Evaluating the Accuracy of Oblique Photography in Determining Urban Tree Heights

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Key words: Tree Height, Oblique Imagery, Surveying Measurements, Urban Forest.

SUMMARY

Trees provide a multitude of ecosystem services for our cities and their inhabitants, from temperature reduction to improved health and wellbeing. To ensure these services are optimised, cities need vigorous, functional and a variety of urban forests, thus requiring appropriate planning and managing schemes. In this context, tree inventory and tree dimensions are an important part of evaluating and monitoring the growth, size, and health condition of urban trees.

In this contribution, the actual tree heights of 25 open-grown eucalyptus trees (Eucalyptus tereticornis) were measured with an electronic surveying total station and compared to the height of the same trees computed via oblique photography. For the case study investigated here, the regression models of actual heights reasonably validated the proposed estimates of height for urban trees using oblique photography (R^2=0.991).

Oblique imagery estimated that tree heights differed by a minimum of 0.03 m and a maximum of 1.18 m from the actual height for all 25 eucalyptus trees, where the average of the differences was equal to 0.53 m. In view of these results, tree height determined via oblique photography can be considered as a viable complement (or substitute) to time consuming field-based tree height estimation in urban settings. This may well be the case of locations found in public open-spaces, parks and/or street areas.

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1. INTRODUCTION

Measuring the size and dimension of trees in urban areas (i.e., streets and open space areas like parks) is important for a variety of reasons. First, it helps to determine the health and vitality of the trees, as well as their potential for growth (Kändler, 2017). This information can be used to make informed decisions about tree maintenance and care (Sumida et al. 2013). According to a study published in the Journal of Arboriculture, regular tree measurement can identify problems early and allow for prompt corrective action, which can help to increase the tree's lifespan (Ferrini and Fini, 2011).

Secondly, measuring the size and dimension of trees can help to identify potential hazards, such as trees that are at risk of falling or causing damage to property (Devaranavadgi et al. 2013). According to a study published in the Journal of Urban Forestry & Urban Greening, regular tree measurement can help to identify hazardous trees and prioritize them for removal or pruning, which can help to reduce the risk of property damage and injury (Klei et al. 2019).

Additionally, measuring the size and dimension of trees can help to determine the amount of shade and cooling they provide, which can be important for urban heat island mitigation and energy conservation. Urban trees can have a significant cooling effect on their surrounding environment, which can help to reduce energy consumption and improve air quality (DeYoung 2019).

Furthermore, it can also be used for conservation and biodiversity studies, to understand the population and distribution of different tree species in urban areas. Regular tree measurement can provide valuable information about the population and distribution of different tree species in urban areas, which can help to inform conservation efforts and promote biodiversity (Phalla et al. 2018). Many techniques to estimate tree height have been developed and demonstrated to be successful and, in general, they encompass three general groups: conventional field methods, remote sensing and remote sensing within a web-based platform.

2. CONVENTIONAL FIELD MEASUREMENTS

Tree height for an open-grown individual tree or average height of a stand of trees has been estimated with clinometers. A comprehensive review of this well-known and useful instrument describing it in detail, including its advantages and disadvantages, can be found in (Clark et al.

2000). It is concluded that clinometers offer the best accuracy for the lowest cost (Williams et al. 1994).

Tree height has also been predicted with laser rangefinders. In principle, the operator stands at a selected distance from the tree with possibly the clearest view of the top and bottom to increase the accuracy of height estimates. The operator then uses the laser rangefinder to visually record the distances to the bottom and top of a tree, and the angle between these two distances, thus providing the dimensions needed to determine the height.

By way of example, the Vertex (Haglof Sweden AB, Langsele, Sweden) use ultrasonic sensing and angle measurement to estimate height or other vertical linear variables. The TruPulse from Laser Technology © is another example of an integrated lightweight laser rangefinder and inclinometer that can be optionally combined with an electronic compass. Data communication is available through standard serial ports or via Bluetooth. A benefit of these instruments is that the tree height is automatically calculated and it is also displayed to the user.

