FOREST GLOBAL POSITIONING METHOD AND EXPERIMENT BASED ON AGRICULTURAL MACHINERY
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基于农业机械的林木全球定位方法与试验

As. PG. Stud Shuo Li [1), 2)], A.P. Ruili Song [3)], Prof. Feng Kang *[1), 2)], Dr. Yaxiong Wang [1), 2)]
[1)] School of Technology, Beijing Forestry University, Beijing / China;
[2)] Key Lab of State Forestry and Grassland Administration on Forestry Equipment and Automation, School of Technology, Beijing Forestry University, Beijing / China;
[3)] Computer Science Department, Hebei Professional College of Political Science and Law, Shijiazhuang, Hebe / China
Tel: 15956263218; E-mail: ejtsuo@163.com

Keywords: *agricultural intelligent vehicle, tree trunk, laser scanner, global positioning*

ABSTRACT

To overcome the occlusion of satellite signals by dense canopy that invalidates the use of global positioning systems with agricultural machinery, the paper proposed a global positioning method to establish the global positions of forest trees. First, the domain division method of Euclidean distance and a geometric tangent algorithm are used. Then, three-dimensional data consisting of the centre points of tree trunks in the WGS-84 coordinate system are obtained by performing a spatial coordinate transformation. Subsequently, the laser scanned the newly detected trunks at a time t, and the scanning area was determined. Finally, the global positioning of trees by agricultural machinery was completed under a dense canopy. The results of field experiments showed that the standard deviation of the positioning error of the per plant tree trunk in the X, Y and Z directions of the space rectangular coordinate in the WGS-84 world coordinate system are 0.03 m, 0.04 m and 0.03 m.

摘要

卫星信号被密集的树冠遮挡,这使得使农业机械全球定位系统的应用失效，为了克服这一问题，本文提出了一种确定林木全局位置的全球定位方法。首先,利用欧几里得距离的域划分方法和几何切线算法。然后,对 WGS-84 坐标系中树干的中心点进行空间坐标变换,得到三维数据。紧接着,在 t 时，激光扫描仪对新探测到的树干进行扫描,确定了扫描面积。最后在密集的树冠下完成树木的全球定位。现场试验结果表明，在 WGS-84 世界坐标系中空间矩形坐标的 x、y 和 z 方向上,每个植物树干的定位误差的标准偏差为 0.03m、0.04m 和 0.03m。

INTRODUCTION

The distribution of trees in a forest is an important information in forests mapping *(Spriggs et al, 2015)*, for precision pesticides application *(Kang et al, 2014)*, and estimating the growth and harvesting of forests *(Kang et al, 2012)*; the tree distribution also serves as a guide for forest management. However, traditional manual contact mapping methods are time consuming and inefficient. Currently, many domestic and foreign scholars and researchers use an airborne mapping system to ascertain the actual locations of tree growth. Nevertheless, while this method is highly efficient, the measurement accuracy is not high, and it is impossible to obtain more detailed information, such as the size and position of a tree trunk, under the canopy. Therefore, vehicle mapping system based on advanced sensor technology was developed, but such systems suffer from a common primary problem: the positioning of the mobile platform. To resolve this issue, several solutions are currently employed. The dead reckoning (DR) method uses odometer information to achieve a higher short-term positioning accuracy. However, the DR method suffers from cumulative errors that gradually approach infinity when estimating the vehicle direction angle. The vision-based positioning method is another option, but it is considerably influenced by optical fibres; moreover, this technique requires a considerable environmental configuration and suffers from a highly complex algorithm with a poor reliability (*Xue et al, 2018*). Alternatively, the Global Positioning System *(Junying et al, 2014)* (GPS) has a high positioning accuracy and fast calculation speed; however, it is easy to lose the signal due to canopy occlusion, thereby limiting its applications on mobile platforms. In contrast, laser scanners *(Bargoti et al, 2015; Xuehua et al, 2013)* are much less influenced by the working environment and lighting conditions and can thus provide larger quantities of accurate distance information at a higher frequency; hence, they can reliably provide the orientations of surrounding objects and better positioning with a mobile platform.

