Affordable air-ground mobile mapping system for precise forestry applications

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Abstract

Precise forest inventory in difficult terrain remains challenging due to mobility constraints and canopy occlusion. This paper presents an affordable air-ground mobile mapping system combining shoulder-mounted double LiDAR with a lightweight FPV drone-based LiDAR. We developed an extrinsic calibration method for dual orthogonally-mounted sensors and implemented a comprehensive processing pipeline incorporating LiDAR odometry, pose graph SLAM, and multi-view Normal Distributions Transform. Field experiments demonstrate successful air-ground data fusion for tree stem detection and dendrometric parameter extraction. The system was validated in extreme environments including a cave survey, proving versatility in difficult terrain. All software components are released as open-source tools: https://github.com/MapsHD/HDMapping.

1. INTRODUCTION

This paper shows a novel affordable air-ground mobile mapping system for precise forestry applications. It is composed of shoulder-mounted double LiDAR system and light weight FPV drone with LiDAR payload. We developed a method for double LiDAR extrinsic calibration. It is available as an open source project available at https://github.com/MapsHD/HDMapping. We provide framework for performing all necessary calculations related with 3D point clouds (air/ground) registration including LiDAR odometry, pose Graph SLAM, multi view Normal Distributions Transform. The result is consistent 3D point cloud that is used for assessing the intrinsic quality characteristics of each point cloud, examining density metrics (overall and vertical distribution profiles), noise levels, and completeness of tree stem representation. The contribution of our is as follows:

- shoulder-mounted double LiDAR system and its calibration,
- light weight payload for small FPV drone,
- novel data registration pipeline for air-ground data registration and georeferencing,
- built prototype and performed experiment in the field.

We believe, that our work will contribute into rapidly growing domain of mobile mapping systems. The added value is light weigh design decreasing fatigue during survey and complementary approach for data collection air-ground. It enables accessing harsh environment.

2. STATE OF THE ART

Mobile mapping systems are already widely used in precise forestry applications (Elhashash et al., 2022),(Stefano et al., 2021), (Holmgren et al., 2019), (Mouafik et al., 2024). Large-scale forest inventory at the individual tree level is critical decision making for natural resource management (Shao et al., 2024),(Thies et al., 2004). Terrestrial laser scanning (TLS) was introduced for basic forest measurements, such as tree height and diameter, in the early 2000s (Calders et al., 2020). An alternative technology is UAV LiDAR scanning (Chisholm et al., 2013),(Hyyppä et al., 2020a). The challenge here is to avoid obstacles using FPV(First Person View) control. Another solution is backpack mobile mapping system (Holmgren et al., 2017). It allows traversing difficult terrain. Unfortunately it itroduces additional fatigue due to overall weight of the system. For this reason a hand-held mobile mapping system (Hyyppä et al., 2020b) can be considered as an alternative solution. The drawback is that this solution is not hand-free, thus it limits the mobility in difficult terrain. The accuracy comparison of various remote sensing data sources in the retrieval of forest stand attributes was elaborated in (Hyyppä et al., 2000). It appears that optical images still include more information for forest inventory than radar images, from all satellite radar methods, the coherence technique seemed to be superior to other methods. Another interesting approach is to incorporate an affordable solution (Jaakkola et al., 2010), unfortunately it suffers from low quality of 3D measurements. Overall quality of data is rather poor. More information concerning accuracy assessment of advanced laser scanner technologies can be found in (Kim et al., 2024). This study evaluated the accuracy and applicability of drone-mounted LiDAR, terrestrial 3D laser scanners, and mobile LiDAR scanners for forest surveying. The terrestrial 3D laser scanner demonstrated the highest accuracy, making it the most suitable tool for high-precision forestry tasks. Drone-mounted LiDAR, while effective for large-scale surveys it is characterised with limited applicability for detailed tree-level analysis. Mobile LiDAR scanners provided moderate accuracy. To conclude, there are plenty of mobile mapping technologies already applied in precise forestry applications. In this paper We show novel approach for measuring in highly inaccessible terrain requiring high mobility. Our light weight wearable solution is not yet elaborated in precise forestry application, thus we hope our open source project will help in such demanding applications.

Our work is related with SLAM (Simultaneous Localization and Mapping) applied for complex environments (Li et al., 2020). It is composed of LiDAR odometry (Lee et al., 2023), loop closure (Sprickerhof et al., 2011) and final refinement with multi view NDT (Normal Distributions Transform) (Zhu et al., 2021). Our contribution is an open source project and data that can be requested on demand.