Although use of a clinometer and/or laser rangefinder is relatively straightforward and easy, estimating tree height for a large volume of trees with either of these instruments (or in combination) over a large geographic area can be time-consuming, logistically intricate, and expensive.

3. REMOTE SENSING

Aerial photography to estimate tree height has also been considered in forest inventory assessments for a long time (Avery 1977). A stereoscopic pair of aerial photographs captured by aerial vessels (i.e., drones) has proven successful for estimating the height of trees. In this instance, the process implies converting the parallax displacement that are measured along a flight path into a height estimate (Krause et al. 2019).

The straight displacement of an object within an aerial photograph, along with flying height, can also be used to estimate tree and building heights as can an object's shadow (Comber 2012). Even though estimation of tree height with aerial imagery provides large geographic coverage that is often not attainable with field-based estimations, it can be time consuming when dealing with a large number of images, and at the same time not applicable in the case of very dense canopy areas.

Light detection and ranging (LiDAR) data are a relatively new form of remotely sensed data if compared with traditional digital imagery obtained from satellites or aerial platforms (Andersen et al. 2006). LiDAR uses laser scanning to estimate the height and elevation of the landscape's physical characteristics (McManamon 2019). LiDAR uses either full-waveform or discrete return laser light that hit objects or the natural ground on the surface of the earth and determines the return location by calculating the time that it takes for the light to return to the sensor. The return time for each pulse is used to compute the distance from the sensor, which can in turn be used to derive the height of a forest canopy and the height of the surrounding ground areas (i.e., Digital Terrain Model or DTM). The variation in elevation between the height of a canopy and the associated DTM is the estimated height of the forest canopy.

As mentioned in Anderson et al. (2006), height estimates achieved from narrow-beam LiDAR data were less than 0.4 m of actual tree height and less than 0.6 m of actual tree height using wide-beam LiDAR data. In another instance, the error attributed to LiDAR exceeded 10% of tree height for 60% of trees with leaves and 55% of trees without leaves (Gatziolis et al. 2010). Manzanera et al. (2016) found that the integration of multispectral imagery and LiDAR data was reasonable for predicting the height of trees in a forest plot-level, and that measurements derived from optical or imagery sensor had the potential for complementing the data obtained from the LiDAR sensor in describing structural attributes of forest stands.

An alternative to LiDAR is structure-from-motion with multi-view stereo-photogrammetry (SfM-MVS), a technology that integrates stereo-photogrammetry with computer vision. Like LiDAR, SfM-MVS produces spatially truthful three-dimensional models using a selected number of overlapping two-dimensional digital images (Kholil et al. 2021). SfM-MVS has seldom been used in urban forestry outside of research applications (Heo et al. 2019) or in the instance of large and densely vegetated areas. However, measuring the structure, size and shape of individual trees with SfM-MVS is appealing because of its high accuracy and relative low cost.

An additional mapping technique referred to as SLAM (Simultaneous Localization and Mapping) has created special interest in forest measurements and assessment in the last decade. SLAM uses devices and/or sensors to collects visible data (camera) and/or non-visible data (RADAR, SONAR, LiDAR) with basic positional data collected using Inertial Measurement Unit (IMU) (Pierzchała et al. 2018). There exist some Common challenges for the full implementation of SLAM techniques which include (a) Localization errors accumulate, causing substantial deviation from actual values (b) on occasions, localization fails and the position on the map is lost (c) High computational cost for image processing, point cloud processing, and optimization.

4. WEB-BASED INTERFACE

Nearmap © web-based interface is an aerial image capture process and is classified as high-resolution remotely sensed data. In principle, oblique photography data is like the data obtainable with the commercial grade satellites IKONOS (St-Onge et al. 2008), QuickBird (Jaehoon et al. 2021), and Geo-Eye (Kempf et al. 2021).

