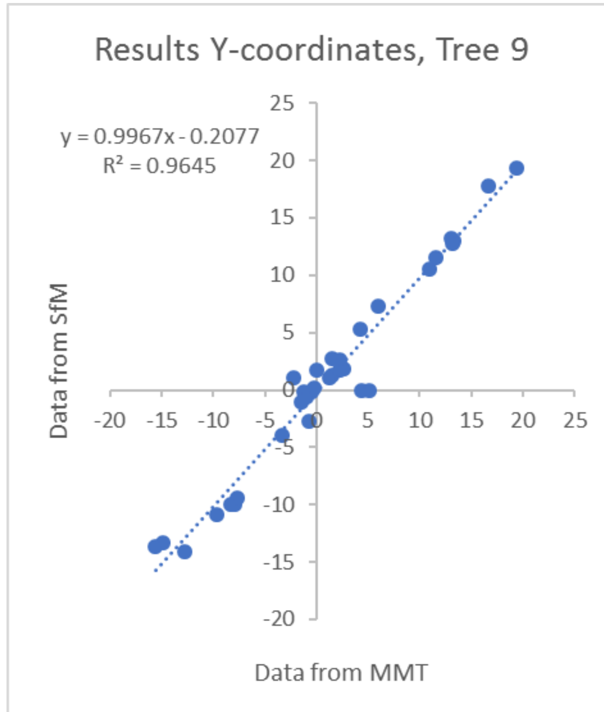

Figure 12. Graph showing Y-coordinates measured for Tree 8 through MMT plotted against those obtained with SfM.

As demonstrated in these graphs, even though the two techniques leave a large scope for human error, the results obtained from both methods are very similar. However, X-coordinates seem to be the least accurate, as there is a wider spread in the X-coordinates obtained, with R^2 ranging from $R^2 = 0.87$ for Tree 10 having the highest correlation, to $R^2 = 0.52$ for Tree 8 with the lowest. In comparison, the Y-coordinates measured are incredibly close, displaying a range of $R^2 = 0.97$ for Tree 10 again being the highest, and $R^2 = 0.91$ for the lowest, Tree 11. The Z-coordinates have the least error, with the highest coefficient being $R^2 = 0.995$ for Tree 10, and Tree 8 once again having the lowest, at $R^2 = 0.92$.

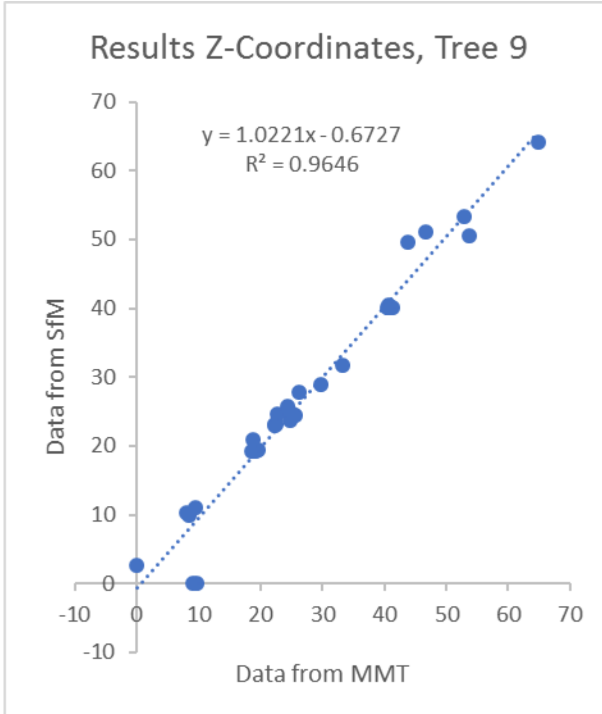

Figure 13. Graph showing Z-coordinates measured for Tree 8 through MMT plotted against those obtained with SfM.

Tree 11 is the largest, and Tree 8 is the second largest of the set. The data suggests the trend that the larger a tree is, the bigger the influence of human error, though a study at a much larger scale would need to be conducted to test this. I believe that in this case however, the higher amplitude of error in Tree 8 is caused by the fact that it was the first tree to be digitized, and the positioning of the FASTRAK stylus was as yet un-practiced. The high correlation for Z-values of Tree 11 (R^2=0.99) supports this theory.

3.5. Evaluation

The following section will assess the methods, both individually and together, and relate my experiences and any difficulties encountered.

3.5.1. Each method individually

3.5.1.1. Magnetic motion tracking

It must be mentioned that the rank code, depending on the tree size and complexity can become long and complicated. Having to constantly move between the tree, to measure a point, and the computer, to enter the rank and level notation, can easily lead to entering the code incorrectly and forgetting which point needs to be measured next, taking extra time to re-orient yourself on the tree and find your position. It also adds time to the process of digitization, due to the time taken to move between the two spots. In addition, the larger a tree is, the exponentially longer it takes to digitize.

e.g. Tree 10 (3 years old) had 36 points to measure, and Tree 11 (6 years old) instead of having merely double the amount of points, has 654 measured points.

