forests

MDPI

Article

A GNSS/INS/LiDAR-SLAM Integrated Positioning Method for High Accurate Forest Stem Mapping

Chuang Qian [1,2], Hui Liu [1],Jian Tang [1,2,*],Yuwei Chen [2], Harri Kaartinen [2], Antero Kukko [2], Lingli Zhu[2],Xinlian Liang[2],Liang Chen[3],Juha Hyyppä [2]

Received: date ; Accepted: date ; Published: date
Academic Editor: name

[1] GNSS Research Centre, Wuhan University, No.129 Luoyu Road, Wuhan 430079, China; qc_gnss@whu.edu.cn
[2] Department of Remote Sensing and Photogrammetry, Finnish Geospatial Research Institute, Geodeetinrinne 2, Kirkkonummi FI-02431, Finland; juha.hyyppa@nls.fi (J.H.);
[3] Department of Remote Navigation and Positioning, Finnish Geospatial Institute, 02430 Kirkkonummi, Finland; E-Mail: liang.chen@nls.fi
* Correspondence: tangjian@whu.edu.cn;

Abstract: Forest mapping, one of the main part of forest inventory is an important driving force in the application of laser scanning. Mobile laser scanning (MLS), in which laser scanners are installed on moving platforms, has been studied as a convenient measurement method for forest mapping in past several years. Positioning and attitude accuracies are important for forest mapping with MLS system. Inertial Navigation System (INS) and Global Navigation Satellite System (GNSS) are the typical and popular positioning and attitude sensors for MLS system. While in forest environment, because of the loss of signals due to the occlusion and the severe multipath effects, the positioning accuracy of GNSS is severely degraded, even that of GNSS/INS decreases obviously. Light Detection and Ranging (LiDAR) based Simultaneous Localization and Mapping (SLAM) can achieve higher positioning accuracy in a rich features environment, and is usually implemented in GNSS-denied indoor environment. Forest is different from indoor environment where GNSS signal is available to some extend. Although the positioning accuracy of GNSS/INS is restricted, the heading angle and the velocity can maintain high accuracy even with fewer satellites. The GNSS/INS and the LiDAR based SLAM can be effectively integrated to form a sustainable high accuarte positioning and mapping solution in forest without extra hardware cost. In this research, the information such as the heading angle and the velocity extracted from the GNSS/INS is utilized to improve the positioning accuracy of the SLAM solution: two information aided SLAM methods are proposed. Firstly, a heading angle aided SLAM (H-aided SLAM) method is proposed by constricting the heading angle from the GNSS/INS to the SLAM. Field test results show that the horizontal positioning accuracy of entire trajectory of 800 meters is 0.13m and significantly improved by 70%, compared to traditional GNSS/INS; secondly, a more complex information added SLAM solution utilizing both the heading angle and the velocity information simutanoulsy (HV-aided SLAM) is investigated, and Experiment results show that the horizontal positioning accuracy can reach a level of six centimetre with the HV-aided SLAM, which is significantly improved by 86%. Thus a more accurate forest map is obtained by the proposed integrated method.

Keywords: Forest Mapping; MLS; GNSS/INS; LIDAR; SLAM; Integration

1. Introduction

Accurate tree spatial distribution and attributes (like height, diameter at breast height (DBH), species, etc.) are the basic and important informations of forest inventory. With the rapid development of sensors, laser scanning technique is more and more widely adopted to obtain such informations for forest inventory, such as the aerial laser scanning (ALS) [1], terrestrial laser scanning (TLS) and mobile laser scanning (MLS) [2-3]. Especially, MLS systems can improve the efficiency of field data collection. And there are many studies on MLS systems and their accuracy recently [4-7].

The quality of the final data (registered point cloud) based on MLS is related to the accuracy of position and attitude. Typically, the position and the attitude are provided by a positioning and orientation system (POS), which consists of an Inertial Navigation System (INS) and a Global Navigation Satellite System (GNSS), and the range is provided with a laser scanning sensor on MLS system [8].

But in forest areas, the satellites are blocked by canopies resulting in the loss of the GNSS signals, and the serious multipath, which results in the degraded positioning accuracy. It is one of the main limitations of using MLS in forest. There are intensive experiments to evaluate the GNSS or the GNSS/INS positioning accuracy in the forest. In general, with GNSS standalone, whether (Precise Point Positioning) PPP mode or (Real-Time Kinematic) RTK mode is used, the positioning accuracy are about meter-level in the mature and dense forest [9-14]. With GNSS/INS integrated navigation system, the positioning accuracy can improve to sub-meter-level [15]. However, an automatic high accuracy positioning solution with GNSS/INS is still not available in the mature and dense forest environments.

SLAM is constructing an environment map and positioning the mobile platform simultaneously. It is first proposed and investigated in robotics in 1980s. Most of the SLAM works are mainly for indoor environment, where GNSS is denied and full of features. Similarly, the application of SLAM for forest has been studied by several researches [16-22]. And many of them have studied the feasibility of using SLAM technology for MLS in forest [17–19]. However, the environment in forest is very different from that indoor. There are rich and obvious features like lines and corners in indoor, and SLAM can acquire satisfactory solution as a feature matching method. The features in forest are not continuous and stable, due to the forest density changes and the uneven terrain, and GNSS satellites can be observed occasionally, espcially in open forest area, where SLAM cannot succeed in scan matching and lead to drift and gross errors [16]. The main reason producing the wrong estimation of heading angle, beacuse there are no enough features for scan matching. And drift errors accumulate rapidly over time. At the same time, the gross errors are introduced in the relative positions between the adjacent epoches. In forest, although the positioning accuracy of traditional GNSS/INS is restricted, some valuable navigation information can be provided by GNSS/INS, because part of the satellites can still be observed. For example, the attitude and velocity can be maintained in high accuracy by fewer satellites. The accurate heading angle by GNSS/INS can fix the drift problem in feature-less environment, and the gross errors in the relative positions can be controlled with the precise velocity. Integrating these navigation information from GNSS/INS with SLAM can eliminate the drift and gross errors and enhance the positioning accuracy in forest.

Summing up the above studies, the navigation information of a MLS system is provided by the GNSS/INS navigation system separately. In fact, the MLS system is normally including both the LiDAR sensor and the GNSS/INS system, so the two methods should be integrated to provide the navigation information for the MLS system. The main contributions of this paper are as follows: (1) the navigation information of the GNSS/INS, more specific the heading and the velocity pararemters, are utilized in LiDAR-based SLAM positioning solution to improve the accuracy and the stability; (2) A H-aided SLAM method is proposed and succeeded in forest test, with a horizontal positioning accuracy of 0.13m in an entire trajectory of 800 meters, which is significantly improved by 70% compared to traditional GNSS/INS; (3) Further more, a HV-aided SLAM method is proposed and utilized in forest, with a horizontal positioning accuracy of 0.06m in an entire trajectory of 800 meters, which is significantly improved by 86% compared to traditional GNSS/INS.

The remainder of this paper is organized as follows: Section 2 describes the materials and methods utilized in this research; Section 3 introduces the field tests; the experimental results are discussed in Section 4; and Section 5 draws conclusions.

2. Methods

2.1. GNSS/INS in GNSS-challenging area

The tightly coupled integration utilizes pseudo-ranges, pseudo-range rates, and other original carrier phase of the GNSS receiver as the Kalman filter observations. When the number of visible satellites is between 0-4, Kalman filter measurement update can limit the INS errors accumulation. Therefore, the tightly coupled integration is more suitable for urban canyons and other GNSS-degraded areas with less visible satellites. The studies also showed that the tightly coupled integration has stronger ability to resist gross errors [24, 25]. The forest environment is similar to the urban canyons, where the number of visible satellites decreases because the several satellites are blocked by tree crowns and serious error are caused by the multipath effect. The tightly coupled integration may overcome the problems and obtain the guranteed navigation solution in forest.