However, the proposed oblique imagery process makes use of finer spatial resolution as compared to the above mentioned commercial-grade satellite sensors. Present technical details of this oblique imagery interface encompass (a) Ground Sampling Distance (GSD), 7.5 cm (b) Vertical measurement accuracy, 15 cm (c) Image bands, RGB natural colour and (d) coverage is carried out regularly for 12 Australia's major cities, covering 66% of the population across

61000 Km^2. These characteriscs make this web-based interface application suitable for measurements in urban environments.

One example of the use of oblique imagery in measurement is in the field of photogrammetry. Photogrammetry is the use of photographs to measure and map the earth's surface. Oblique imagery, taken at an angle, can be used to create more accurate digital elevation models (DEMs) and 3D models of buildings and other structures. These models can then be used for a variety of purposes, such as construction planning, disaster response, and urban planning.

Another example of the use of oblique imagery in measurement is in the field of industrial metrology. Industrial metrology involves the use of precision measurements to ensure the quality and accuracy of manufactured parts. Oblique imagery can be used to capture detailed images of parts and objects, which can then be analyzed to ensure that they meet the necessary specifications and tolerances. Oblique imagery is also used in the field of cultural heritage. Oblique imagery can be used to create 3D models of cultural heritage sites such as temples and monuments. These models can be used for conservation, restoration and planning of these sites.

In essence, oblique imagery is acquired via a low flying aircraft that follows a predetermined flight path and altitude above mean sea level within the area of interest. Flight paths are mutually parallel and perpendicular and equidistant from each other so to acquire images from several perspectives. The images are captured from a vertical viewpoint and oblique angles of up to 45° that portray the fronts and sides of ground features observable on a web-based interface.

The acquired images can portray up to 12 oblique perspectives and are “stitched” collectively to create a composite image that can be used to estimate the vertical and horizontal dimensions of the object of interest and its relative position as required. The height estimates can be assessed quickly (i.e., seconds) using the proposed oblique web-based interface as compared to the time needed to estimate tree heights using a clinometer, a laser rangefinder, aerial photograph, or LiDAR data.

For examples regarding applications and uses of oblique imagery for the purpose of measuring object dimensions the reader is referred to Ayyalssomayajula et al. (2009), who estimated height for citrus trees in a lemon orchard with an accuracy of 89%. On the other hand, Hohle (2008) had an average error of 0.2 m when using oblique data to determine the height of buildings and electricity towers. Also, Molinari (2014) established that the RMSE (Root Mean Square Error) for the heights of buildings investigated using oblique images was 0.8 m.

5. MOBILE PHONES

In recent years there has also been a proliferation of apps for mobile phones that use AR (Augmented Reality) incorporating sensors such as clinometers and laser that enable the phone to measure the *height* and at the same time estimate tree volumes (www.arboreal.se/en/). On the other hand, the integration of the LIDAR scanner into smart phones (i.e., the smart phone iPhone 12 Pro) has made these devices capable of measuring tree dimensions, as well as additional spatial data in the field (Pace et al., 2021)

6. METHOD

In this study, oblique imagery was used to estimate the height of 25 tall and mature eucalyptus trees (Eucalyptus tereticornis, common name Forest Red Gum) located in a small public park as part of an administration precinct (-27.984506, 153.339859) of the Gold Coast (Queensland, Australia). Eucalyptus trees are almost entirely Australian, and they belong to the family Myrtaceae. Only a few of the 700+ species recognized by science live completely outside Australia. This group of evergreen trees has been introduced to countries all over the world, becoming one of the most widely cultivated trees across the globe .

The goal of this research was to assess the accuracy of estimating tree height via oblique imagery as obtained from a web-based interface and compare the estimated heights with the actual height (of the same trees) measured in the field with a precise land surveying total station instrumentation (Sokkia Set3x reflector-less total station, 2011, Figure 1). The reader is referred to the Sokkia website for angle/distance measurement procedures and accuracy details and capabilities of this precise surveying measuring instrument (https://sokkia.com/).

Accordingly, the actual height of 25 tall mature eucalyptus trees was measured during the month of July 2022 so to coincide with a recent coverage of oblique imagery of the area of interest. The actual tree height was measured in situ with the above-mentioned total station instrument. Only one person was required to carry out the measurements, which in essence followed the process related to a standard land surveying technique called trigonometric levelling (Schofield and Breach, 2007).

