Research paper

Using Ground-based LiDAR Data to Measure Standing Trees in a Red Cypress Plantation

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【Summary】

The three-dimensional (3D) scanning light detection and ranging (LiDAR) system is able to make non-destructive transcriptions of individual tree structures. Gaining 3D information on a forest using a ground-based LiDAR system is a swift and popular method. This study used ground-based LiDAR data and traditional data of field surveys to obtain individual tree characteristic values, such as tree height, diameter at breast height (dbh), individual tree location, and diameter simulations at different heights (DSDHs). This study estimated the feasibility using LiDAR data in a forest area and a predictive model, for mapping individual 3D tree positions. To analyze the accuracy of the determined 3D information, results of 24 investigated trees in a field survey were compared to those using laser scanning. The results showed directional errors of 0.020~0.796 m in the X direction and 0.007~1.774 m in the Y direction. Although the trees were heterogeneous, the results showed good correlations of the LiDAR tree height with field tree height (root mean squared error (RMSE) = 0.2584) and the LiDAR DBH with field DBH (RMSE = 0.7632). We also found high accuracy in diameter simulations without occlusion. Comparing the LiDAR results with traditional methods showed that the new survey method developed can be pragmatically applied to different measurement fields. The LiDAR-based measurement system in this study was proven to be a valuable tool for measuring physical and structural characteristics of plants, such as tree height, dbh, diameter simulations, and individual tree location maps.

Key words: forest management, LiDAR technology, stand characteristics, diameter simulations at different heights (DSDHs).

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研究報告

應用地面光達資料於紅檜人工林立木測計

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摘　要

光達系統有能力針對單木結構進行非破壞性紀錄，且藉地面光達系統獲得森林的三維資訊是一種快速而普遍的方式。本研究藉由地面光達與傳統野外調查資料來獲得樣區內每株林木的樹高、胸徑(dbh)、立木位置以及不同高度直徑模擬(DSDH)，同時藉統計分析與預測模型評估地面光達資料於森林地區應用之可行性以俾繪製三維林木位置。三維資訊之準確性透過野外24株林木之調查結果與光達資料進行比較，結果顯示X軸誤差範圍介於0.020~0.796 m，Y軸誤差範圍介於0.007~1.774 m。儘管兩種林木資料有著差異性，但其間還是具有良好的相關性，例如光達測量之樹高與實際測量之樹高，兩者有著高度的相關性(RMSE = 0.2584)，且光達測量之胸徑與實際測量之胸徑亦有著高度的相關性(RMSE = 0.7632)；此外，透過三株立木位置準確且樹冠底下無遮蔽之林木，發現地面光達可進行高準確性的直徑模擬。本研究比較光達與傳統調查方法，結果顯示即使在不同的測量位置，以地面光達進行調查值得期待，其運用於測量林木之外部與結構特徵，包括樹高、胸徑、不同高度直徑模擬與立木位置圖確實可行。

關鍵詞：森林經營、光達技術、林分結構、不同高度直徑模擬。

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INTRODUCTION

Thinning operations are important in forest tending and are efficacious not only for increasing timber growth, and biodiversity, and decreasing competition, but also for providing better growing space, sunlight, nutrients, and water resources for trees (Weatherley 1963, Amateis et al. 1996, Hagar et al. 2004, Ohsawa 2004, Waltz and Covingtiu 2004, Sullivan et al. 2005). However, the timber selection process involves certain problems for which organizational qualities need to be analyzed. Therefore, it is crucial to conduct quantification and spatial research of thinning operations, such as investigating the competition index (Moravie et al. 1999).

Ground-based light detection and ranging (LiDAR) with high positional accuracy and dense automation is widely applied to many fields, including terrain and building measurements, earthwork, engineering, architectonics, archeology, and forestry (Omasa et al. 2002, Urano and Omasa 2003, Hopkinson et al. 2004, Hosoi and Omasa 2006, Barber et al. 2008, Al-kheder et al. 2009, Côté et al. 2009, Polo et al. 2009, Keightley and Bawden 2010, Mariano et al. 2011). For applications in the forestry field, Omasa et al. (2002) proposed mapping and estimating LiDAR data to obtain many parameters related to the geometric characteristics of *Larix leptolepis* woods (diameter at breast height (dbh), biomass, and an individual tree location map).