Therefore, it is best to work as a pair: while one person is at the tree taking measurements with the stylus, the other person enters information on the computer. This is much more efficient, and greatly speeds up the work flow, especially with larger trees.

Another aspect that increased the time taken for digitisation was the Fastrak Digitizer software used. As it is version 1.0, the software contains a few bugs, which could at times cause it to stop working correctly, usually when attempting to access an unavailable function. If the measurements were not saved regularly, and the program crashed, valuable data would be lost. However, the real-time addition of cylinders, in the visual representation window with each new point measured, was incredibly useful, as it allowed for a visual comparison of the model generated with the tree being digitised, making any distortion caused by digitization too close to the edge of the magnetic field, or any other larger error, immediately apparent.

3.5.1.2. Photogrammetry – Structure from Motion

Using a tripod slowed down the process, but using a smaller aperture, the elimination of motion blur, as well as having all the images in a series taken from the same height was advantageous.

Navigation of the model in PhotoScan can be difficult, often moving the model in unintended ways. It is necessary to move the reconstructed model a lot to clean up the noise, as well as to measure the nodes along the axes with the polyline, and therefore requires a significant amount of time. It is also hard to maintain an overview of the model, as you are trying to view and navigate a 3D object on a 2D screen, however, the incredibly photo-realistic reconstruction is helpful in this regard. This gets more problematic the more complex a tree is, sometimes making the placement of a marker at the correct point on the model impossible, as it will attach to a point in front of or behind it, due to not being able to navigate into a good perspective.

The bigger a tree, and the more complex it is, the more small extremities it has, which, after a certain point, can no longer be accurately reconstructed in PhotoScan. It is impossible to capture enough views of the small twigs for them to be reconstructed as more than just vague clusters of points, making it often impossible to distinguish them from noise, due to overlap from all angles.

4. Conclusions

4.1. Comparisons

Based on the analysis and evaluation, this section will conclude the study. The factors which will be discussed are the scope for human error, ergonomy, economic considerations, and scalability. Based on these considerations, this paper concludes that, for obtaining structural measurements of small samples of *Pinus sylvestris* in laboratory conditions, MMT is the preferred method. However, it emphasizes that there are distinct advantages and disadvantages to both methods; whether SfM or MMT is more suitable will therefore be determined by a variety of context-specific factors.

4.1.1. Accuracy

As discussed in Section 2.2, it has been demonstrated that both SfM and MMT are accurate methods of obtaining data. As such, both methods should in theory produce the same results: the Polhemus FASTRAK can measure to 3/100 of an inch, whilst the potential for accuracy of SfM is limited only by the resolution of the photographs and the quality of reconstruction of the point cloud. Thus, considering that the same trees were measured using the two methods, the same results should have been obtained.

As demonstrated in Section 3.4, the results are indeed very similar, having a high correlation co-efficient, but some have a margin of error of up to 5 cm. This is due to the fact that human error in implementing the methods can result in inaccuracy. The human error in the case of the Polhemus FASTRAK may be caused by unintentional movement of the object being measured, as it cannot be fully fixed in place. As the FASTRAK is hand-held, it must be held steady, as close as possible to the tree without touching it. Additionally, pressing the button to record the point causes unintentional movement of the hand, thus affecting the point at which the measurement is taken, and causing inaccuracy.

Figure 14. Screenshot of Fastrak Digitizer, showing the displacement of points due to measuring from different angles.

Furthermore, the points will necessarily be measured from different angles, otherwise it will not be possible to reach the intended points, so the thickness of the stem and branches displaces the connection between two adjoining axes. An example is shown in Figure 14, in which axis r1 is measured along one side of the stem, however, depending on how the branches are attached, the measurement needs to be taken from the other side of the stem, causing a displacement at the node. Although algorithms can be written to try and rectify this problem by translating the measurements and bringing the lines together, this potentially results in further inaccuracy.

For SfM, the recreated point cloud theoretically has no scope for human error, as it is generated by the PhotoScan algorithms matching the photographs. However, the point cloud must then be cleaned up correctly (i.e. the noise must be removed without deleting any data). When drawing the polyline to obtain structural data, the points must be manually placed on the digital model of the tree. The problems of causing inadvertent movement of the tree, inherent in MMT, are avoided. The tree should not move while photos are taken, and if the resolution is high enough, it is possible to adjust and reposition the points as many times as necessary. This still requires visual identification of the correct point, but allows for far greater accuracy. The disadvantage is that this may be far more time-consuming.