In this paper, the GNSS/INS data is collected by NovAtel SPAN, and processed by the Waypoint Inertial Explorer (IE) software to obtain the navigation solution. The SPAN system is a GNSS/INS solution for continuous position, velocity and attitude information. By using INS data, in addition to GNSS, SPAN provides better position, velocity and attitude solution which seamlessly bridges GNSS outages [26]. IE software supports both the loosely and the tightly coupled integration model, which combines the base and the rover GNSS data with INS data to conduct differential processing. In the process, a bidirectional filtering and a variety of quality control methods are adopted to obtain high accuracy results. Accroding to the field test, the root mean square (RMS) of velocity error is in centimetre/second level and the RMS of attitude error is less than 0.1 degree in all 3 axises [26].

2.2. SLAM in forest

SLAM is a process of building and updating a map of an unknown environment calculated by the data collected by the range sensors [27]. Among SLAM methods, LiDAR-based SLAM is a widely used in positioning and environment-recognizing filed and has made a number of successful experience [28].

In general, the classical method for laser scan matching is the Iterative Closet Point (ICP) algorithm [29], which is matching by minimizing the sum of distances between two clouds of points. There are many improvements based on classical ICP algorithm such as Polar Scan Matching (PSM) [30], Iterative Closed Line (ICL) [31] and so on. These methods mainly use the consecutive pairs of scans for matching without using the historical scans. Thus the matching error will accumulate over time. To improve this issue, grid-map based method is proposed to process the laser scan matching. Generally, a grid-based occupancy likelihood map will be built based on all previous scans, and then the rigid-body transformation will be calculated by scan-to-map matching [29]. One of excellent grid-map based methods is Maximum Likelihood Estimation (MLE) [32]. Tang et al. [16] apply the Improved Maximum Likelihood Estimation (IMLE) for positioning in forest and obtain promising result in mature forest. In the process of this method, a grid map is built based on probabilistic and feature uncertainty model, then a totally brute search matching method is applied for scan-to-map matching to find the optimal rigid-body transformation. Because of the complexity of the natural conditions in forest, the features such as undergrowth trees (?) and irregular rocks will introduce noise to the point cloud data. More accurate initial value and search range will significantly improve the robustness of the totally brute –force (?) search matching method, which indicates the integration with GNSS/INS navigation information may obtain remarkable positioning accuracy in forest. So in this paper, the integration method of GNSS/INS and IMLE-SLAM algorithm is studied to improve positioning accuracy in forest.

The IMLE-SLAM is to search the best body transformation to acquire the maximum likelihood value:

$$T^* = \mathrm{argmax}(P(T \propto S_t|M)) \quad (1)$$

where T^* is the optimal body transformation, M is the likelihood map storing likelihood value built by previous scans, S_t is the current scan. The detailed process and performance of IMLE-SLAM can be found in [32].

Moreover, some premises same as the [16] have been taken into account, which are that multiple segmental laser scans from 3D spatial space are projected onto 2D stem profiles to generate the stem map according to the roll and pitch by assuming that most mature stems have straight and circular stems.

2.3. Instrumentation

The research is based on the self-developed FGI ROAMER R2 mobile mapping system installed on an all-terrain-vehicle (ATV) and shown in Fig. 1. The GNSS/INS of this MLS system is NovAtel Synchronized Position Attitude Navigation (SPAN) navigation system, which consists of a GNSS receiver (NovAtel Flexpak6) and an INS (NovAtel UIMU-LCI). The LiDAR sensor adopted for SLAM research is a FARO Focus3D X330, mounted horizontally which can generate approximately 1M points per second. All sensors are mounted on a rigid platform made of hard aluminum. The beam divergence of the FARO Focus3D X330 is 0.011°, and the beam diameter at exit is 2.25 mm. Because the maximum valid range measurement utilized in this research is 25 m, resulting in a maximum footprint size of 7.3 mm compared to 10–20 cm of large beam divergence models at same distance. The synchronized pulse of the LiDAR is utilized to trigger an event pin of the GNSS/INS device to obtain synchronization [16]. The detailed technical specifications of the GNSS/INS navigation system and the laser scanner can be found in [15]. The raw laser point cloud data in a scanner coordinate system are transformed to a real word coordinates by the vehicle position and attitude fetched from the GNSS/INS. Therefore, the accuracy of the point cloud is dependent on the accuracy of the position and attitude measurements of the GNSS/INS.

Figure 1. ATV and two POS devices including NovAtel SPAN and FARO Focus3D X330.

2.4. Integration Method in forest

According to the aforementioned analysis, the forest environment is similar to the urban canyon environment. the satellite signal is blocked and the number of visible satellites is unstable , shown in Fig. 2, but not all the satellites are completely lost. It implies that a tightly coupled integration of GNSS/INS can effectively conduct measurement update to suppress the error accumulation over time. Though, the positioning accuracy will be affected and degenerated, due to the less number of visible satellites and serious multipath effect. However, velocity and attitude can still be maintained at a high accuracy level.

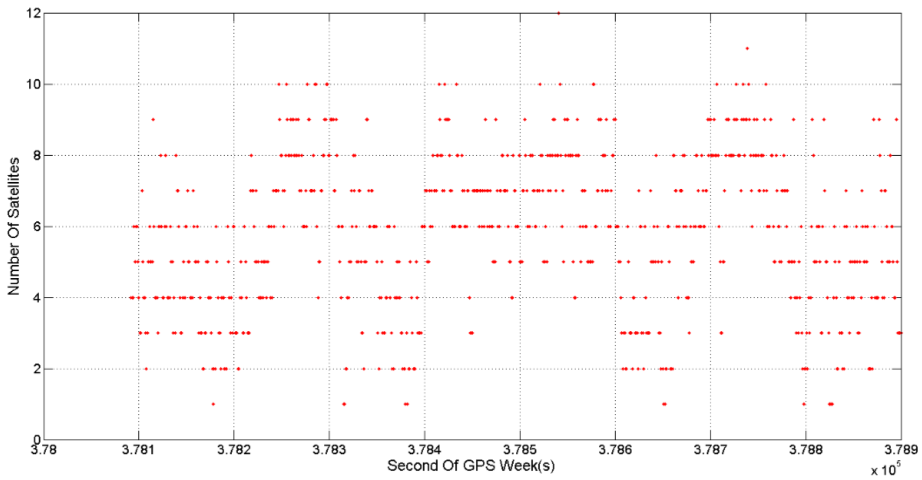


Figure 2. The number of visible satellites (GPS+GLONASS) in forest(what is the red dot?)

The IMLE-SLAM method is based on the maximum posterior probability criterion. The brute-force search method is applied to calculate the posterior probability of the current scan based on the grid-map. The map is built by previous scans with different body transformation. To find the maximum posterior probability corresponding to the optimal body transformation, it is able to obtain centimeter-level positioning accuracy for long-term running in an indoor environment [32] and produce a more accurate and clearer tree trunk map which is benefit to extracting tree trunk information such as DBH [16]. But IMLE-SLAM also has drawbacks. It is strongly dependent on the features in the environment. In the two-dimensional coordinate system, the body transformation includes two position parameters and one heading angle parameter which means a three-dimensional search scope. The high dimensional search scope also reduces the robustness of the algorithm. If the posterior probability is regarded as a function of position and heading angle, that brute-force search method is to search the function extremum in a certain three-dimensional scope. However, due to the complexity of the environment and noise effect, there may be a plurality of extreme points in an inappropriate search scope. The influence of these disadvantages will be enlarged in the forest. If the dimension of the search scope can be reduced, the robustness and computational efficiency will be improved greatly. As a result, a more precise search scope will weaken the influence of noise and the environment.