Studies based on 3D point clouds have improved data collection efficiency. Accounting for the effects of non-uniformity and precisely estimating vertical foliage distributions remain arduous with either airborne or ground-based LiDAR (Omasa et al. 2007). Hosoi and Omasa (2006) proposed a voxel-based canopy profiling method that divides the 3D space into voxels that are the 3D equivalent of pixels in a 2D image. This method was developed to estimate vertical foliage profiles with reduced non-uniformity effects in the foliage distribution and non-photosynthetic tissues.

The structural and geometrical parameters of trees and stand characteristics, such as individual tree biomass and leaf area density, are respectively derived from manual volume measurements and leaf destructive sampling. In addition, forest destructive sampling techniques are both slow and costly, and other inexpensive methods, such as ground-based LiDAR used in recent years, were found to be reliable.

To determine the suitability of laser sensors for characterizing forest trees, this study computed several parameters based on LiDAR data and field survey data. In addition to comparing the height of trees, dbh, and maps of individual tree locations determined using the 2 datasets, this research also evaluated the accuracy of trunk simulations. The developmental procedures and their results are presented in this study.

MATERIALS AND METHODS

Ground-based LiDAR and field tests

This research used ground-based LiDAR acquired with the Trimble GS200 system (Mensi SA, Paris, France). The LiDAR has a 360º horizontal field of view (HFOV) and a 60º vertical field of view (VFOV), so it can collect data using wider vision. The distance measurement was operated on the time-of-flight measurement principle, and the intensity wavelength of 532 nm was provided by a green laser. The LiDAR range permits distance measurements at a maximum of 200 m, with a spot size of 3 mm at a distance of 100 m; the standard deviation of the distance measurement is 6 mm for a single shot. The laser scanning system can measure 5000 points per second. During data collection, a calibrated video snapshot of 768×576-pixel resolution is additionally captured, and is automatically mapped to the corresponding point measurements. Table 1 shows the ground-based LiDAR parameters of this study. The ground-based LiDAR was used to characterize a plantation of red cypress *Chamaecyparis formosensis* (Fig. 1) in the Liouguei area of Taiwan.

LiDAR measurements

The ground-based LiDAR uses an optical sensor, which may cause some problems

Table 1. Ground-based LiDAR parameters of this study

Item	LiDAR Information
Speed	up to 5000 points s^{-1}
Wavelength	532 nm
Field of view	360°×60° (at 1 site)
Camera	768×576 pixel resolution
Vertical resolution	100 mm at 100 m
Horizontal resolution	100 mm at 100 m
Area	20×30 m
Point clouds information	X, Y, Z, I, R, G, B
Point clouds numbers	74.5 points m^{-3}

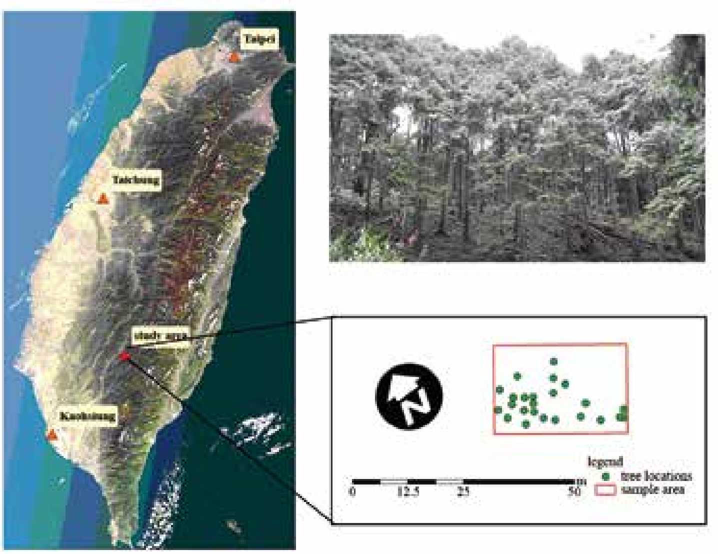

Fig. 1. Plantation of Taiwan red cypress (*Chamaecyparis formosensis*) in the Liouguei area of Taiwan.

in the shooting process. Figure 2 shows the types of occlusion problems according to computer graphic applications: ambient, self, and view frustum occlusions.