Additionally, the problem with wrong alignment of the nodes encountered in MMT can be somewhat reduced using SfM, as it is possible to zoom in on the digital model to place the point further towards the centre of the stem or branch, as well as ensuring the connected axes start at the same node point, allowing for greater accuracy than a measurement taken from a point on the surface. Based on these factors, there is a smaller scope for human error in measurements taken using SfM.

4.1.2. Ergonomy

The Polhemus FASTRAK involves some effort at the outset: to take the initial measurements, it is necessary to set up the device, determine the points to be measured on the object, and to hold the FASTRAK to each of these points in order to record the data. Once the set-up process is complete, it is possible to immediately obtain the desired coordinate values. Depending on the size and complexity of the tree being measured, this may take a considerable amount of time – anything from half an hour to two weeks for a much larger tree, as mentioned by Surový *et al.* (2011). Furthermore, use of the FASTRAK involves movement – for example: having to crouch into uncomfortable positions to reach the right points. However, once the initial measurements have been taken, the data has been collected and is ready to be used. Depending on how the transmitter was positioned during measurement-taking, the model may be upside-down when recorded on the computer. Thus, in order to create a 3D model whose position more closely resembles the original object, it will be preferable (though not necessary) to translate the model to the origin (0,0,0) as well as adjusting the angle of the stem and rotation of the model.

By contrast, using SfM, taking photographs may be quick and straightforward. However, this depends on a number of factors. Depending on the tree size, it may be necessary to take a series of more than 300 photographs from the right positions. Taking a smaller number of photographs, freehand, will be much quicker and easier, however it also means that many of them are likely to not align, either resulting in wasted photographs or not having enough points for reconstruction of the tree. In order to ensure that all photographs will align, it is preferable to ensure that there are photos from the right angles to have enough overlap. In a laboratory setting this can involve setting up markers on the floor showing angles and positions from which photographs are to be taken. A tripod will also ensure focused images, but it will need to be moved each time a new photograph is taken. This is to do with the exposure settings, as discussed in Section 3.2.2. This takes additional time.

Unlike with MMT, further work is necessary using SfM, as the photographs must be aligned. The computer programme will do this automatically, but the process can take up to 12 hours. Additionally, the possibility of the computer not having enough memory is a potential problem.

The point clouds must be manually cleaned up: in this thesis, it has proven ineffective to select points by attributes, or in the case of the dense point cloud, by colour, as trees are too similar in colour to the noise generated. It thus runs the risk of deleting actual data instead of just noise. Therefore, in order to ensure that accurate data can be obtained, it is necessary to manually go through and select the desired points, determine whether or not they are noise and then delete them. After this, the markers must be placed accurately in the photographs to ensure the best possible calibrations of scale and reference coordinates. Once these steps have been completed, it is possible to obtain measurements of structural data, which again, depending on tree size, can take hours, as the same order of points is followed as that with MMT, but speeded up by moving in a digital space.

Thus, SfM requires users to spend more time over all, especially at the computer, working on the digital model. However, one consideration is, that for SfM, once the required images have been captured, there are no more requirements for you to be in any specific place. At the same time a lot more data gets recorded, meaning a much wider range of metrics can be derived or measured. Therefore, if there is a time constraint when accessing the trees, SfM would be the preferred option, as it is possible to record the maximum amount of data in a minimum time, before taking time to work on processing it later. If the trees to be measured can be easily and constantly accessed, the shorter amount of time taken overall for digitization with MMT means that it is the preferred option.

4.1.3. Economic aspects

The initial reaction is to assume that SfM is economically much more viable, as any camera can, in theory, be used to take the measurements, and even semi-professional handheld cameras and equipment are still within the range of hundreds of euros, compared to the initial expenditure for the acquisition of a magnetic motion tracker, which, for the Polhemus FASTRAK is within the range of USD 5000 to USD 8000 (depending on the vendor)[3]. In addition, unlike a camera which is widely useful, such a device can be used solely for MMT.

However, photogrammetry does have hidden costs in the purchase of the Agisoft software (if not already owned), the cheapest stand-alone license option of which is PhotoScan standard costing USD 179[4]. However, it can be expected that the added features from PhotoScan professional will be required, costing USD 3499[5], putting SfM already close to the same price range as MMT. The advantage of PhotoScan is that it can be used for a variety of other purposes, such as the construction of a topographic map and other remote sensing compositions.

One also needs to consider the expense of a computer capable of doing the complex calculations necessary for PhotoScan. For the digitization of a small tree (2-3 years) the Agisoft minimum requirements should be sufficient, if kept below 100 image sources. But Agisoft do strongly encourage the use of a current generation Intel Core i7 processor, or equivalent, with a minimum of 32GB RAM and a top of the line

[3] http://www.vrealities.com/products/motion-trackers/fastrak.
[4] http://www.agisoft.com/buy/online-store.
[5] *Ibid.*

discrete graphics processing unit (dGPU). With computers, there is no upper limit as to pricing and performance but a typical minimum price for an adequate computer is around USD 1500[6]. Therefore, neither option has a significant financial advantage.