It can be observed that strong complementarity between GNSS/INS and IMLE-SLAM exists. Although, the accuracy of GNSS/INS positioning in the forest is only sub-meters even in meters, but the heading angle is accurate enough for IMLE-SLAM, and the precise velocity can provide accurate relative displacement in a short time interval as analysed in [34].

IMLE-SLAM can use the heading angle from GNSS/INS to reduce the dimension of search scope, and obtain a more precise search scope with the precise relative displacement with high data sampling rate. The workflow of the data process by integrating GNSS/INS and IMLE-SLAM is shown in Fig. 3. Firstly, GNSS and INS data is processed to obtain velocity and heading angle over time. When matching laser scan data at one epoch, the heading angle is regarded as the known parameter and inputted to the brute IMLE search process, and the velocity is integrated by the epoch interval , then the displacement is added with the estimated position of the last epoch to obtain the initial position of current epoch, which constitutes the search scope with an uncertainty of position. The uncertainty is mainly determined by the maximum resolution of the grid-map. Supposing the length of maximum resolution grid is σ, the search scope is ranging from minus 3σ to plus 3σ on each component, centring on initial position. Then the search scope of T in Eq. (1) can be written as:

$$T = \begin{cases} \varphi = \varphi_0 \\ X \in [X_0 - 3\sigma, X_0 + 3\sigma] \\ Y \in [Y_0 - 3\sigma, Y_0 + 3\sigma] \end{cases} \quad (2)$$

where the φ_0 is the heading angle estimated by GNSS/INS, X_0 and Y_0 is the initial position estimated by the velocity from GNSS/INS.

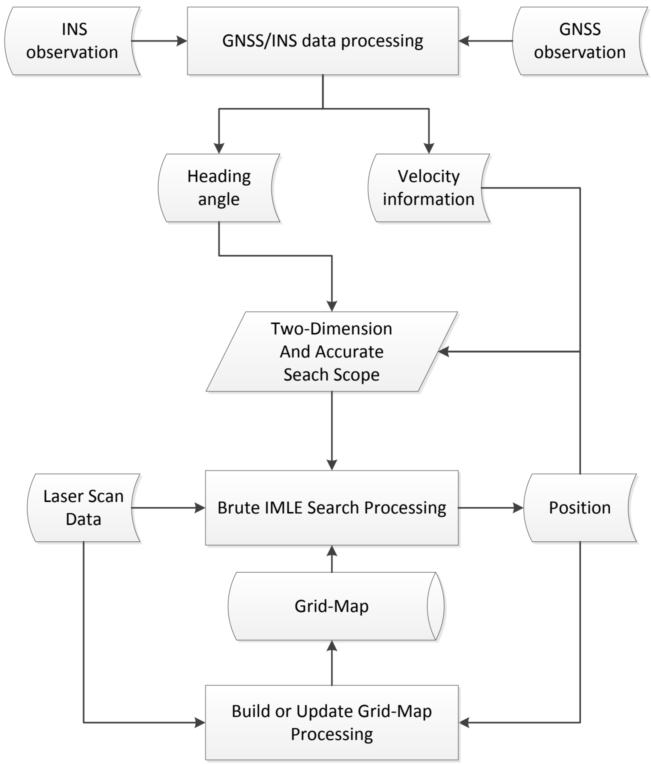


Figure 3. Workflow of High accurate data process by integration with GNSS/INS and IMLE-SLAM

(In the middle of the figure, 'Two-Dimension And….Seach Scope' , 'Seach' should be 'Search')

3. Field Test

In this paper, field tests were carried in the Evo, Southern Finland (61°19′ N, 25°11′ E). The area lies within the southern boreal forest zone and comprises. The dominant tree species are Scots pine and Norway spruce. The detailed information about this test field can be found in [16].

In the field, there are 224 trees measured to the center of the stem at breast height by a total station and RTK GNSS. The positions of these trees in a 2D coordinate system are precisely estimated as the reference targets to evaluate the position accuracy. When the ROAMER R2 mobile mapping system passed through this field, GNSS/INS observations and laser scan measurements were recorded. Then, the laser point cloud was calculated based on the position and attitude of MLS, from which the positions of the reference trees could be extracted. The accuracy of position and attitude of MLS could be evaluated by comparing the positions of these trees with the reference positions indirectly. In the field tests, the average driving speed of the ATV was about 4 km/h and the length of the trajectory was about 800 m. The reference trees and the vehicle trajectory are shown in Fig. 4.

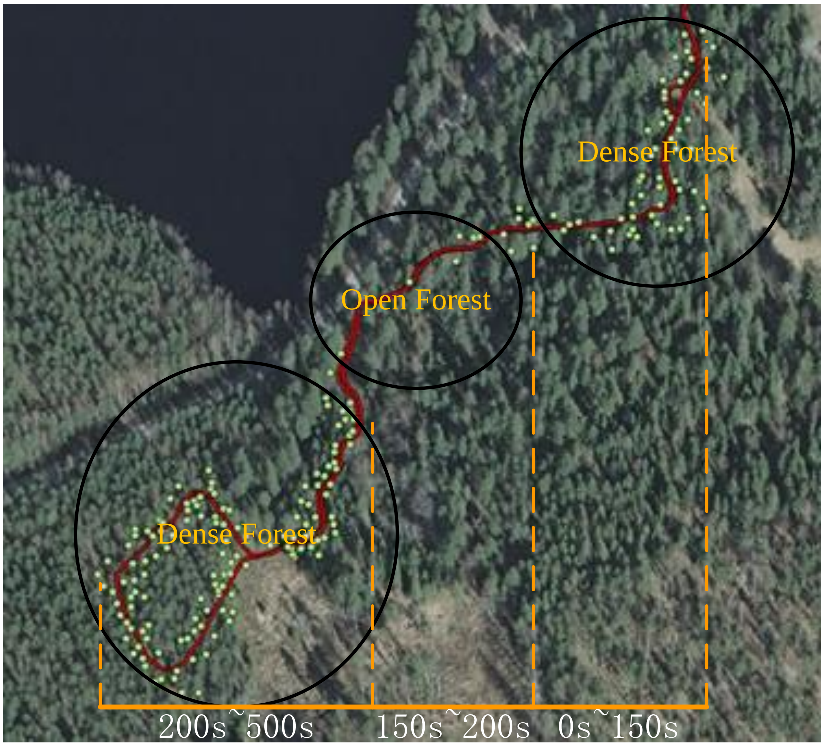


Figure 4. Vehicle Route (red) and Reference Trees (green) (Background orthoimage: NLS 2012).

The whole field test can be divided into 3 parts, which starts from a dense forest, after about 150s then goes into an open forest, and after about 50s then into another dense forest again. In dense forest, SLAM can take advantage of the rich features for scan matching, where the signals of satellites are blocked seriously, which will result in the positioning accuracy degeneration of GNSS/INS. On the contrary, in open forest, SLAM may introduce errors because of the feature-less environment while the GNSS/INS will work well with enough visible satellites.