In order to reduce occlusion problems, we calculated 3D point clouds from 7 different positions. Figure 3 shows the 4 outside positions which were around our study area. In the inside place, we set up 3 different positions for decreasing occlusion. The procedure coordinates point cloud conversion from the same coordinate system, determined by movement and rotation elements in the 3D space, and coalesced linked targets to make the root mean squared error (RMSE) close to 0 (Fig. 3).

As a crucial element for geo-referencing, we also used a Sokkia SET530RK3 reflectorless total station (Kanagawa, Japan) in the reflectorless mode in the field survey with a range measurement accuracy of ± (2 mm + 2 ppm×D) in the prism mode and ± (3 mm + 2 ppm). The point clouds formulated by the same coordinated system through registration were converted to targets of absolute coordinates that were merged with control points by geo-referencing.

LiDAR and manual measurements of tree height, dbh, individual tree location map, and diameter simulations at different tree heights (DSDHs).

The geo-referencing process of LiDAR data was described above. The LiDAR tree height measurement began with the measurement of the maximum tree height and the height of the bare trunk in a plane perpendicular to the row including the trunk axis (Fig. 4A, B). We extracted points from the LiDAR data of the 1.3-m ground base of every tree as the LiDAR DBH (Fig. 4C). We used equation (1) to calculate the distance between 1 point and another in the 3D space. Therefore, the same standards were applied in this study:

$$d = \sqrt{(\triangle X)^2 + (\triangle Y)^2 + (\triangle Z)^2} \qquad \text{Eq. (1)}$$

where d is the distance; $\triangle X$ is the displacement of the X coordinate, $\triangle Y$ is the displacement of the Y coordinate, and $\triangle Z$ is the displacement of the Z coordinate.

For this study, we also cut some trees and calculated their diameters at different

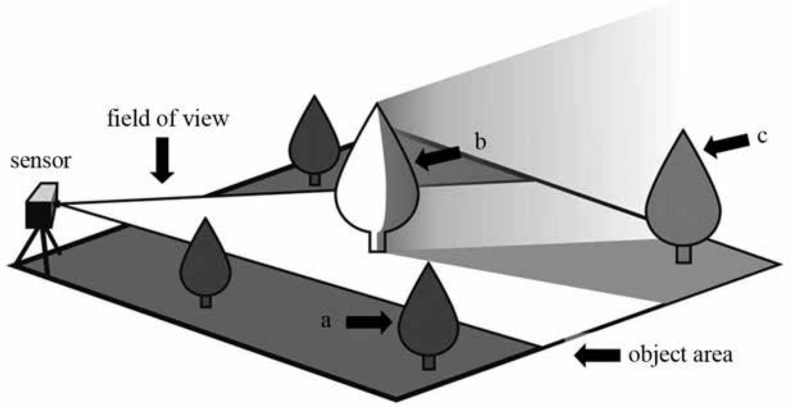

Fig. 2. The 3 types of occlusion problems: (a) view occlusion; (b) self occlusion; and (c) ambient occlusion.