It is worth noting that most academic institutions have high performance IT facilities available, and are most likely eligible for an educational license of PhotoScan professional.

4.2. Overall conclusions

SfM is visually much more appealing, a factor which has no empirical value, but since 3D object reconstruction is very reliant on visual representation, it is a factor that must be considered when choosing techniques. In addition, SfM naturally captures surface data, which in the case of trees also contains the structural data. Therefore, if other metrics are desired, obtaining that information does not require much additional work. However, this also makes the process of obtaining structural data unnecessarily convoluted, unlike MMT which can measure it directly. As shown by Yoshimoto et al. (2014), MMT can also be used to measure surface data and generate mesh models, but requires a vastly different methodology than the one applied in this case study.

From the results of the case study, it is likely that obtaining structural data through SfM does not scale well, as shown by the difficulty in digitizing the complex sections of Tree 11, and inability to accurately view and digitize anything beyond axes with rank code of the third order ($r1r_nr_n$ and further). In addition, to try and accurately reconstruct all the segments of a large tree, a lot more photos would be needed, possibly resulting in unmanageable computer processing. However, as shown by Surový et al. (2011), MMT can scale to fully-grown trees, though measurement time is increased dramatically.

Taking into account the factors discussed above, MMT allows for more straightforward and equally accurate digitization. I conclude that for measuring small samples of *Pinus sylvestris* in laboratory conditions, where the goal is to obtain structural data, MMT is the preferable method.

[6] i.e. HP Z240 Tower Workstation, i7, 16GB, 512GB SSD
http://store.hp.com/UKStore/Merch/Product.aspx?id=J9C07EA&opt=ABU&sel=DTP.

5. Critical reflection

5.1. Limitations of the study

The study was limited due to the small number of trees measured. Such a small number of sample objects can only provide a general impression; although it was possible to test the methodology quite accurately, no concrete conclusions to the results can be made as the sample size was simply too small to be reliable.

Furthermore, the sample trees were all young trees of small size, which could be measured in laboratory conditions. As a result, it was not possible to assess the two methods and compare their usage in outdoor settings, as well as comparing the methods with regard to obtaining structural data from larger trees. As mentioned by Danjon & Reubens (2008), the FASTRAK and a laptop can be attached to a typical 12V car battery in combination with a 220V 1.1A converter and be used for approximately 10 hours. Therefore, it would be possible to assess the viability of either option outside of laboratory settings, which has not been addressed in this thesis.

5.2. Problems

5.2.1. Obtaining Data

Measuring with the FASTRAK was difficult, due to fact that any contact with the small tree would cause the entire tree to move. Eventually the tree would stop moving and seem to settle in approximately the same position, but there is no way to guarantee that the node intended for measurement would settle exactly where it was before. This means that the resulting point measurement is not strictly accurate. However, as mentioned in section 4.1.1, due to the necessity of avoiding contact with the tree, the stylus needed to be held as close to the node as possible, and measurement taken when the person measuring determined the stylus to be as close to the node as they could hold it. Depending on the fine motor skills of the person taking measurements this can present some difficulties, and could mean a difference to the node of several mm to less than 1 mm.

There were no significant issues in taking the photographs of the tree, apart from not being able to photograph the larger Tree 11 from above, as the tripod was not tall enough. It was still possible to reconstruct the tip of the tree, albeit with a lot of noise, as it had been captured enough times from below.

However, even with all the steps taken to ensure good series of photos, one could never be certain that the PhotoScan algorithms would be able to match enough of the images taken to reconstruct all the parts of the tree until after the lengthy process of aligning the cameras, potentially spending a lot of time on an invalid result.

In addition, as already mentioned in 3.5.1, the small twigs at the end of the axis are unlikely to be correctly reconstructed in the point cloud, and often indistinguishable from the noise. This made it increasingly hard to measure axes above rank order 3 ($r1r_nr_n$) with the polylines in the PhotoScan model.

5.2.2. Analysing Data

This study was not carried out to test the accuracy of the methods by themselves, as they have been repeatedly proven to be accurate (see Section 2.2). As such, no baseline physical measurements were taken other than those obtained using SfM and MMT. As a result, it was not possible to compare the results of these two methods with an independent third method, instead of simply comparing them to each other.

The point of this would be to see which method produced results closer to the actual physical positions of the tree.

5.2.3. Other problems

The MMT method was the guideline for gaining structural data from SfM, and therefore dictated the way the structural data was measured in PhotoScan, however, the extra and somewhat convoluted steps required to arrive at the same type of measurement leads me to believe that if a comparison to MMT was not required, a more streamlined process might be employed.

5.3. Discussion of open issues

In order to draw accurate conclusions on the issues addressed in this paper, as well as to test the scalability of the two methods, a more extensive study could be carried out using a larger number, and different species of trees. This would include older and taller trees with more complex structures and measurements taken in different environments. This would determine the better method across all conditions, as well as help standardize 3D digitization of structural data.