Currently, scholars all over the world value the ability to position mobile platforms based on laser scanners. For instance, Barawid Jr O C et al. used two-dimensional laser scanners as navigation sensors for agricultural navigation *(Barawid et al, 2007)*; he applied the Hough transform to detect rows of trees and applied return to launch-based GPS (RTL-GPS) to determine the direction, thereby achieving the straight line moving of a mobile platform between forest rows, and he produced a positioning result with a lateral deviation of 0.11 m and a navigation deviation of 1.5°. Unfortunately, this method is suitable only for the straight-line walking of vehicles and does not involve the positioning of surrounding objects. Libby et al. used a laser scanner sensor to measure the relative position between an agricultural vehicle and a landmark to correct the predicted path of the vehicle based on a wheel encoder. The test results revealed an average error of approximately 20 cm and a maximum error of 1.2 m. Nevertheless, this method is applicable only to road sign measurements in the relatively flat environment of a road surface, and relatively large corrections are needed for vehicle positioning in hilly or mountainous areas *(Libby and Kantor, 2010)*. Freitas et al. used different kinds of Kalman filtering algorithms to study the positioning of mobile platforms; however, this algorithm is mainly suitable for forest trees in the form of "tree walls" *(Freitas et al, 2012)*. In China, Xue Jinlin used laser scanner sensors to obtain the positioning information of tree rows and studied the navigation performance of an agricultural mobile platform between tree rows with a defined plant spacing and between tree rows without equidistant plant spacing *(Jinlin and Shunshun, 2014)*. In the experiment with an equidistant plant spacing, the lateral maximum deviation of their mobile platform was 17.5 cm, and the longitudinal maximum deviation was 28 cm. However, the deviations measured by their method are within the two-dimensional plane only, while the deviation of the pitch axis is not considered. Zhou Jun et al. proposed a method for positioning a mobile platform between densely planted orchards in combination with global navigation satellite system (GNSS) or artificial identification location information *(Zhou and Hu, 2015; Chen et al, 2018)*. Their experiment showed that the standard deviations of the positioning errors of a mobile platform in the X and Y directions for a world coordinate system are approximately 0.08 m; however, this method considers only the positioning of a mobile platform between rows of trees and does not currently involve the global positioning information of the orchard.

In this paper, a laser scanner is used as the scanning device, and the position information of the vehicle provided by real-time kinematic differential GPS (RTK-DGPS) in conjunction with an altitude and heading reference system (AHRS) is used to extract the position information of forest trees in real time. Even when the working vehicle is not operating properly and the GPS has no signal, this method can still achieve a centimetre-level positioning accuracy and obtain global positioning information of forest trees.

MATERIALS AND METHODS

- **Principles and method for the global positioning of forest trees**

The mobile platform walks between the forest trees; simultaneously, the laser scanner scans the trunks on both sides and identifies and extracts relevant parameters according to the point cloud data acquired from the scans. The laser scanning field of view can be divided into three regions: 1) the clear region, which comprises the reliable centre positions of established tree trunks; 2) the fuzzy region, i.e., the laser scanner is able to scan the trunks, but there are large errors in the determined positions of the centre points of those trunks; and 3) the invisible region, in which the laser scanner cannot scan the trunks on both sides. Among these regions, the laser scanner divides the data from one frame composed of original scanning points into several clusters, where per plant tree is represented by a cluster of points. The division of clear and fuzzy regions is determined according to the number of minimum scanning points returned by the same cluster of laser scanning points.

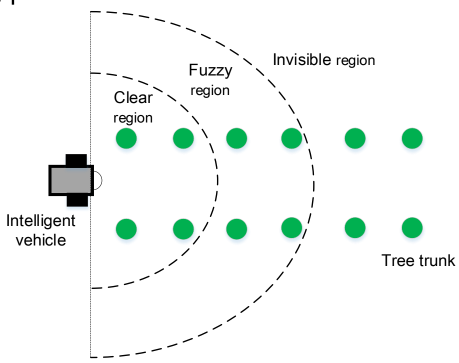

Fig.1 - Visual field of vehicle laser scanner

- **Trunk feature extraction**

When the laser scanner performs non-contact scanning on the trunk of a forest tree, the tree trunk can be approximated as a cylinder, and thus, a two-dimensional scanning point cloud of an approximately arcuate shape can be formed *(Yu et al, 2015; Wang et al, 2015; Xiao et al, 2016)*. According to the point cloud data acquired by the laser scanner, the data set is divided into different clusters by using the domain division method of Euclidean distance, after which the clustered data are fitted to extract the effective positioning information of the trunk *(Ferrara et al, 2018; Maalek et al, 2018)*.