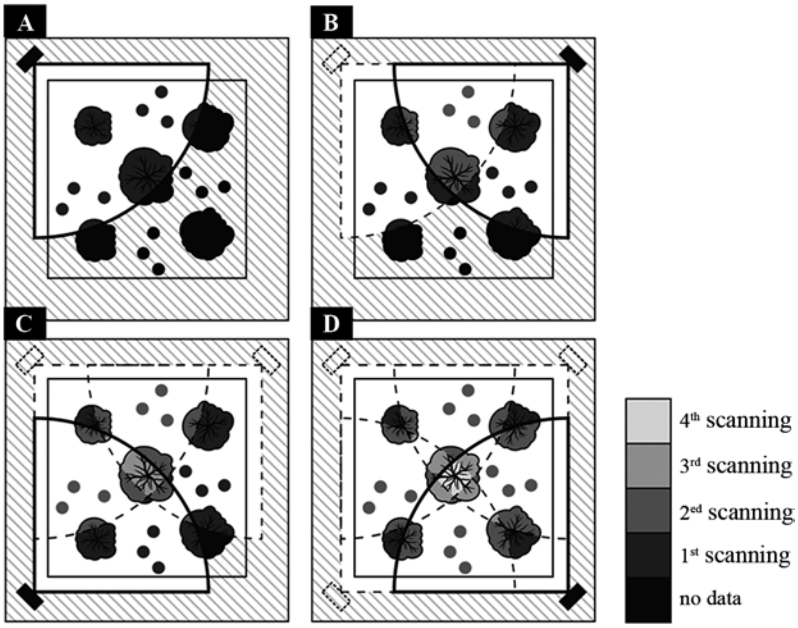

Fig. 3. Principles of registering point clouds measured from different locations and geo-referencing point clouds passing through a registration process.

heights including 0.3, 1.3, 3.3, 5.3, and 7.3 m and so on (the method was the same as that shown in Fig. 4C).

To compare the stand characteristics with the results of LiDAR measurements, 24 trees in a sample area were chosen, and the stand characteristics which included the tree height, DBH, and location of trees, were manually measured at the start. After LiDAR scanning, we cut 11 trees and choose 3 trees with less occlusion from among them in the sample area, and compared the diameters at different heights from LiDAR measurements with those manually measured. We then used

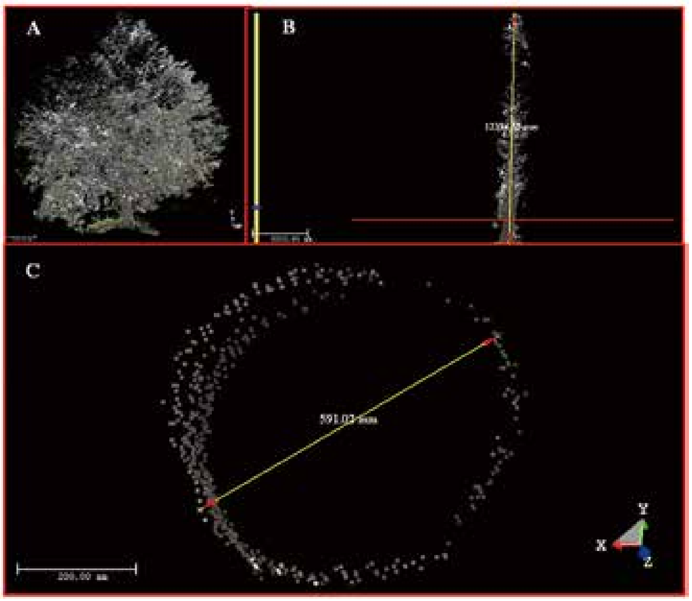

Fig. 4. A. Using LiDAR data to extract stumpage; B. using LiDAR data to measure tree height; C. using LiDAR data to measure diameter at breast height.

statistical methods including paired-sample *t*-test to analyze the relationships between the LiDAR data and ground survey data.

RESULTS AND DISCUSSION

The point clouds rotate and move in 3D spaces through registration and georeferencing. To analyze the accuracy of the determined 3D information, results from 24 investigated trees in the field survey were compared to those from laser scanning. The outcomes indicated directional errors of 0.020~0.796 m in the X direction and 0.007~1.774 m in the Y direction. Compared to results with traditional methods, these values show that the new survey method developed can practically be applied to various measurement fields.