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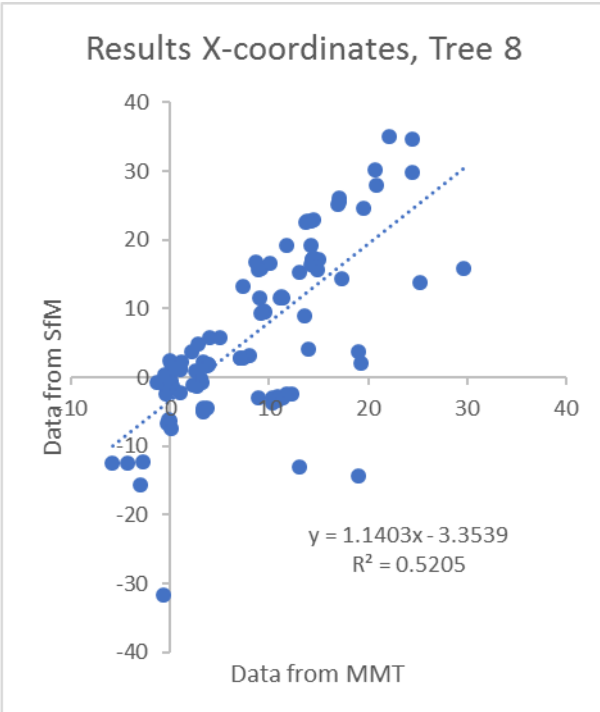
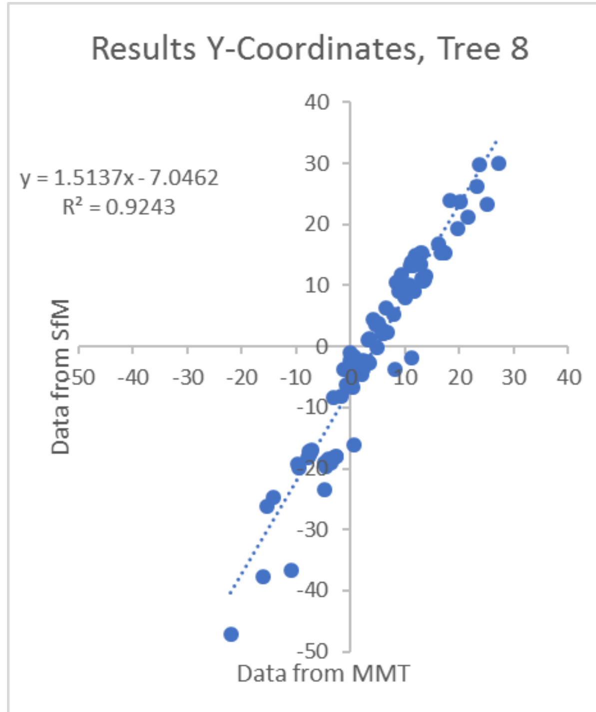
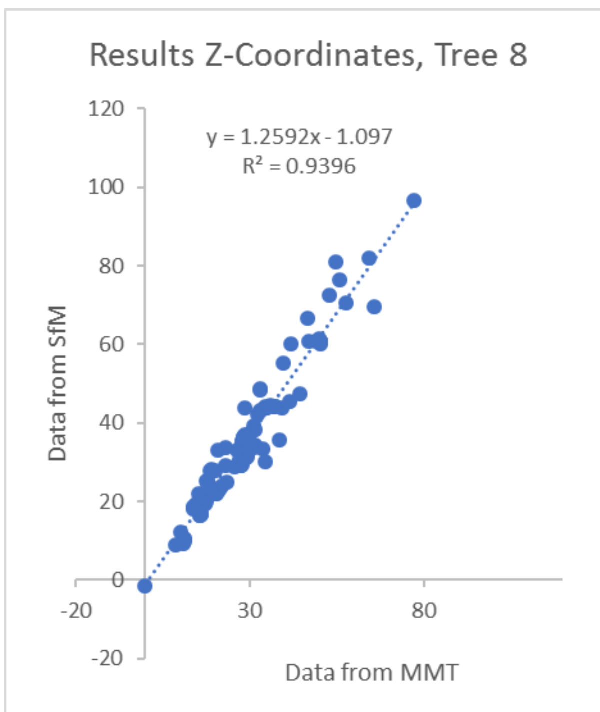
7. Appendices