First, the data are clustered by analysing one frame of raw data acquired with the laser scanner by using the domain division method of Euclidean distance *(Nguyen et al, 2007)*. Assume that the laser scanner collects n discrete information data points in one scanning cycle; the purpose of the region segmentation technique is to divide these discrete data points into regions that are not connected to each other according to the distance between two adjacent points.

Second, the tangent method is used in the geometric class algorithm, as shown in Fig. 2, to standard circle fitting of clustered point-clusters. The principle of this fitting process is as follows: the lines connecting the first and last points of the point cloud cluster belonging to a certain trunk to the centre of the laser cluster are strictly tangential to the cross-sectional circle representing the trunk. The formula for the diameter of this circle is as follows:

$$d = 2l_{\min} \frac{\sin\frac{\Delta\theta}{2}}{1-\sin\frac{\Delta\theta}{2}} \tag{1}$$

In formula (1), $\Delta\theta$ is the laser scanning angle of the same cluster data, and $l_{\min}$ is the shortest distance between the scanning point for the same data cluster and the centre of the laser.

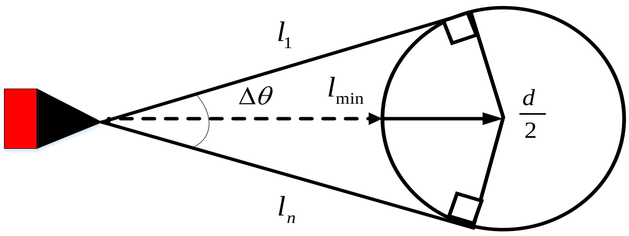

Fig.2 - Principle diagram of calculating the diameter for the tangent method

- **The trunk centre position in the world coordinate system**

To determine the position of the mobile platform between two rows of trees, it is necessary to convert and record the positions of the centre points of trunks in the working space detected by the laser scanner to the world coordinate system. Since the mobile platform is located at the beginning at the starting point of movement and has not yet entered the forest area, the occlusion of the satellite signal by the canopy is not serious. At this time, GPS can be used to output the longitude, latitude and altitude of the mobile platform in the WGS-84 world coordinate system. The AHRS outputs the pitch angle φ, the roll angle ω, and the yaw angle κ under the local horizontal reference system. The system then uses a four-step coordinate transformation to derive the spatial rectangular space coordinates of the centre points of trunks in the WGS-84 world coordinate system fitted by the laser scanner point cloud data.

This coordinate conversion process uses four coordinate systems, the laser scanner reference coordinate system $O\text{-}x_Ly_Lz_L$, the attitude and heading reference coordinate system $O\text{-}x_Iy_Iz_I$, the local horizontal reference coordinate system $O\text{-}x_Gy_Gz_G$, and the WGS-84 world coordinate system $O\text{-}x_{84}y_{84}z_{84}$.

$$Q_{84} = O_{GPS} + R_W\left[R_N\left[O_{LI} + R_M Q_L - O_{IG}\right]\right] \tag{2}$$

Q_L is the coordinates of the trunk centre point Q in the laser scanner coordinate system. O_{LI} denotes the offset between the coordinate origin of the laser scanner coordinate system and the coordinate origin of the AHRS coordinate system, and R_M is the rotation matrix between the laser scanner coordinate system and the AHRS coordinate system. O_{IG} denotes the offset between the GPS antenna phase centre and the AHRS centre, and R_N is the rotation matrix between the AHRS coordinate system and the local horizontal reference frame. R_W represents the rotation matrix from the local horizontal reference system to the WGS-84 world coordinate system, and O_{GPS} is the position of the GPS phase centre in the WGS-84 coordinate system. Q_{84} is the position of the trunk centre in the WGS-84 world coordinate system.

Based on the above formula, Q_L can be obtained from the output data from the laser scanner, O_{LI} and O_{IG} can be obtained with more accurate data through static measurements, R_N can be obtained from the ARHS, R_W and O_{GPS} can be calculated by the GPS-measured latitude, longitude and altitude.

Therefore, the centre point of the trunk in the working space detected by the mobile platform at its initial position can be expressed as the following collection:

$$B=\{(x_1,y_1,z_1),(x_2,y_2,z_2),L(x_i,y_i,z_i)\} \tag{3}$$

In formula (3), i denotes the centre point sequence number of the detected trunk, and *(x,y,z)* (x,y,z) represents the rectangular space coordinates of the centre point of the trunk in the WGS-84 world coordinate system.