Some studies used several different directions to scan objects, which can decrease occlusion problems (Strahler et al. 2008, Al-kheder et al. 2009, Wei et al. 2013). By comparing inaccurate individual tree locations, we found that these trees were close to each other, and this situation affected ambient occlusion (Fig. 2). Wei et al. (2013) used different directions to scan a forest area. The results showed that the absolute value of the horizontal error of < 0.1 m was 28.26%, and the vertical error of < 0.1 m was 32.61%. In addition, the absolute values of the horizontal and vertical errors of < 0.5 m were 76.09 and 82.61%, respectively.

We used a *t*-test to check the accuracy of the LiDAR data. Table 2 shows the relationship between the tree height and dbh calculated from LiDAR data and manually measured in 24 trees. The results show that there was no difference between the LiDAR data and manual measurements ($p > 0.05$). Thus, we obtained LiDAR data with fewer occlusion problems from 7 different positions.

This study separately probed the relationship between tree height and dbh calculated from LiDAR data and manually measured.

Table 2. Paired sample *t*-test (tree height and diameter at breast height (dbh))

	Paired differences							
Tree height	Mean	Std. deviation	Std. error of the mean	95% Confidence interval of the difference		t	d.f.	p Value
				Lower	Upper			
Pair 1 field data-LiDAR data	0.270	0.647	0.132	-0.004	0.543	2.040	23	0.053
	Paired differences							
DBH	Mean	Std. deviation	Std. error of the mean	95% Confidence interval of the difference		t	d.f.	p Value
				Lower	Upper			
Pair 2 field data-LiDAR data	0.492	1.243	0.254	-0.034	1.017	1.937	23	0.065

Note: $p > 0.05$.

The manually determined data and LiDAR-obtained results were not unanimous for tree height and dbh, but a simple relationship existed between the values. Although every single tree differed, good correlations existed between the LiDAR tree height and field tree height (root mean squared error (RMSE) = 0.2584) and the LiDAR DBH and field DBH (RMSE = 0.7632). This consequence is acceptable because of the 3 types of occlusion problems that cause some errors in the laser scanning process.

Keightley and Bawden (2010) used tripod LiDAR (ground-based LiDAR) to establish 3D volumetric modeling of a grapevine's biomass. The LiDAR analog volume indicated a high correlation. Estimating using a simple linear equation was an indirect way in that study, because of different objects. However, it showed that the laser scanning technique yielded a highly linear relationship between the vine volume and tissue mass, and revealed a new, rapid, non-destructive method to remotely measure standing biomass. In this study, we used a direct method to compare the same objects, such as tree height, DBH, and individual tree location. This application shows promise of a capacity for use in other ecosystems such as orchards and forests.

On the other hand, we compared the DSDHs of LiDAR measurements with manual measurements of 3 cut trees. We also used a *t*-test to check the accuracy (Table 3). Table 3 also shows that there was no difference between the LiDAR and manually measured data ($p > 0.05$) as also seen in Table 2. Based on the 3 trees used to discuss diameter simulations, there was a smooth, close line between the LiDAR and field data as shown in Fig. 5, that was about the case of DSDHs of the trunk. In fact, we found high accuracy in diameter simulations without occlusion (at heights below 3.3 m), but there were underestimates and over-calculations at the tip of tree (at heights of approximately over 9.0 m) and tree crown (almost 4.0~9.0 m), respectively.

Although the errors arose from self occlusion and view occlusion problems, when controled the tropism of ground-based LiDAR data and revised it properly, the LiDAR system still was a good measurement instrument for forest investigations.

Lovell et al. (2011) presented a method for automatic tree locations detection and

Table 3. Paired samples *t*-test of diameter simulations at different heights (DSDHs)

DSDH	Paired differences					t	d.f.	p Value
	Mean	Std. deviation	Std. error of the mean	95% Confidence interval of the difference				
				Lower	Upper			
Pair 1 field data-LiDAR data	-0.332	2.714	0.543	-1.452	0.788	-0.612	24	0.547

Note: $p > 0.05$.