7.1. Scatter Graphs of Coordinates from the two techniques

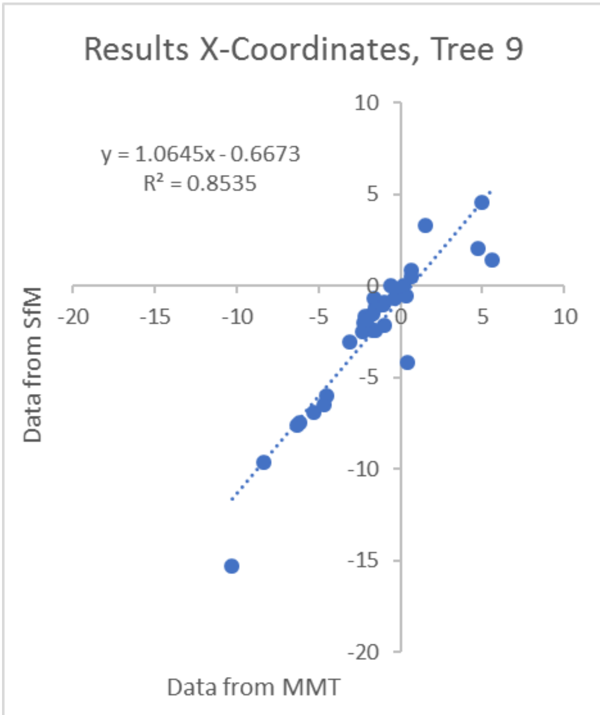
7.1.1. Tree 8

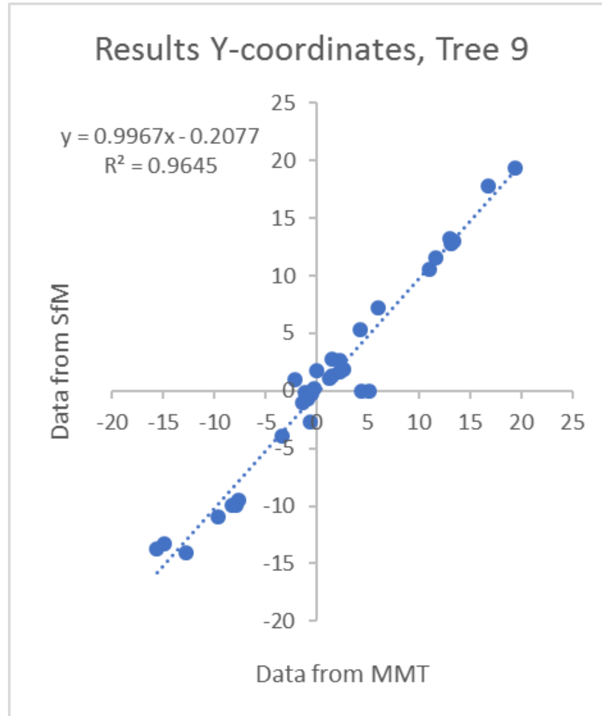


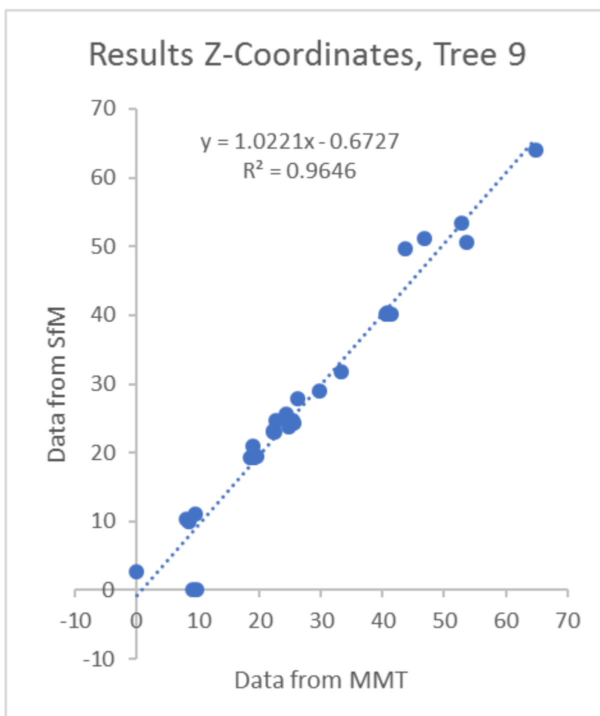




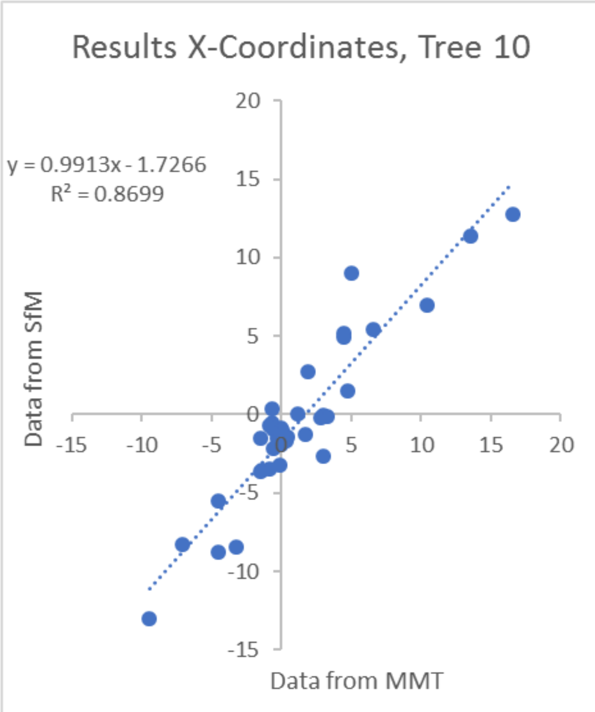
7.1.2. Tree 9

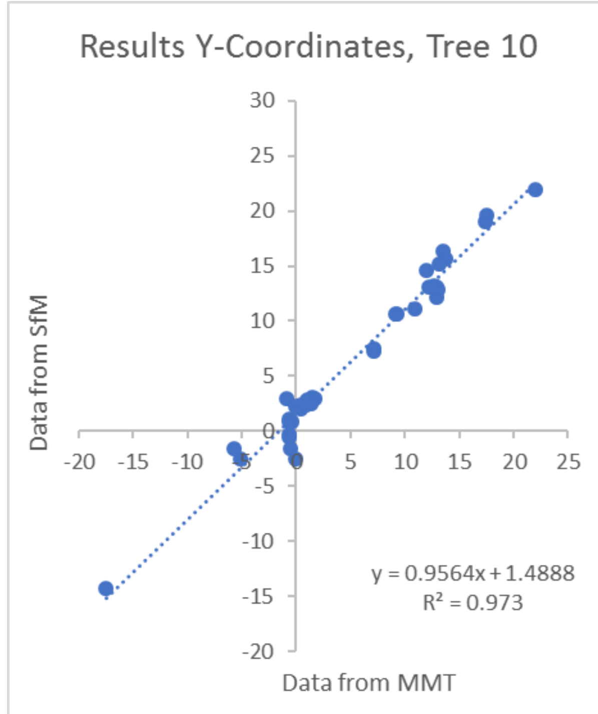