When performing standard circle fitting on a laser scanning point cluster, the number of scanning points within the same data cluster should be greater than M_{min}, which determines the scanning range of the laser scanner. Therefore, during any subsequent movement of the mobile platform between the forest trees, the set is updated only when the mobile platform scans a trunk and the number of scanning points in the data cluster exceeds M_{min}. This method can reduce the number of calculations as well as the accuracy of fitting the standard circle of the trunk section area.

- **Mobile platform inter-row positioning method**

In the inter-row positioning scheme, a threshold T needs to be established to match the coordinates of the centre point of the trunk detected at time t acquired from the mobile platform during its movement between the trees with the data stored in set *B* consisting of the initial centre point of the trunk. When the mobile platform is within the position coordinate difference $d_{ij}<T$ of the trunk centre position in the laser scanner coordinate system during the two scans at times t_i and t_j, t_i and t_j are any two moments in the course of driving. this position is considered the same tree in both scans; otherwise, a new tree is considered to have appeared.

$$d_{ij}=\sqrt{(x_i-x_j)^2+(y_i-y_j)^2+(z_i-z_j)^2} \tag{4}$$

In formula (4), (x_i, y_i, z_i) denotes the centre point coordinates of trunk i detected at time t_i, and $(x_j, y_j\ z_j)$ represents the centre point coordinates of trunk j detected at time t_j.

After the trunk centre point is matched, the trunk centre points of 3 trees in set B are randomly selected. The rectangular space coordinates $A=(x_A, y_A, z_A)$, $B=(x_B, y_B, z_B)$ and $C=(x_C, y_C, z_C)$ in the WGS-84 world coordinate system are used to calculate the spatial rectangular space coordinates $D=(x_C, y_C, z_C)$ of mobile platform at time t in the WGS-84 world coordinate system, as shown in Fig. 3.

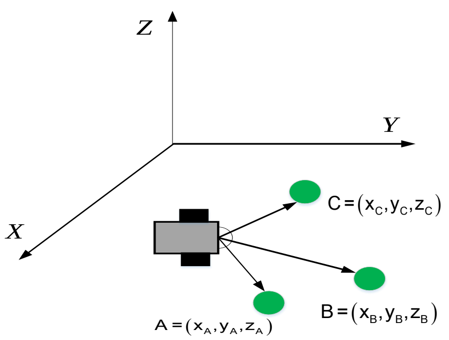

Fig.3 - Mobile platform position prediction model

- **Test system**

This experiment uses a forest precise positioning mobile platform that was independently developed by Beijing Forestry University for data collection. The system uses a crawler-type mobile platform with a laser detection module and a portable computer on the platform, as shown in Fig. 4.

The laser detection module consists of a laser scanner and an AHRS. The laser scanner uses a LMS511-20100 PRO laser scanning radar produced by SICK. The scanning range of the laser scanning radar is -5°~185°, the angular resolution is set to 0.333°, the corresponding scanning frequency is 50 Hz, the maximum detection distance is set according to the number of scanning points M_{min} within the same data cluster, and the power supply is a 24 V DC lithium battery. The AHRS is fixed onto the vehicle body in a tight and stable manner. The lightweight 9-axis altitude-sensor LPMS-CU has a resolution of 0.06°. The data update frequency is 50 Hz for measuring the pitch angle, roll angle and yaw angle of the laser scanner during the movement of the platform in real time.

Fig.4 - The structure of forest precise positioning mobile platform
Laser scanner; Attitude and heading reference system; Portable computer

The three arc-shaped logs at each distance were distributed in the range of 30°~150° in front of the laser scanning radar, and each distance was measured 11 times, as shown in Fig. 5. The three logs (A, B, and C) were each 5 m away from the centre of the laser scanner; the resulting log radius were 92.8, 89.9, and 91.8 mm, respectively. By comparing the radius and distance measurements obtained by scanning the trunks using the laser scanner with the corresponding real values, we analysed the error precision and determined the number of scanning points M_{min} within the same data cluster.