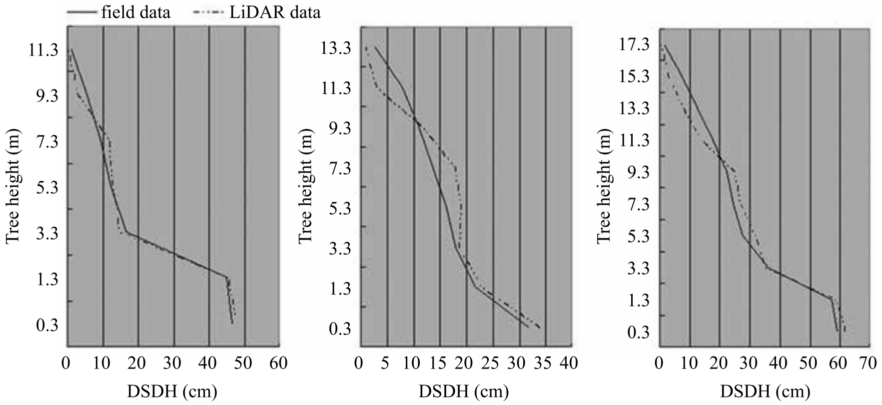

Fig. 5. Distributions between field-measured diameter simulations at different heights (DSDHs) and LiDAR-measured DSDHs.

provided stand statistics up to 50 m in range within a forest. As shown in that paper, the data also provided stem diameters with accuracy dependent on the tree size and range. Polo et al. (2009) used ground-based LiDAR to estimate leaf biomass. The scanning direction was around the target. The results for orchards showed reasonable relationship of volume of tree-row plantations between destructive and non-destructive leaf sampling methods.

There are some similar conditions and results in that research and ours, such as the scanning distance, scanning direction, number of point clouds, and study area. Although our objects were not the same, we also obtained similar results. Comparing the results with traditional methods showed that the new survey method developed can be pragmatically applied to different measurement fields. The LiDAR-based measurement system in this study was proven to be a valuable tool for measuring the physical and structural characteristics of plants, such as tree height, dbh, diameter simulations, and individual tree location maps.

Many studies utilized ground-based LiDAR data in a small area for making non-destructive recordings to provide observations of tree measurements (Omasa et al. 2002, Hosoi and Omasa 2006, Côté et al. 2009, Polo et al. 2009, Keightley and Bawden 2010, Mariano et al. 2011). Applications included tree-rows in orchards and vineyards, grapevine biomass, estimation of dbh and biomass, estimation of leaf area density, and estimation of plot-level forest canopy fuel properties.

This study also used ground-based LiDAR for a forestry process to overcome some of the limits of agricultural applications.

The results with reasonable agreement were similar to the results derived from a destructive sampling method. The LiDAR system was proven to be a powerful technique with repeatable, prompt, and non-destructive estimates of plant properties.

CONCLUSIONS

Taiwan possesses rich species because of its unique climate and environment. Managed plantations often have miscellaneous species growing like weeds. Therefore, recorded data in our field are needed for statistically robust, repeatable, and unbiased measurements obtained in a cost-effective way.

This study has proven the LiDAR-based system to be a valuable tool for measuring those characteristics. Measurements can be taken as frequently as needed without injuring trees. This research surveyed those characteristics by measuring 3D point clouds, depending on which technique was used. Measurements using LiDAR data showed a close correlation to field data modeled by a simple linear equation.

The strength of the LiDAR technique is its speed and accuracy, with as few numerical value measurements as 4 instrument views per tree, without needing to destroy the harvest. The ground-based LiDAR technique yielded a highly linear relationship between LiDAR data and field survey revealing a new, rapid and non-destructive method to remotely measure the volume of individual trees. But the limitations of this technique are the availability of instrumentation and software, loss of accuracy at the finest target scales, and errors. Application of this technique in the field requires multiple repositioning of the instrument to increase data collection time; however, no difference in data accuracy is anticipated.

3D laser scanning can obtain highly accurate scans of cloud data, and provide basic information on individual tree spatial distributions. This method not only can determine tree competition, forest health, forest measurement, and thinning operations by ground-based LiDAR scanning, but also solves quantification and spatial research problems with thinning operations, and advances simulations of thinning operations. Most of all, 3D laser scanning is also very easy to understand and apply for decision makers.

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