3. DATA AND METHODS

3.1 Hardware

We designed custom chassis for double LiVOX MID 360 orthogonal mount (figure: 1). It also protects LiDARs from impact with obstacle. It is built from alluminium, thus it is rather shock and vibration resilient. The base between LiDARs does not change, thus we incorporate constant calibration matrix for entire survey data set. This orthogonal mount provides sufficient 3D data overlap for calibration procedure (see section 3.2). We use it as a part of wearable mobile mapping system onto shoulder.

Figure 2 shows our light weight (250g) UAV DJI Avata2 (`https://www.dji.com/pl/avata-2`) that is customer-grade FPV drone capable flying up to 8 minutes without payload. Once we add 350 grams the overall flying time was reduced down to 5 minutes. The basic specification of LiVOX MID 360 LiDAR is as follows:

- laser Wavelength: 905 nm,
- laser Safety: Class 1 (IEC60825-1:2014)(Eye Safety),
- detection Range: 40 m at 10% reflectivity, 70 m at 80% reflectivity,
- close proximity blind zone: 0.1m (imprtant for tiny spaces),
- field of view: horizontal: 360°, vertical: -7° 52°,
- range precision (1σ): $\leq$ 2 cm (at 10m), 3 cm (at 0.2m),
- angular precision1σ 0.15º,
- point rate: 200,000 points/s (first return),
- weight: 265g,
- scanning pattern: non repetitive.

More information can be found at `https://www.livoxtech.com/mid-360/specs`.

3.2 Calibration of shoulder-mounted double LiDAR system

Double LiDAR system calibration is using Iterative Closest Point algorithm (Zhen-kang, 2009). This algorithm minimizes the sum of Euclidean distances set of pairs of neighboring points from two different LiDARs. Due to overlap between LiDARs with wide (half sphere) field of view this method is

(a) Top view.

(b) Side view.

Figure 1. Custom chassis for double LiVOX MID 360 orthogonal mount.

Figure 2. UAV - DJI Avata2 equipped with LiVOX MID 360 LiDAR.

sufficient. More details can be found (Bedkowski, 2022). Iterative closest point is formulated as follows: Starting from 3D point transformation from local to global coordinate system as function:

$$\Psi_{[R^{cal},t^{cal}]}(R^{cal},t^{cal},x^l,y^l,z^l) = \begin{bmatrix} x^{source} \\ y^{source} \\ z^{source} \end{bmatrix} \tag{1}$$

we formulate an observation equation(2) as a source to target distance:

$$\boxed{\underbrace{\begin{bmatrix} x^{\delta} \\ y^{\delta} \\ z^{\delta} \end{bmatrix}}_{residuals} = \underbrace{\begin{bmatrix} x^{target} \\ y^{target} \\ z^{target} \end{bmatrix}}_{target\ values} - \underbrace{\left(\Psi_{[R^{cal},t^{cal}]}(R^{cal},t^{cal},x^l,y^l,z^l)\right)}_{model\ function}} \tag{2}$$

where $\begin{bmatrix} x^{\delta} & y^{\delta} & z^{\delta} \end{bmatrix}$ are *residuals*, $\begin{bmatrix} x^{target} & y^{target} & z^{target} \end{bmatrix}$ are *target values* and $\Psi_{[R^{cal},t^{cal}]}(R^{cal},t^{cal},x^l,y^l,z^l) - \begin{bmatrix} x^k & y^k & z^k \end{bmatrix}$ is the *model function*. We want to minimize residua by finding $[R^{cal},t^{cal}]$ that solves following optimization problem:

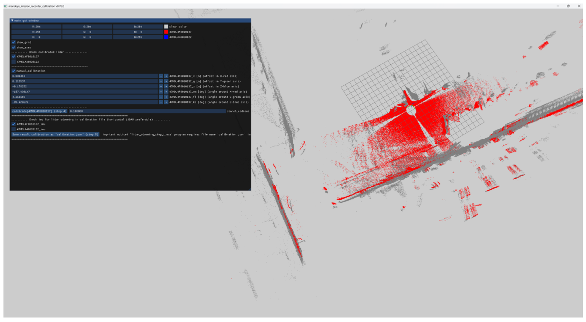
$$\min_{R^{cal},t^{cal}} \sum_{i=1}^{C} \left(\begin{bmatrix} x^{target} \\ y^{target} \\ z^{target} \end{bmatrix} - \left(\Psi_{[R^{cal},t^{cal}]}(R^{cal},t^{cal},x_i^l,y_i^l,z_i^l)\right) \right)^2 \tag{3}$$

Where there are C pairs of points (source to target) contributing into optimization process that is solve iteratively to reach convergence. We provide open-source software to make the calibration process more user-friendly. Figure 3(a) demonstrates data before calibration. Figure 3(b) demonstrates data after calibration. It can be observed the improved consistency of the point cloud due to calibration.

