Novel (re-configurable, wearable, light weight, ergonomic) low cost 3D mobile mapping system not only for extreme mapping applications

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Abstract

This paper presents a novel low cost 3D mapping system designed for fulfilling the gap between existing solutions and constantly growing end-users' expectations. Firstly, the cost was reduced to minimum by providing an open-source, open-hardware projects. Secondly, the ergonomic, light weight, reconfigurable approach enables a wearable approach to maximize the mobility of the end user. It allows among other things the freedom to walk, crawl and climb. Those are necessities in extreme mobile mapping applications such as cave mapping, construction site survey, search and rescue missions and other unexplored yet applications such as mobile mapping with K9s (trained dogs equipped with 3D mobile mapping systems). The significance of this research is to provide cost effective mobile mapping solution for as large audience as it is possible. Thus, our software is constantly improved for covering more applications e.g. air + ground + underground mapping.

1. Introduction

This paper shows recent results related with a design and a development of a low cost 3D mapping system. The main goal of research is to fulfill the gap between the existing solutions and constantly growing end-users' expectations (Elhashash et al., 2022). We focus on the re-configurable, wearable, light weight and ergonomic design such as handheld Zebedee (Bosse et al., 2012) that is successful lightweight mobile mapping system accepted by many end-users. Further developments yield into the backpack systems (Hyyppä et al., 2020). Looking at potential applications such as culture heritage (Grussenmeyer et al., 2011), environmental management (Son et al., 2020), geology (Buckley et al., 2008), urban search and rescue (Isaacs et al., 2022), urban mapping (Münzinger et al., 2022), ground truth for Automated Guided Vehicles (Sier et al., 2023), navigation, precision forestry (Åkerblom and Kaitaniemi, 2021), agricultural robotics (Rivera et al., 2023), underground mining (Wang et al., 2023), education, entertainment, forensics (Cunha et al., 2022) (Park et al., 2018), critical infrastructure inspection, space exploration (Katzer et al., 2021), protection systems (Saponaro et al., 2020), digital twin content generation etc... we can distinguish routine cases and extreme mobile mapping applications. The difference is determined by the probability to injure during data collection. For this reason mobile mapping system should guarantee safety and minimize effort during operation. Thus, we designed hands-free wearable on the shoulder re-configurable mobile mapping system shown in figure 1. It enables mounting on the shoulder (figure 2), on the search and rescue canine (figure 3). Its flexible design enables building hand held device (figure 4) and mounting onto a long stick (figure 5) to reach higher filed of view. The result of the construction site survey is shown in figures 6, 7 where installations such as pipes etc. are easy to identify. This novel design provides ability to crawl (figure 8) and climb (figure 9).

Caving employs a wide range of movement techniques such as climbing, scrambling, chimneying and traversing which require a three-points contact from various body parts. In particular scrambling use more body parts than climbing would such as: hands, feet and leg, shoulders, arms, head, back, stomach, hips. Therefore, an adaptive and re-configurable mapping tool which supports the cavers movement in most of situations is considered necessary. The body part being occupied by the mapping tool is the shoulder and the trunk through the assistance of a vest for mounting the equipment. This body parts are challenging due to its different adaptations and shapes between individuals. However, the shoulder and the upper chest, core and the hips are protected by the flat bones as point of attachments of various muscles. The latter allows for cavers to adapt at any given time during various caving techniques applications thanks to the wider range of movements performed by the shoulder and the scapulae. The efficiency of the performance will be depended on the skill of the cavers to adapt to situations during explorations.

It can be seen in recent literature (Hamesse et al., 2024) an interest in re-configurable wearable mobile mapping system applications. The challenge is to satisfy end-users' expectation of full aromatic 3D map making process in all scenarios. At this stage our software (`https://github.com/MapsHD/HDMapping`) is partially ready for full automation and robust enough for almost all addressed scenarios. The limitation is lack of observations (e.g. flat surface or long tunnel without vertical obstacles) or extremely tiny spaces. It is composed of following components:

- multiple LiDAR system calibration,
- LiDAR odometry,
- multi view registration,
- multi session registration,
- georeferencing.

The software does not require any installation which makes it unique compared to other available solutions. It is designed for both scenarios: out-of-the-box usage and development basis for other mobile mapping applications such as construction site survey (see figure 5).

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Figure 1. Re-configurable mobile mapping system - all main components. 1: GNSS antena, 2: data collection unit, 3: battery, 4 and 5: LiDAR LIVOX MID 360.

2. Multiple LiDAR system calibration

Multiple 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 satisfactory overlap between LiDARs with wide (half sphere) field of view this method is sufficient.