4. Results and Discussion

The mapping and positioning results are evaluated with reference trees because the referenced trajectory cannot be observed directly during the field test. The positions of the reference trees are estimated from the generated stem distribution map, which is built by the laser point cloud data transformed to a real 2D coordinates by the position of sensor. The accuracy of position can be evaluated by the comparison with the positions of the reference trees. The position accuracy of one epoch is calculated by the position errors of the reference trees located within the effective LiDAR range. It is a circle with centred at the calculated position and radius of LiDAR effective range (25m in this experiment), as shown in Fig. 5. The Root Mean Square Error (RMSE) of position error is calculated by the reference tree network with

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} d_i^2}{N}} \quad (\mathrm{r} < \mathrm{R}) \tag{3}$$

where d_i is the centre offset of the i-th reference tree within the effective LiDAR range.

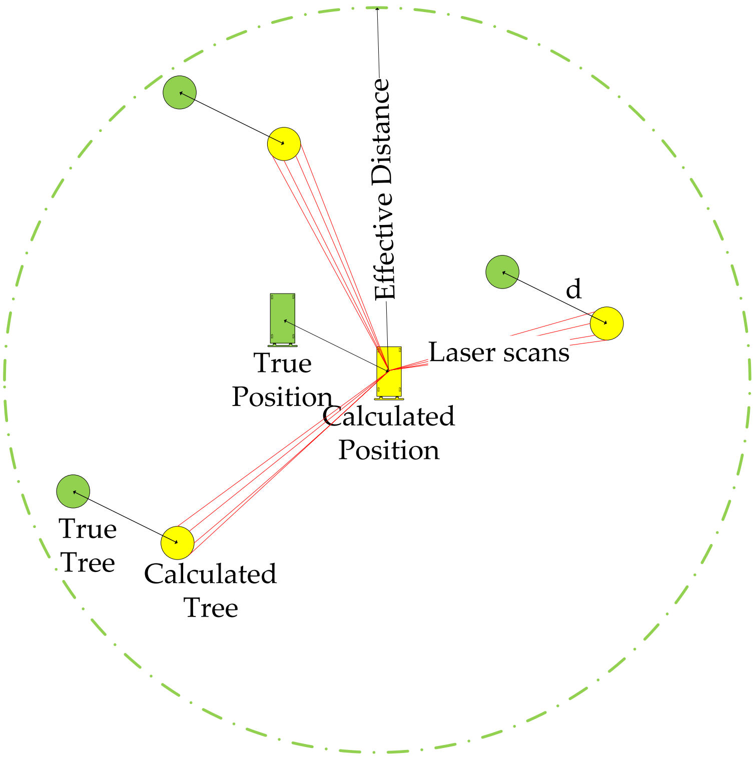
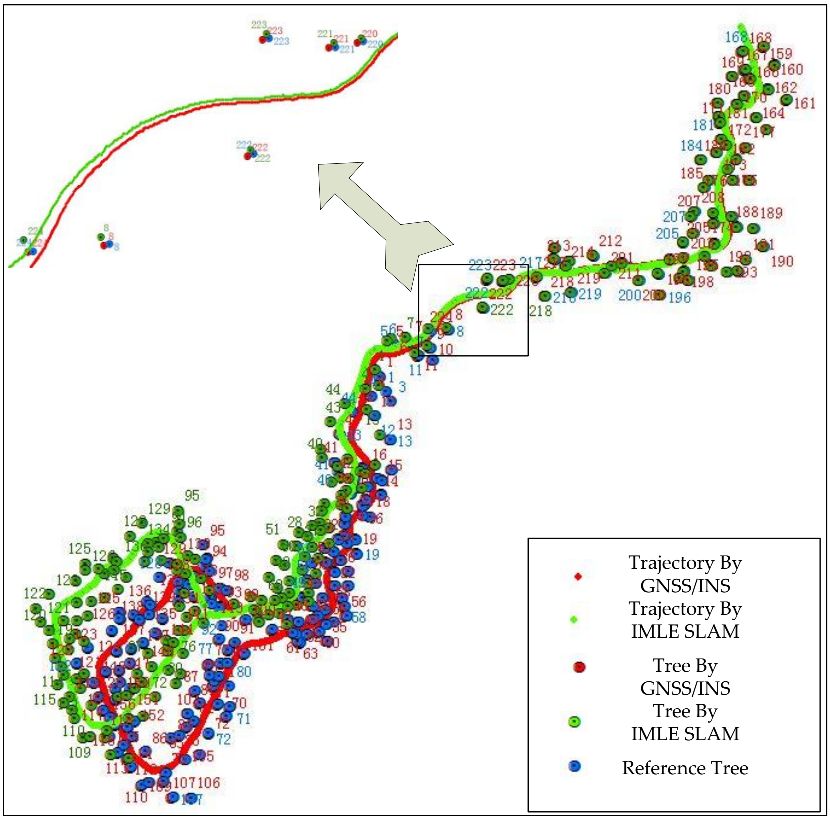


Figure 5 The Schematic diagram for evaluating the position accuracy by reference trees.

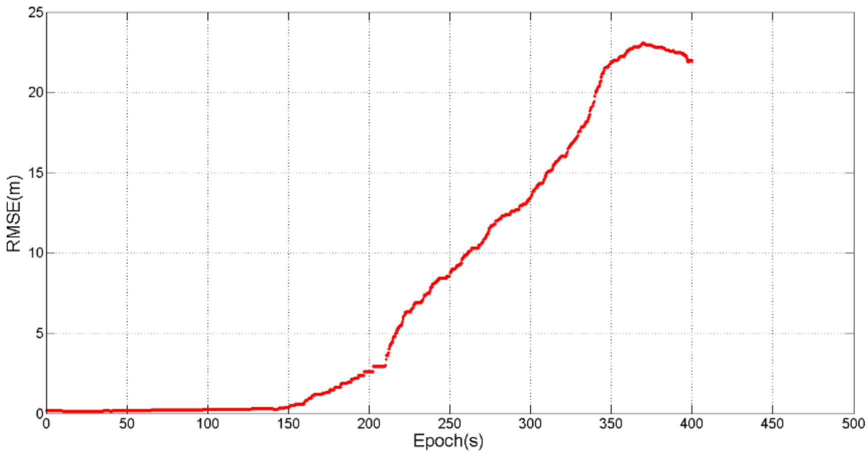
4.1. Evaluation of GNSS/INS and IMLE-SLAM method only

Firstly, the mapping and positioning results are evaluated with GNSS/INS, and IMLE-SLAM algorithm,respectively. The trajectories and stem positions of GNSS/INS and IMLE-SLAM methods are compared in Fig. 6(a) for the entire test. The RMSE of trajectory position error by the GNSS/INS and IMLE-SLAM methods for the entire test is presented in Fig. 6(b) and 6(c) respectively.