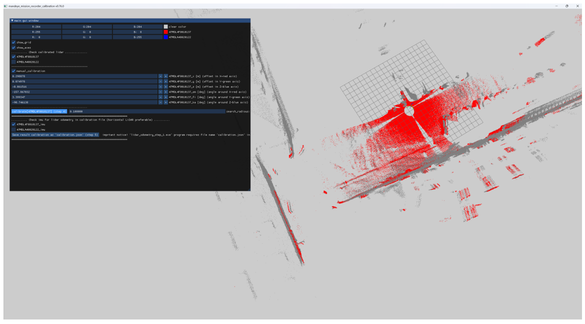
3.3 Data acquisition and processing - simple case

Figure 4 shows the data collection result. Figure 5(a) shows surveyor equipped with our mobile mapping systems. The idea of this particular experiment was to conduct air-ground survey to cover the same space from air and ground, the density of point cloud suppose to be similar to some extend from ground up to level of UAV mapping (approximately 3-4 meters). The processing pipeline is composed of:

- Two LiDARs calibration.



(a) Before calibration.



(b) After calibration.

Figure 3. Our tool for two LiDARs calibration.

- LiDAR odometry.
- Single session registration.
- Multiple sessions registration and final refinement.

The comparison of point clouds acquired with UAV and shoulder-mounted LiDAR systems, including detected tree stems shown in blue in figure 5.

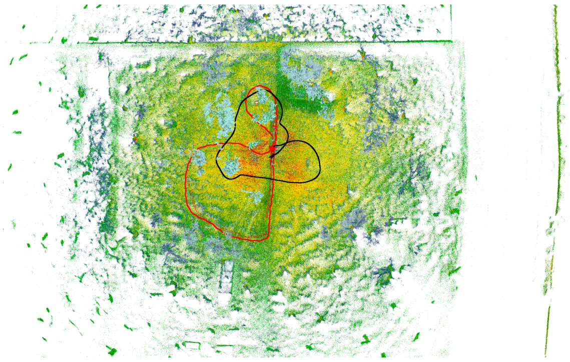
3.4 Extreme mobile mapping application

Our mobile mapping system is designed to cope with extremely difficult terrain. It is possible to climb and crawl during survey. Light weight UAV is available in small bag, thus it does not introduce meaningful fatigue. To test our system we went to survey the Meziad Cave in Romania (see figure: 6). The challenge was to perform mapping of the trees in front of the cave where walking was to dangerous, thus we incorporated UAV mapping. Figure 7 shows data collected in extreme environment (Meziad Cave, Romania) with drone and shoulder wearable mobile mapping system. Extreme mobile mapping applications are very demanding, since there is high probability of the injury. Thus, we do not recommend to follow such risky scenarios without professional training and assistance of professional personnel.

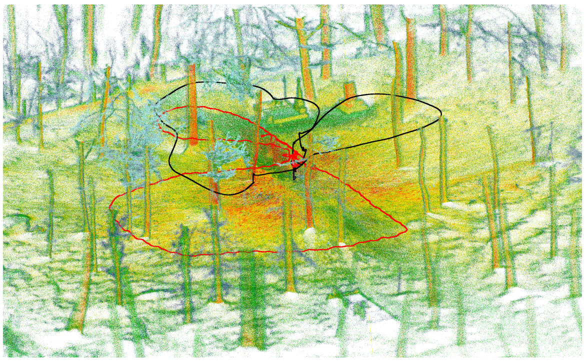
4. CONCLUSION

The contributions of our research are shoulder-mounted double LiDAR system and its calibration, light weight payload for small FPV drone, data registration pipeline for air-ground data registration, novel LiDAR odometry, built prototype and performed experiment in the field.

This study evaluates the applicability of under-canopy UAV LiDAR for forest measurements. It opens opportunity for further comprehensive comparative analysis. Several point cloud



(a) Top view.



(b) Perspective view.

Figure 4. Data collection. Red line: trajectory obtained from shoulder-mounted double LiDAR system, black line: trajectory obtained from UAV.

datasets were collected: the UAV-collected data, a reference dataset acquired using a shoulder-mounted personal LiDAR device traversing the same forest plot, and a merged dataset combining both sources through co-registration. This data are available on demand, thus it is our main contribution.

We have shown following functionalities of our open source project:

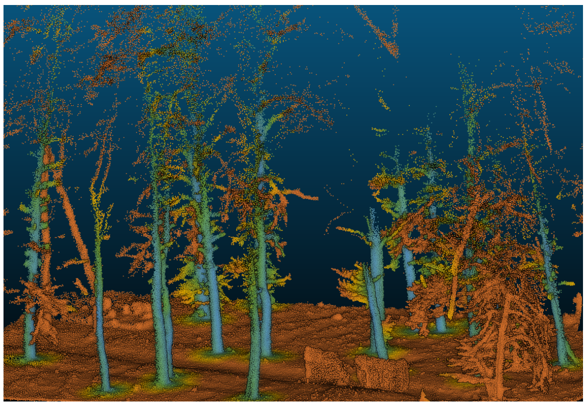
- calibration,
- LiDAR odometry,
- single session registration,
- multiple sessions registration and final refinement.