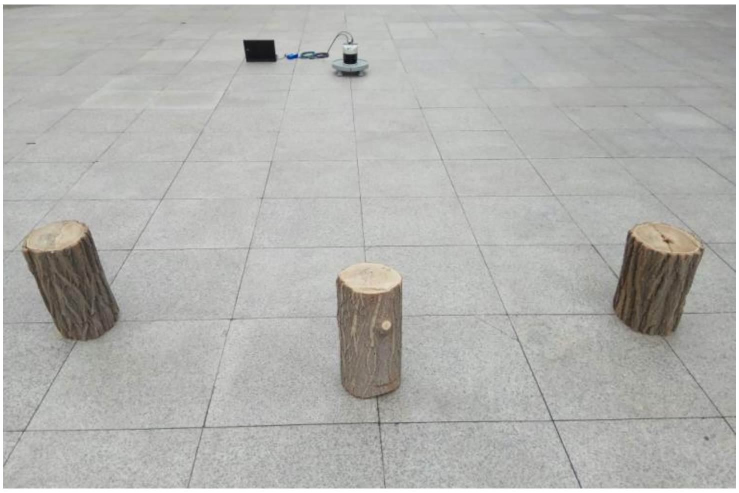

Fig.5 - Photo of the scene for the verification experiment

- **Forest dynamic positioning test**

A trial was conducted in Beijing Dongsheng Eight Country Park, as shown in Fig. 6. Among the two rows of trees in the scene, the left and right sides are both composed of poplar trees, the trunks of which have different thicknesses, and the ground undulates. Whether from trunk features, trunk alignment, or ground effects, it can be used to test the effectiveness of the proposed algorithm.

Fig.6 - Experimental scene and the intelligent mobile platform

RESULTS

Fig. 7 shows the average standard deviation in the log radius and placement distance after acquiring 11 measurements at five different placement distances. The average standard deviation measurement unit is mm, the resulting log radius were 92.8, 89.9, and 91.8 mm.Therefore, when performing standard circle fitting of the laser spot cluster in subsequent tree trunk positioning experiments, the number of scanning points within the same data cluster should be greater than 4 to determine the scanning range of the laser scanner.

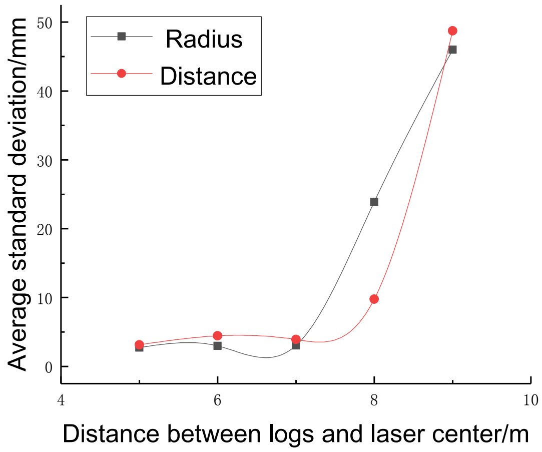

Fig.7 - Average standard deviation at different placement distances

The actual values in the X, Y, and Z directions were subtracted from the corresponding measured values of the positioning method to obtain the positioning errors in the three directions. Figs. 8, 9, and 10 illustrate the positioning errors in the X, Y and Z directions for the first test. As shown in these figures, the positioning errors in the X, Y and Z directions increased slowly with an increase in the moving distance. An analysis revealed that the positioning results of the mobile platform derived from the tree trunk positioning results in the clear region caused a cumulative error during the movement of the mobile platform. This finding is an important reason for the slow rise in the trunk positioning error in the fuzzy and invisible regions.