Results X-Coordinates, Tree 9
y = 1.0645x - 0.6673
R² = 0.8535
Data from SfM
Data from MMT

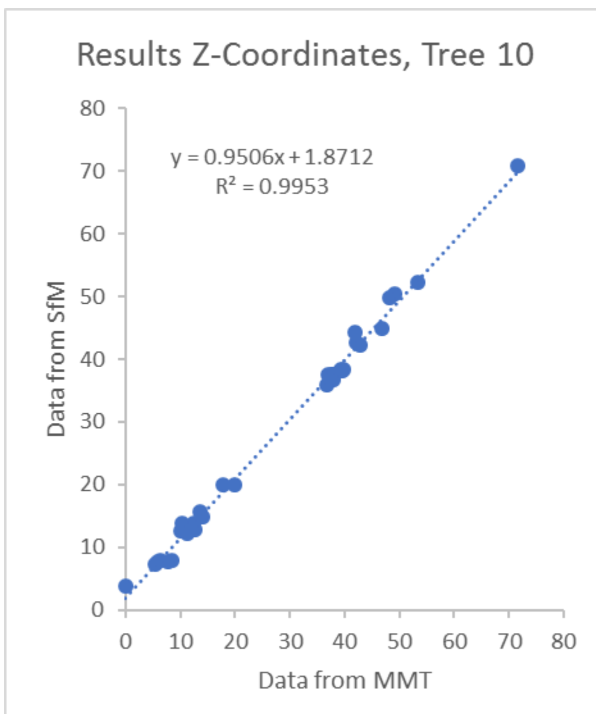

Results Y-coordinates, Tree 9
y = 0.9967x - 0.2077
R² = 0.9645
Data from SfM
Data from MMT


Results Z-Coordinates, Tree 9
y = 1.0221x - 0.6727
R² = 0.9646
Data from SfM
Data from MMT