These functionalities are essential for surveying in extremely difficult terrain. Moreover, proposed lightweight and ergonomic design reduce fatigue, thus we can survey much longer. Our solution is open source and affordable.

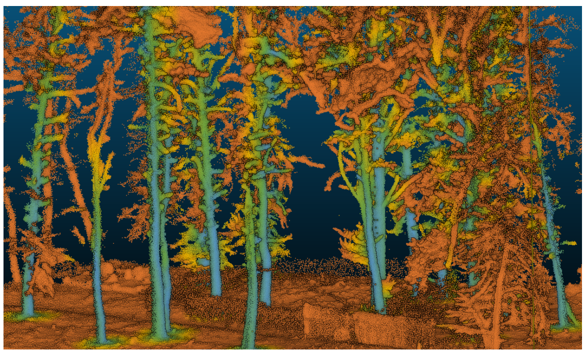
5. FUTURE WORK

Our open source project opens plenty of future work opportunities. E.g. we can assess the intrinsic quality characteristics of each point cloud, examining density metrics (overall and vertical distribution profiles), noise levels, and completeness of tree stem representation. We can investigate correlations between point cloud quality parameters and acquisition factors, particularly focusing on the relationship between point density

(a) Affordable air-ground mobile mapping system composed of shoulder-mounted double LiDAR system and light weight FPV drone with LiDAR payload.



(b) UAV LiDAR point cloud.



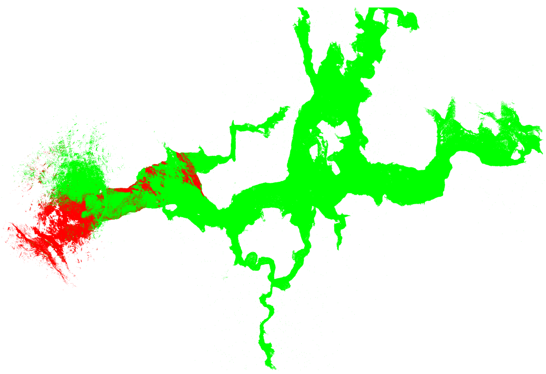
(c) Shoulder-mounted LiDAR point cloud

Figure 5. Comparison of point clouds acquired with UAV and shoulder-mounted LiDAR systems, including detected tree stems shown in blue

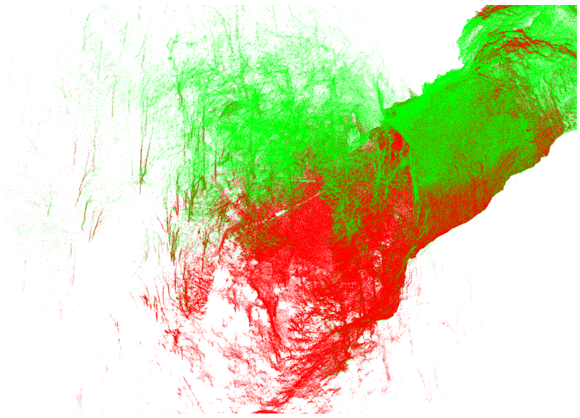
(a) Inside cave view.

(b) Outside cave view.

Figure 6. Data collection in extreme environment (Meziad Cave, Romania).



(a) Top view (green: map from shoulder wearable mobile mapping system, red: map from UAV).



(b) Perspective view (green: map from shoulder wearable mobile mapping system, red: map from UAV).

Figure 7. Data collected in extreme environment (Meziad Cave, Romania) with drone and shoulder wearable mobile mapping system.

and height above ground, as well as the influence of distance from the sensor trajectory.

We can evaluate the practical utility of each dataset for forest inventory applications by extracting key dendrometric parameters using 3DFin software (Laino et al., 2024), which is specifically designed for processing ground-based LiDAR point clouds in forest environments. For each detected tree within the comparative dataset, we can derive tree position coordinates, Diameter at Breast Height (DBH), and total tree height. These attributes can be compared against direct field measurements obtained through conventional forest mensuration techniques, providing ground truth validation for assessing absolute accuracy.

Statistical analysis can be also performed on quantifying differences in detection rates, measurement bias, precision (RMSE), and correlation between the derived parameters from each dataset and the field reference data. This framework will enable a systematic evaluation of the strengths and limitations of under-canopy UAV LiDAR compared to established ground-based acquisition methods for forest inventory applications, with implications for orientation and navigation quality in challenging GNSS-denied environments.

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