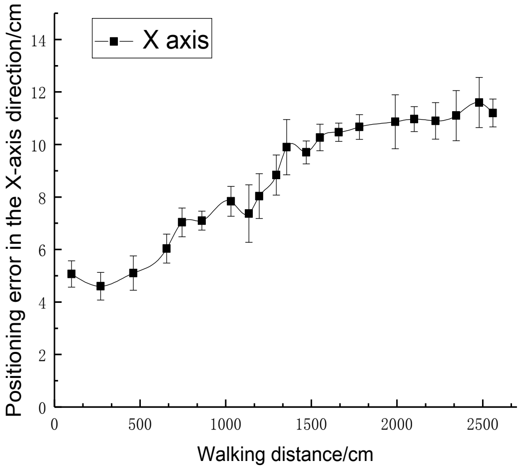

Fig. 8 - Localization errors of the 1st experiment in the X direction

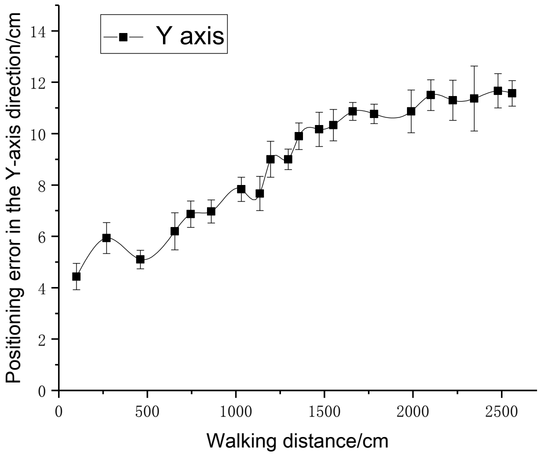

Fig. 9 - Localization errors of the 1st experiment in the Y direction

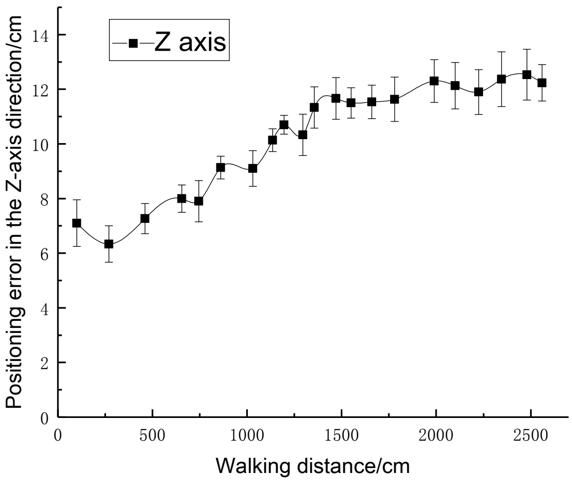

Fig. 10 - Localization errors of the 1st experiment in the Z direction

The statistical results obtained from 11 replicated experiments are shown in Tables 1, 2 and 3. From these 11 experiments, the average value of the maximum error in the X-axis direction was 0.13 m, and the average standard deviation of the positioning error was 0.03 m. The average value of the maximum positioning error in the Y-axis direction was 0.12 m, and the average standard deviation of the positioning error was 0.04 m. The average value of the maximum positioning error in the Z-axis direction was 0.13 m, and the average standard deviation of the positioning error was 0.03 m. These data show that the system boasts a certain controllability and accuracy; furthermore, the maximum error was 0.14 m, which meets the requirements of forest management applications.

Table 1

Localization errors in the X direction (m)

Experiment	Maximum error	Average error	Standard error
1	0.12	0.09	0.02
2	0.12	0.07	0.03
3	0.13	0.09	0.04
4	0.13	0.08	0.03
5	0.14	0.07	0.03
6	0.13	0.08	0.03
7	0.13	0.09	0.03
8	0.12	0.08	0.04
9	0.13	0.08	0.03
10	0.14	0.08	0.03
11	0.13	0.07	0.04
Average	0.13	0.08	0.03

Table 2

Localization errors in the Y direction (m)

Experiment	Maximum error	Average error	Standard error
1	0.12	0.09	0.02
2	0.12	0.08	0.04
3	0.11	0.08	0.04
4	0.11	0.08	0.04
5	0.10	0.09	0.03
6	0.14	0.07	0.04
7	0.13	0.08	0.03
8	0.13	0.08	0.03
9	0.12	0.09	0.05
10	0.12	0.07	0.04
11	0.13	0.08	0.05
Average	0.12	0.08	0.04

Table 3

Localization errors in the Z direction (m)

Experiment	Maximum error	Average error	Standard error
1	0.13	0.09	0.02
2	0.12	0.08	0.04
3	0.13	0.09	0.03
4	0.12	0.09	0.03
5	0.12	0.09	0.03
6	0.13	0.09	0.03
7	0.12	0.08	0.04
8	0.13	0.09	0.03
9	0.14	0.09	0.04
10	0.12	0.09	0.03
11	0.13	0.10	0.03
Average	0.13	0.09	0.03

CONCLUSION

Canopy occlusion attributable to forest trees will affect the GPS positioning accuracy in agricultural machinery; hence, we propose the use of RTK-DGPS to locate mobile platforms in the initial position. Then, we combine the altitude information of an AHRS with laser scanner detection information, which are outputted in real time during the movement of the mobile platform. The platform directly calculates the three-dimensional data consisting of the centre points of tree trunks in the WGS-84 world coordinate system by a spatial coordinate transformation. The proposed positioning method is complementary to the RTK-DGPS positioning information, which overcomes the influence of canopy occlusion on GPS signals in agricultural machinery, and overcomes the influence of irregularities in forest planting on the positioning accuracy of forest trees.

ACKNOWLEDGEMENT

This research was funded by the Fundamental Research Funds for the Central Universities (No. 2015ZCQ-GX-01).

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