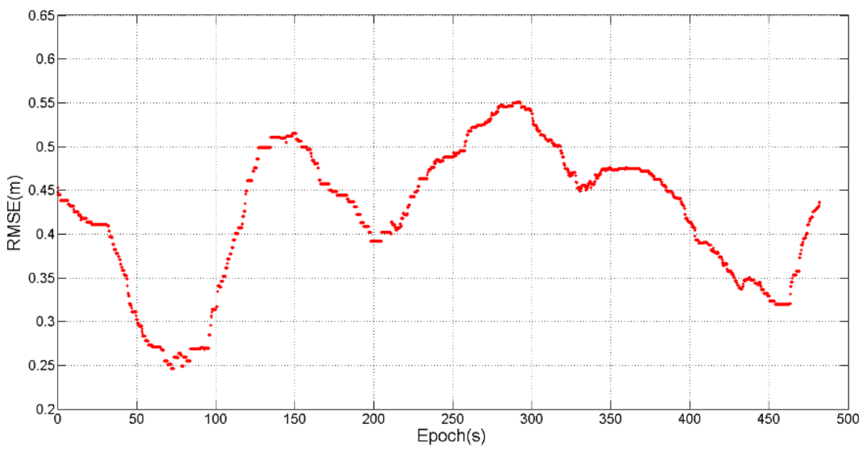
As shown in Fig. 6(a), the IMLE-SLAM solution is effective in the dense forest, where the position errors are moderated. But in the open forest, the position errors accumulates quickly and cannot be mitigated even when driving back to the dense forest again. The GNSS/INS solution is continuous and stable in the entire test with sub-meter position errors. The RMSEs of GNSS/INS and IMLE-SLAM position trajectory are given in Tab. 1.


Trajectory By GNSS/INS
Trajectory By IMLE SLAM
Tree By GNSS/INS
Tree By IMLE SLAM
Reference Tree

(**a**)


RMSE(m)
Epoch(s)

(**b**)


RMSE(m)
Epoch(s)

(**c**)

Figure 6. **(a)** Trajectories and stem position by IMLE-SLAM and GNSS/INS methods for the entire test. **(b)** Position errors of the IMLE-SLAM solution for the entire test. **(c)** Position errors of the GNSS/INS solution for the entire test.

Table 1. The accuracy of the GNSS/INS position trajectory for entire test (Unit: m).

RMSE (m)	EAST	NORTH	2D
GNSS/INS	0.36	0.23	0.43
IMLE-SLAM	8.73	6.82	11.07

As shown in Fig. 7, the heading angle estimated by IMLE-SLAM is unstable, compared with that estiamted by GNSS/INS. It can be observed that there are some jump errors between epoch 100s and epoch 200s, when the ATV drove from the mature forest to the open forest. Heading angle error leads to large positioning error. Thereby, when both heading angle and position are estimated in IMLE-SLAM the dependence on the environment features will be much higher. And once the heading angle is estimated wrong, the enormous error will be introduced in position estimation, as illustrated in Fig. 6(b) and Tab. 1.

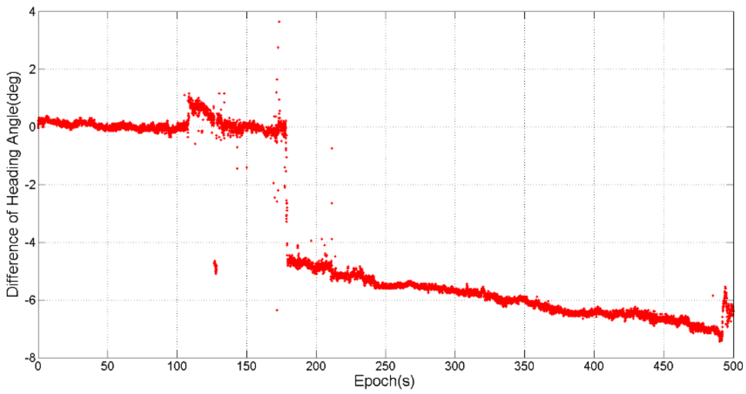
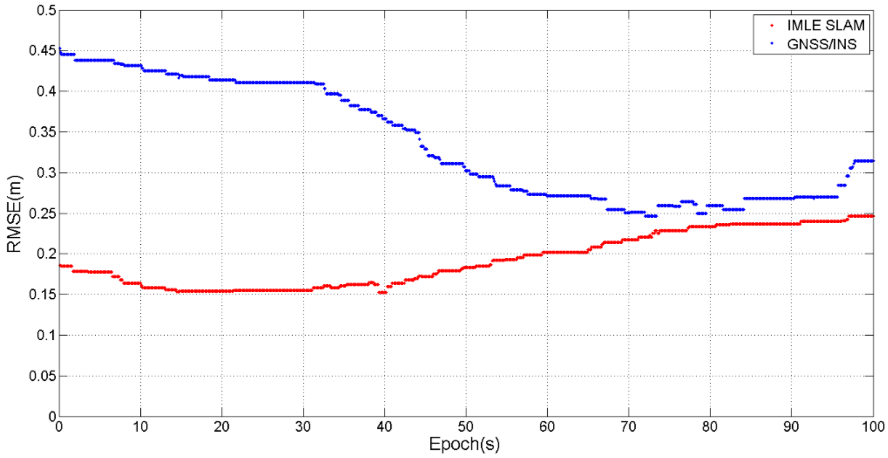
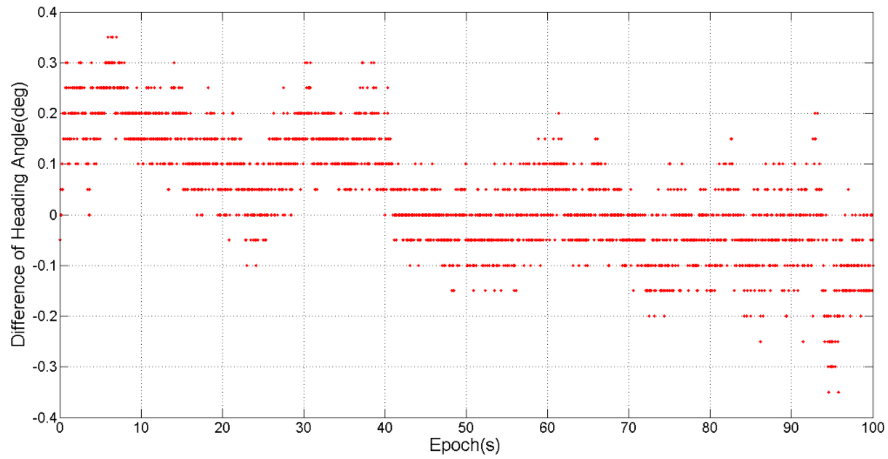


Figure 7. The difference of heading angle estimated by GNSS/INS and IMLE-SLAM

The heading angle error of IMLE-SLAM accumulates quickly due to fewer features in open forest which leads to position error. The estimation of heading angle is a weakness of SLAM algorithm, which is depending heavily on the number and conspicuousness of features, and sensitive to noise [35]. If searching the heading angle, the dimension of search scope will be higher, which will greatly increase the instability of the algorithm, especially in complex environments. and it affects the accuracy of the position finally. However, the performance is degraded in open forest with IMLE-SLAM, against the moderated performance in the mature forest. The statistics of position error of IMLE-SLAM and GNSS/INS method in the first dense forest is shown in Fig. 8(a), the heading angle difference in the first dense forest is shown in Fig. 8(b), and the RMSEs of GNSS/INS and IMLE-SLAM position trajectory in dense forest are given in Tab. 2.



(**a**)



(**b**)

Figure 8. (a) Position errors of the IMLE-SLAM solution and GNSS/INS in the dense forest. **(b)** The difference of heading angle estimated by GNSS/INS and IMLE-SLAM (not easy to understand).