All vertical angle and distance measurements for each tree were taken from two different locations (i.e., measuring stations) with a clear view of the top/bottom of each tree. Results obtained from these two measurements where then compared and averaged. The result of this average was considered as the actual “true” height of the measured tree. Note that the differences of the tree heights computed via the total station instrumentation from two different stations were consistently less than 0.07 m (absolute value).

On the other hand, the heights of all 25 eucalyptus trees were estimated on-screen (see Figure 1) using the oblique imagery of Nearmap © via a web based “black box” proprietary interface. On-screen estimates were recorded by two separate operators so to reduce tree height bias estimation which in the end resulted in negligible differences (i.e., the absolute tree height differences determined by the two operators were 0.04 m).

Linear correlation coefficients between actual tree heights and those estimated via oblique imagery for all 25 trees were calculated. A paired *t*-test was then conducted with the purpose of testing the statistical significance between actual and estimated tree height. This is shown in the ensuing section.

Figure 1. Measuring urban tree heights on the screen using Nearmap © oblique imagery (left) and the Sokkia Set3x reflector-less total station.

7. RESULTS

There were minimal differences between actual tree heights and estimated tree heights (Table 1). The mean of actual tree height for all 25 trees was 34.26 m, whereas the mean of estimated tree height for the same trees was 34.41 m. Actual tree heights varied between a maximum value of 44.95 m and a minimum of 25.51 m with the range being equal to 18.9 m. The height median was 33.81 and 34.05 m and the standard deviation 3.45 m and 3.78 m for actual and estimated heights respectively.

A scatter graph of estimated tree height versus actual tree height indicated a strong relationship between in situ and remotely sensed tree height (Table 2, Figure 2). A linear correlation coefficient between actual tree height and estimated height for all 25 trees was 0.991 with a standard error of estimates (Sy.x) equal to 0.586. The estimated heights constantly overestimated the height of the 25 eucalyptus trees. It was thought that this bias could be attributed to the difficulty in identifying the top of the crown on said trees from a set of oblique images and the fact that only two independent operators were involved in estimating said heights.

Although the estimated and actual heights did not turn out to be statistically identical from each other (see Table 2 and values of degree of freedom and t-test), a user of oblique imagery web-based interface may need to reflect on the propensity of overestimating actual tree height and could perhaps adjust the measurement depending on the number of measurements of the same tree taken from different image perspectives or orientations.

Tree No.	Actual height m	Nearmap height m	Height Diff. m	Absolute Diff. m	Diff. %
1	39.55	38.86	0.69	0.69	1.7
2	42.31	43.11	-0.8	0.8	1.8
3	44.95	43.77	1.18	1.18	2.2
4	32.56	32	0.56	0.56	1.7
5	31.32	32.33	-1.01	1.01	3.1
6	34.76	34.82	-0.06	0.06	0.2
7	37.49	37.12	0.37	0.37	0.98
8	27.23	27.66	-0.43	0.43	1.6
9	34.77	33.88	0.89	0.89	2.5
10	33.81	33.78	0.03	0.03	0.1
11	29.67	30.07	-0.4	0.4	1.34
12	28.11	27.95	0.16	0.16	0.56
13	34.64	34.51	0.13	0.13	0.37
14	27.22	27.87	-0.65	0.65	2.4
15	28.61	28.44	0.17	0.17	0.6
16	33.64	34	-0.36	0.36	1.07
17	25.51	25.88	-0.37	0.37	1.45
18	31.11	32.05	-0.94	0.94	3.02
19	26.7	27.2	-0.5	0.5	1.87
20	38.42	37.77	0.65	0.65	1.69
21	26.58	25.9	0.68	0.68	2.4
22	41	41.33	-0.33	0.33	0.8
23	37.74	37.95	-0.21	0.21	0.55
24	44.29	44.78	-0.49	0.49	1.1
25	44.47	44.21	0.26	0.26	0.58