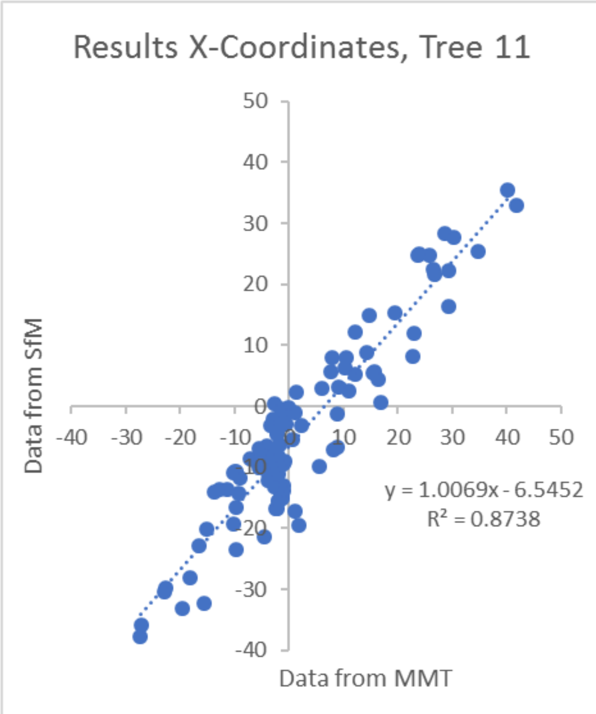
7.1.3. Tree 10

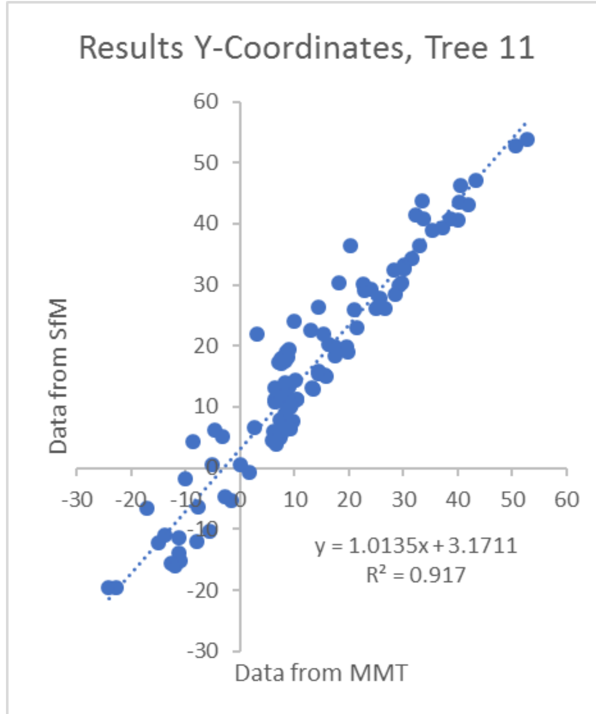

Results X-Coordinates, Tree 10
y = 0.9913x - 1.7266
R² = 0.8699
Data from SfM
Data from MMT

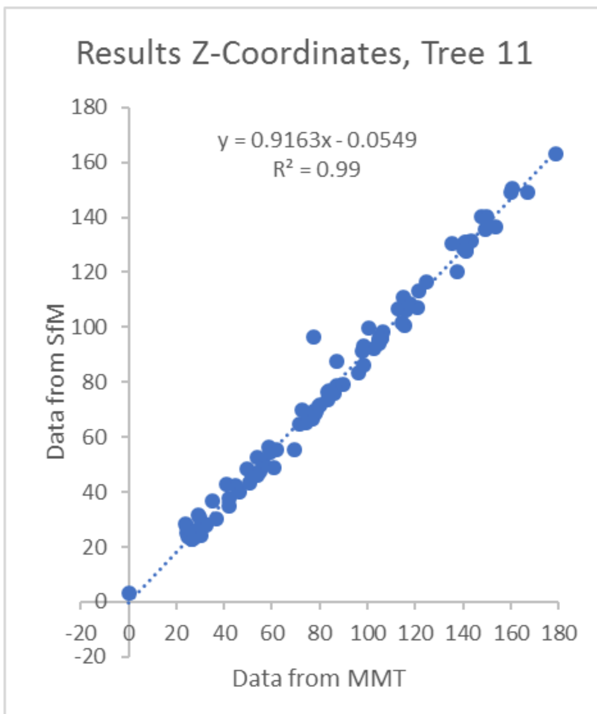

Results Y-Coordinates, Tree 10
y = 0.9564x + 1.4888
R² = 0.973
Data from SfM
Data from MMT


Results Z-Coordinates, Tree 10
y = 0.9506x + 1.8712
R² = 0.9953
Data from SfM
Data from MMT

7.1.4. Tree 11


Results X-Coordinates, Tree 11
y = 1.0069x - 6.5452
R² = 0.8738
Data from SfM
Data from MMT


Results Y-Coordinates, Tree 11
y = 1.0135x + 3.1711
R² = 0.917
Data from SfM
Data from MMT


Results Z-Coordinates, Tree 11
y = 0.9163x - 0.0549
R² = 0.99
Data from SfM
Data from MMT

7.2. Statement of good practice.

I submit this thesis titled "Obtaining 3D Data from Trees: A Comparison of Photogrammetric Reconstruction and Digitization with a Magnetic Motion Tracker" in partial fulfilment of the requirements for the Degree of Bachelor of Science in Forest Sciences and Forest Ecology at the Georg-August-University Göttingen.

I declare that this thesis is my own work and that I have correctly acknowledged the work of others by including full references for all sources in the bibliography.

Tuesday, 02 May 2017

Joel De Saint-Ours, matriculation number 21226907