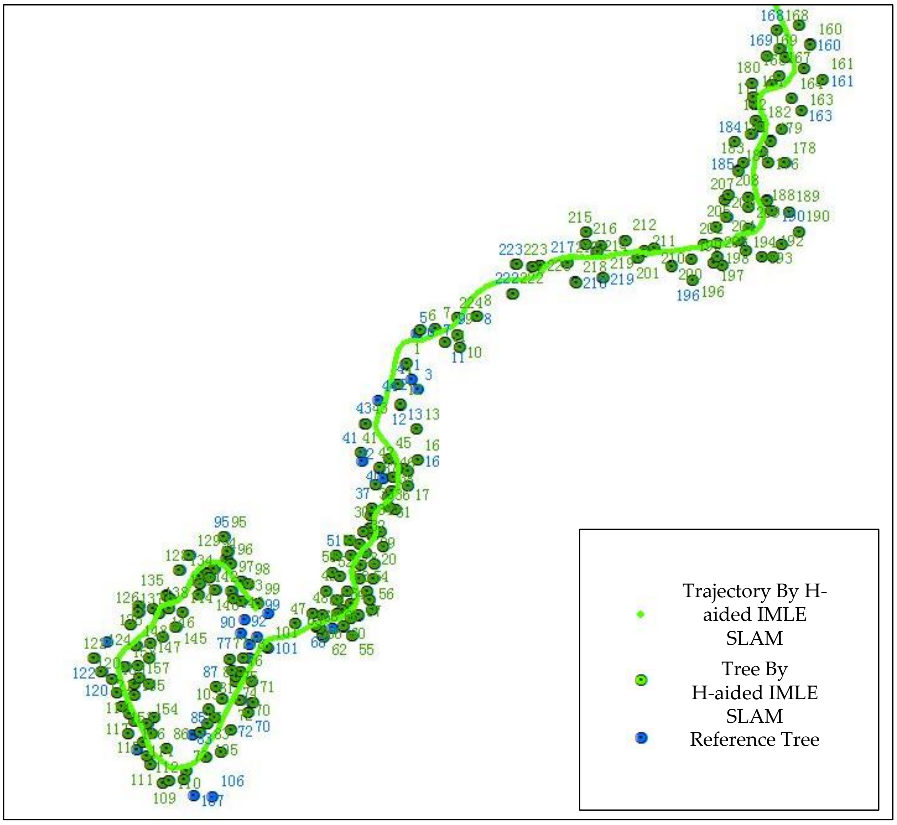
Table 2. The accuracy of the GNSS/INS and IMLE-SLAM position trajectory in the dense forest (Unit: m).

RMSE (m)	EAST	NORTH	2D Position
GNSS/INS	0.29	0.17	0.34
IMLE-SLAM	0.17	0.08	0.19

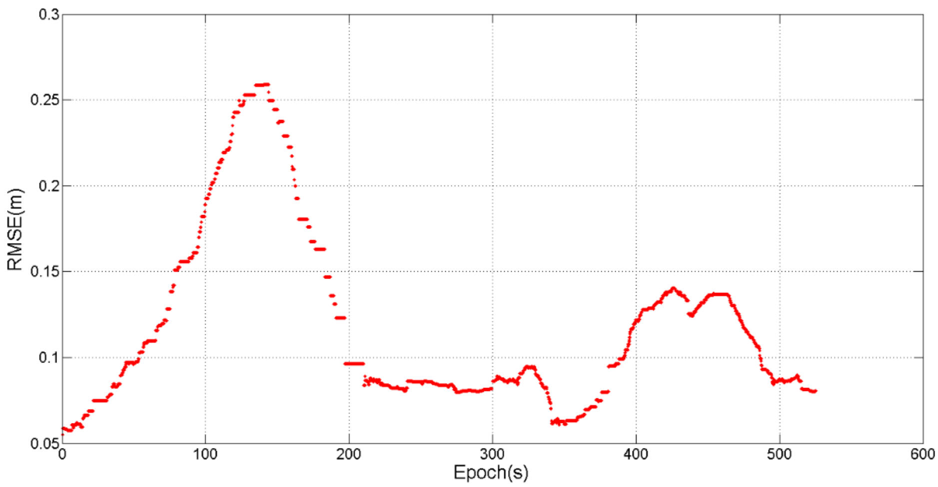
As shown in Fig. 8(a), that the position accuracy of IMLE-SLAM is higher than GNSS/INS in the dense forest. At the same time, the heading angles of IMLE-SLAM and GNSS/INS are in good agreement shown in Fig. 8(b). But the difference of heading angle compared with GNSS/INS is still larger than 0.1 degree in some period. The reason may be that, the angular resolution of LiDAR limits the accuracy of the heading angle. The accurate heading angle estimated by GNSS/INS can be integrated with IMLE-SLAM to improve the position accuracy.

4.2. Result of IMLE-SLAM method aided by heading angle

After constraint the heading angle from GNSS/INS to IMLE-SLAM, also called H-aided IMLE-SLAM, the searching scope degrades from 3 dimentional to 2 dimentional. The trajectories and tree stem positions of the entire test are shown in Fig. 9(a). And the RMSE of position trajectory for the entire test is presented in Fig. 9(b).



(**a**)



(**b**)

Figure 9. (a) Trajectories and stem position by H-aided IMLE-SLAM for the entire test. **(b)** Position errors of the H-aided IMLE-SLAM solution for the entire test

As shown in Fig. 9, when the heading angle of GNSS/INS is integrated with IMLE-SLAM algorithm, the rapid drift does not appear when entering the open forest area. IMLE-SLAM can obtain high accurate trajectory of the entire test. The RMSEs of H-aided IMLE-SLAM trajectory are given in Tab. 3. Comparing the position accuracy of GNSS/INS, the position accuracy of H-aided IMLE-SLAM is improved significantly. The RMSEs of east and north directions are 0.12m and 0.05m and improved by nearly 66.7% and 75%, respectively. The horizontal accuracy is 0.13m and improved by nearly 70%.

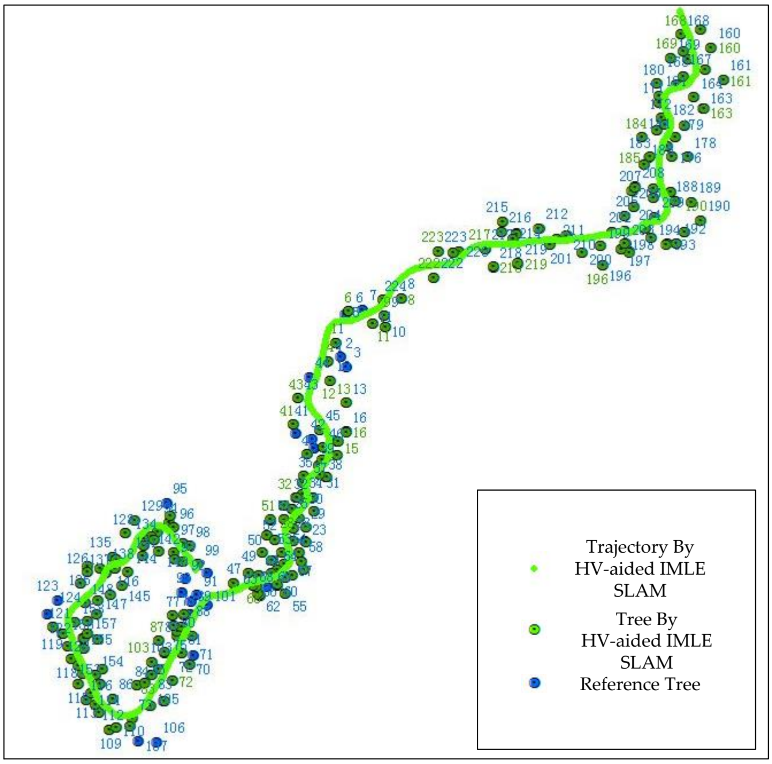
Table 3. The accuracy of the IMLE-SLAM position trajectory with heading angle for entire test (Unit: m).