Table 1. Tree height measurements of actual height and estimated height. Differences between the two, and percentage of disagreement

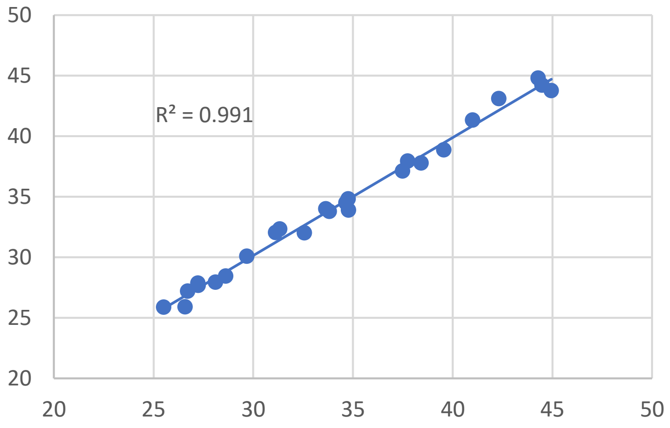

Figure 2. Scatterplot of Nearmap-estimated heights (vertical axis) vs. actual tree heights .

	Actual height	**Estimated height**
Mean	34.26 m	34.41 m
Variance	36.0 m	34.5 m
Standard Deviation	6.0 m	5.8 m
Number of observations	25	25

Degree of Freedom 48, t => -0.0186, Critical Value => 2.01, |t| < critical value, hence => no significance difference

Table 2. Statistical Summary of the measured data for all 25 eucalyptus trees (actual and estimated).

8. CONCLUSIONS AND DISCUSSION

Estimating tree height has been a critical factor of forest inventory assessments for several decades. Although estimating the height of a tree in the field is a relatively straightforward procedure, the capacity to estimate tree height for multiple individual trees or stands of trees over urban and extended areas can be time-consuming, logistically difficult, and expensive.

Remote sensing with its ability to collect data systematically over large geographic areas has the potential to support field-based tree height measurement and estimation within an urban environment. For the case considered in this work, the integration of high-resolution imagery into a web-based interface was effective in estimating tree height in a relatively short period of time.

In recent years, oblique imagery has been used to measure the size of trees in various forested areas. For measuring trees this technique has a number of benefits over traditional methods of tree measurement, such as manual measurement or the use of overhead imagery. One of the main benefits is the ability to capture detailed images of the tree canopy. Traditional methods of tree measurement, such as manual measurement or the use of overhead imagery, often result in a lack of detail in the images of the tree canopy. Oblique imagery, on the other hand, can capture detailed images of the tree canopy from different angles, providing a more accurate representation of the tree's size.

Another benefit of using oblique imagery for measuring trees is the ability to capture images of the tree's canopy from different angles. This allows for a more accurate representation of the tree's size, as it contemplates the tree's shape and structure. For example, a tree that is tall but has a narrow canopy will have a different size than a tree that is shorter but has a wide canopy. By capturing images of the tree's canopy from different angles, oblique imagery can provide a more accurate measurement of the tree's size.

Oblique imagery can be used to measure the size of trees in remote or hard-to-reach areas. Traditional methods of tree measurement, such as manual measurement, may not be feasible in these areas due to safety concerns or lack of accessibility. Oblique imagery, on the other hand, can be captured using drones or other remote sensing technologies, allowing for the measurement of trees in remote or hard-to-reach areas.

This technique allows for the capture of detailed images of the tree canopy from different angles, providing a more accurate representation of the tree's size. Oblique imagery can also be used to measure the size of trees in remote or hard-to-reach areas, making it a valuable tool for forest management and conservation efforts. Oblique imagery allows for a more accurate representation of the tree's height, as it considers the tree's shape and structure. For example, a tree that is tall but has a narrow canopy will have a different height than a tree that is shorter but has a wide canopy. By capturing images of the tree's canopy from different angles, oblique imagery can provide a more accurate measurement of the tree's height.

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BIOGRAPHICAL NOTES

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