RMSE (m)	EAST	NORTH	2D
H-aided IMLE-SLAM	0.12	0.05	0.13

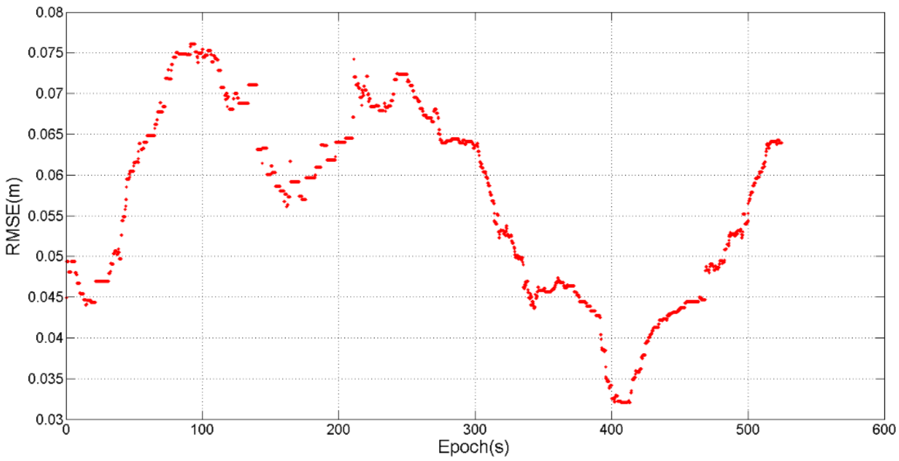
4.3. Result of IMLE-SLAM method aided by heading angle and velocity

Integration with heading angle, IMLE-SLAM algorithm has been greatly improved. But it can still be observed that the position error in the open forest increased . As shown in Fig. 9(b), though the accuracy is recovered after re-entering the dense forest, the stem position in open forest is inaccurate due to the position error. The reason is that the real position cannot be searched out, even after the dimension is reduced by the heading angle in a feature-less environment. Under normal circumstances, the optimal position is searched in a a certain search range scope. The range is an empirical value based on the position of the previous epoch, which is generally coarse. When processing a feature-less data frame with a lot of noisy points, such search scope can easily lead to a false optimum position, as analysed in section 2.4.

By aiding with the velocity estimated by GNSS/INS, a more narrow range search scope which contains the true position can be calculated from the velocity and the position of last epoch, which is described in section 2.4. The brute search method can easily find the optimal position corresponding to a maximum likelihood score. The trajectories and the stem positions of the heading angle and velocity aided (HV-aided) IMLE-SLAM methods are shown in Fig. 10(a). And the trajectory RMSE of HV-aided IMLE-SLAM is presented in Fig. 10(b).



(**a**)



(**b**)

Figure 10. (a) Trajectories and stem positions of the entire test by HV-aided IMLE-SLAM; **(b)** Position errors of the entire test by HV-aided IMLE-SLAM.

As can be seen from Fig. 10, when the velocity of GNSS/INS is used further to provide a more narrow and precise search scope for IMLE-SLAM algorithm, the large positioning errors due to the less features in the open forest area between 100s-200s are mitigated, higher accurate position trajectory can be obtained. The trajectory RMSEs of HV-aided IMLE-SLAM are given in Tab. 4. The RMSEs of east and north directions are 0.04m and 0.04m. The horizontal accuracy is 0.06m and improved 86% by GNSS/INS, which means more accurate stem-map. The results shows that the position accuracy of HV-aided IMLE-SLAM reaches to centimetre-level.

Table 4. The accuracy of the HV-aided IMLE-SLAM position trajectory with heading angle and velocity for entire test (Unit: m).

RMSE (m)	EAST	NORTH	2D
HV-aided IMLE-SLAM	0.04	0.04	0.06

5. Conclusions

In summary, the position and attitude play an important role of the MLS for forest mapping. Traditionally, the position and attitude mainly relies on GNSS/INS system, which can only achieve sub-meter positioning accuracy in forest. SLAM method has recently been studied to provide navigation information and achieved some promising results. Most of SLAM algorithms are utilized in indoor environment and combined with INS only. GNSS/INS navigation information is rarely utilized in the SLAM algorithm. Different from the indoor environment, the forest is much more complex and part of satellites can be observed. The high precision attitude and velocity can be obtained by GNSS/INS. And SLAM method can only provide good results in feature rich forest, and cannot handle with feaure-less open forest. The high precision attitude and velocity of GNS/INS can be integrated with SLAM to improve the robustness and accuracy for high-precision positioning in forest.

Field test results showed that when standalone IMLE-SLAM is used in dense forest, heading angle can estimated correctly, and horizontal accuracy of position is decimetre-level and better than standalone GNSS/INS method, but navigation fails in open forest because heading angle error leads to enormous positioning error. When integrated with high-precision heading angle estimated by GNSS/INS, the H-aided IMLE-SLAM can successfully offer guaranteed positioning results for entire test, the horizontal accuracy of entire trajectory is 0.13m and significantly improved by 70% than GNSS/INS. But positioning error in the open forest is still greater, compared to that in dense forest. When integrated with high-precision velocity further, the position accuracy of HV-aided IMLE-SLAM in open forest is greatly improved. The horizontal accuracy of entire trajectory reaches to 0.06m, which is improved by 86% than GNSS/INS. The results show that the integration with GNSS/INS and SLAM is high-precision navigation method in forest and more accurate stem maps can be obtained.

Although the device used herein are relatively expensive and better, but the integration methods may also be applicable to low-cost equipments. Therefore, our future work is to study the possibility of this integration method with the low-cost equipments.

Acknowledgments: This study was financially supported by the National Key Research and Development Plan (No.2016YFB0502202 & No.2016YFB0501803). the Finnish Academy projects "Towards Precision Forestry", "Centre of Excellence in Laser Scanning Research (CoE-LaSR) (272195)" the National Nature Science Foundation of China (41304004), the Chinese Academy of Science (181811KYSB20130003), Chinese Ministry of Science and Technology (2015DFA70930).

Author Contributions:

Chuang Qian and Jian Tang conceived and designed the experiments and wrote the paper, performed the experiments; Harri Kaartinen, Antero Kukko performed the field test and provided the LiDAR, IMU, GPS raw data and tree reference; Yuwei Chen, Hui Liu Lingli Zhu,Xinlian Liang,Liang Chen and Juha Hyyppä, reviewed the paper and gave constructive advises.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Hyyppä, J.; Holopainen, M.; Olsson, H. Laser scanning in forests. Remote Sens. 2012, 4, 2919–2922.
2. Leeuwen, M.; Nieuwenhuis, M. Retrieval of forest structural parameters using LiDAR remote sensing.Eur. J. For. Res. 2010, 129, 749–770.
3. Jaakkola, A.; Hyyppä, J.; Kukko, A.; Yu, X.; Kaartinen, H.; Lehtomäki, M.; Lin, Y. A low-cost multi-sensoral mobile mapping system and its feasibility for tree measurements. ISPRS J. Photogramm. Remote Sens. 2010,65, 514–522.
4. Liang, X.; Kukko, A.; Kaartinen, H.; Hyyppä, J.; Yu, X.; Jaakkola, A.; Wang, Y. Possibilities of a PersonalLaser Scanning System for Forest Mapping and Ecosystem Services. Sensors 2014, 14, 1228–1248.
5. Rutzinger, M.; Pratihast, A.K.; Oude Elberink, S.; Vosselman, G. Detection and modelling of 3D trees from mobile laser scanning data. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. 2010, 38, 520–525.
6. Holopainen, M.; Kankare, V.; Vastaranta, M.; Liang, X.; Lin, Y.; Vaaja, M.; Yu, X.; Hyyppä, J.; Hyyppä, H.; Kaartinen, H.; et al. Tree mapping using airborne, terrestrial and mobile laser scanning—A case study in a heterogeneous urban forest. Urban For. Urban Green. 2013, 12, 546–553.
7. Kukko, A.; Kaartinen, H.; Hyyppä, J.; Chen, Y. Multiplatform mobile laser scanning: Usability and performance. Sensors 2012, 12, 11712–11733.
8. Bauwens S, Bartholomeus H, Calders K, et al. Forest Inventory with Terrestrial LiDAR: A Comparison of Static and Hand-Held Mobile Laser Scanning. Forests, 2016, 7(6): 127.
9. Andersen, H.-E.; Clarkin, T.; Winterberger, K.; Strunk, J. An accuracy assessment of positions obtained using survey-and recreational-grade global positioning system receivers across a range of forest conditions within the Tanana valley of interior Alaska. Western J. Appl. For. 2009, 24, 128–136.
10. Danskin, S.D.; Bettinger, P.; Jordan, T.R.; Cieszewski, C. A comparison of GPS performance in a southern hardwood forest: Exploring low-cost solutions for forestry applications. South. J. Appl. For. 2009, 33, 9–16.
11. Bakuła, M.; Oszczak, S.; Pelc-Mieczkowska, R. Performance of RTK positioning in forest conditions: Case study. J. Surv. Eng. 2009, 135, 125–130.
12. Bakula, M.; Przestrzelski, P.; Kazmierczak, R. Reliable technology of centimeter GPS/GLONASS surveying in forest environments. IEEE Trans. Geosci. Remote Sens. 2015, 53, 1029–1038.
13. Tachiki, Y.; Yoshimura, T.; Hasegawa, H.; Mita, T.; Sakai, T.; Nakamura, F. Effects of polyline simplification of dynamic GPS data under forest canopy on area and perimeter estimations. J. For. Res. 2005, 10, 419–427.

14. Ucar, Z.; Bettinger, P.; Weaver, S.; Merry, K.L.; Faw;K. Dynamic accuracy of recreation-grade GPS receivers in oak-hickory forests. Forestry 2014, 87, 504–511.
15. Kaartinen H, Hyyppä J, Vastaranta M, et al. Accuracy of kinematic positioning using Global Satellite Navigation Systems under forest canopies. Forests, 2015, 6(9): 3218-3236.
16. Tang J, Chen Y, Kukko A, et al. SLAM-Aided Stem Mapping for Forest Inventory with Small-Footprint Mobile LiDAR. Forests, 2015, 6(12): 4588-4606.
17. Ringdahl, O.; Hohnloser, P.; Hellström, T.; Holmgren, J.; Lindroos, O. Enhanced Algorithms for Estimating Tree Trunk Diameter Using 2D Laser Scanner. Remote Sens. 2013, 5, 4839–4856.
18. Takashi, T.; Asano, A.; Mochizuki, T.; Kondou, S.; Shiozawa, K.; Matsumoto, M.; Tomimura, S.; Nakanishi, S.; Mochizuki, A.; Chiba, Y.; et al. Forest 3D Mapping and Tree Sizes Measurement for Forest Management Based on Sensing Technology for Mobile Robots. In Field and Service Robotics; Springer: Berlin, Germany; Heidelberg, Germany, 2014.
19. Ding, X.; Yan, L.; Liu, J.; Kong, J.; Yu, Z. Obstacles Detection Algorithm in Forest based on Multi-sensor Data Fusion. J. Multimed. 2013, 8, 790–795.
20. Öhman, M.; Miettinen, M.; Kannas, K.; Jutila, J.; Visala, A.; Forsman, P. Tree measurement and simultaneous localization and mapping system for forest harvesters. In Field and Service Robotics; Springer: Berlin, Germany; Heidelberg, Germany, 2008; pp. 369–378.
21. Miettinen, M.; Ohman, M.; Visala, A.; Forsman, P. Simultaneous Localization and Mapping for Forest Harvesters. In Proceedings of the IEEE International Conference on Robotics and Automation, Roma, Italy, 10–14 April 2007; pp. 517–522.
22. Chen, Y.; Tang J.; Hyyppä, J.; Holopainen M.; Liang X. Liu J., Chen L., Hakala T., Litkey P., Niu X. and Hyyppä H. Automated Stem Mapping Using SLAM Technology for Plot-Wise Forest Inventory. In Proceedings of Ubiquitous Positioning Indoor Navigation and Location-Based Services(UPINLBS 2014), Corpus Christi, TX, USA, 20–21 Novenber 2014; pp. 130–134.
23. Ryding J, Williams E, Smith M J, et al. Assessing handheld mobile laser scanners for forest surveys. Remote Sensing, 2015, 7(1): 1095-1111.
24. Godha S. Performance evaluation of low cost MEMS-based IMU integrated with GPS for land vehicle navigation application. Library and Archives Canada= Bibliothèque et Archives Canada, 2006.
25. Petovello M G. Real-Time Integration of a Tactical-Grade IMU and GPS for High-Accuracy Positioning and Navigation. Calgary: The University of Calgary, 2003.
26. Kennedy, S. Hamilton, J. Martell. Architecture and System Performance of SPAN NovAtel's GPS/INS Solution. Proceedings of IEEE/ION PLANS 2006, San Diego, USA, April 23- 25, 2006.
27. Bailey, T.; Durrant-Whyte, H. Simultaneous localization and mapping (SLAM): Part II. IEEE Robot. Autom. Mag. 2006, 13, 108–117.
28. Li L, Yao J, Xie R, et al. LASER-BASED SLAM WITH EFFICIENT OCCUPANCY LIKELIHOOD MAP LEARNING FOR DYNAMIC INDOOR SCENES. ISPRS. Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences, 2016: 119-126.
29. Besl, P.J.; McKay, N.D. Method for registration of 3-D shapes. In Proceedings of the Robotics-DL Tentative. International Society for Optics and Photonics, Boston, MA, USA, 30 April 1992; pp. 586–606.
30. Diosi A, Kleeman L. Laser scan matching in polar coordinates with application to SLAM. 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems. IEEE, 2005: 3317-3322.
31. Censi A. An ICP variant using a point-to-line metric. Robotics and Automation, 2008. ICRA 2008. IEEE International Conference on. IEEE, 2008: 19-25.
32. Tang, J.; Chen, Y.; Jaakkola, A.; Liu, J.; Hyyppä, J.; Hyyppä, H. NAVIS-An UGV Indoor Positioning System Using Laser Scan Matching for Large-Area Real-Time Applications. Sensors 2014, 14, 11805–11824.
33. Titterton, D.H.; Weston, J.L. Strapdown inertial navigation technology. Peter Peregrinus Ltd: 2004.
34. Zhang Q, Niu X, Chen Q, et al. Using Allan variance to evaluate the relative accuracy on different time scales of GNSS/INS systems. Measurement science and technology, 2013, 24(8): 085006.
35. Tang, J.; Chen, Y.; Niu, X.; Wang, L.; Chen, L.; Liu, J.; Shi, C.; Hyyppä, J. LiDAR Scan Matching aided Inertial Navigation System in GPS Denied Environments. Sensors 2015, 15, 16710–16728.