3. LiDAR odometry

LiDAR odometry is our main contribution. It is based on Normal Distributions Transform (Saarinen et al., 2013) integrated with pose Graph SLAM (Sünderhauf and Protzel, 2012). For the initial rotation calculation it uses Madgwick filter (Madgwick, 2010) since Livox MID-360 LiDAR provides also IMU data. Thus, input data for LiDAR odometry is 200Hz trajectory with all nodes at origin (x=0, y=0, z=0) but with estimated rotation. Pitch and roll angles are rather accurate but the drift of the yaw angle is evident. It is typical output of the filtered IMU data. The goal of the LiDAR odometry is to refine 200Hz trajectory by providing x, y, z, yaw, pitch, roll corrections. The algorithm is using sliding window approach. Thus, previous updates form reference data. Sliding window contains 20 nodes, thus assuming 2m/s maximum speed and 200Hz we should expect maximum displacement less than 0.2m. For this purpose NDT uses regular grid decomposition composed of buckets 0.3m × 0.3m × 0.3m. Each bucket contains mean $\boldsymbol{\mu}$ (eq. 1) and covariance matrix $\boldsymbol{\Sigma}$ calculated with point cloud coordinates $\boldsymbol{P}^g_k$ (eq. 2). $\boldsymbol{P}^l$ is 3D point expressed in local coordinate system. $\boldsymbol{P}^g$ is 3D point expressed in global coordinate system.

Figure 2. Configuration 1: Mobile mapping system mounted on the shoulder.

$$\boldsymbol{\mu} = \frac{1}{m}\sum_{k=1}^{m} \boldsymbol{P}^g_k \tag{1}$$

$$\boldsymbol{\Sigma} = \frac{1}{m-1}\sum_{k=1}^{m} (\boldsymbol{P}^g_k - \boldsymbol{\mu})(\boldsymbol{P}^g_k - \boldsymbol{\mu})^\intercal \tag{2}$$

The NDT optimization problem for two rigid point clouds is defined as the maximization of the likelihood function given in equation (3).

$$\begin{gathered}
[\boldsymbol{R},\boldsymbol{t}]^*_{W\leftarrow Lidar} = \max_{[\boldsymbol{R},\boldsymbol{t}]_{W\leftarrow Lidar}} \prod_{m=1}^{N} p(\boldsymbol{\Psi}([\boldsymbol{R},\boldsymbol{t}]_{W\leftarrow Lidar}, \boldsymbol{P}^l_m)) \\
p(\boldsymbol{\Psi}([\boldsymbol{R},\boldsymbol{t}]_{W\leftarrow Lidar}, \boldsymbol{P}^l_m)) = \frac{1}{(2\Pi)^{\frac{1}{2}}\sqrt{|\boldsymbol{\Sigma}|}} \exp\left(-\frac{(\boldsymbol{P}^g_m-\boldsymbol{\mu})^\intercal \boldsymbol{\Sigma}^{-1}(\boldsymbol{P}^g_m-\boldsymbol{\mu})}{2}\right) \\
\boldsymbol{P}^g_m = [\boldsymbol{R},\boldsymbol{t}]^{3\times4}_{W\leftarrow Lidar} \begin{bmatrix} \boldsymbol{P}^l_m \\ 1 \end{bmatrix}
\end{gathered} \tag{3}$$

Furthermore, the optimization problem is equivalent to the minimization of the negative log-likelihood given in equation (4).

$$[\boldsymbol{R},\boldsymbol{t}]^*_{W\leftarrow Lidar} = \min_{[\boldsymbol{R},\boldsymbol{t}]_{W\leftarrow Lidar}} -\sum_{k=1}^{N} \log\left(p(\boldsymbol{\Psi}([\boldsymbol{R},\boldsymbol{t}]_{W\leftarrow Lidar}, \boldsymbol{P}^l_m))\right) \tag{4}$$

Finally, LiDAR odometry of 20 nodes is composed of NDT and 19 relative pose constraints. Thus, it is capable preserving motion model derived from Madgwick filter. More information concerning construction of such data fusion implementation can be found in (Bedkowski, 2022).

Figure 3. Configuration 2: Mobile mapping system mounted on the search and rescue canine.

4. Multi view registration

Each single trajectory obtained by LiDAR odometry can be refined using pose Graph SLAM and later on with multi view Norma Distributions Transform algorithm (Bedkowski, 2023). For this purpose data is organized in consecutive point clouds formed by local consecutive trajectories with length not exceeding 5m. It is enough to find loop closures to form pose Graph SLAM system. Finally, the best accuracy and precision can be reached with Norma Distributions Transform.

5. Multi session registration

Our system is designed for large scale surveys. Typical single survey can provide trajectory with length more than 5km. Thus, data collection of multiple surveys can be registered with using pose Graph SLAM and later on with multi view Norma Distributions Transform algorithm. We use the same approach as for multi view registration.

6. Georeferencing

We provide multiple ways for georeferencing such as:

- using ground truth reference point cloud,
- using ground control points,
- using control points,
- using GNSS trajectory.

These common georeferencing techniques enables obtaining satisfactory result against ground truth data.

Figure 4. Configuration 4: Hand held mobile mapping system.

7. Experiments

We provide results of four experiments. First experiment is typical indoor layout generation. As other mobile mapping systems our solution is sufficient for this job (see figure 10). Second experiment is interesting looking from climbing ability point of view (see figure 11). we consider this as extreme mapping scenario due to high probability of injury. Third experiment shows robust solution mounted on K9. Our system is capable reconstruct entire simulated search and rescue mission (see figures 12, 13). Finally, figures 14, 15 demonstrate the robustness to create point cloud from cave survey.

8. Accuracy and precision assessment

We conducted accuracy and precision assessment in our previous works (Bedkowski, 2023)(Bedkowski, 2024b)(Bedkowski, 2024a). It can be read that centimeter accuracy and precision is feasible and it strongly depends on the application and the scope of the survey. Work on extreme mobile mapping applications is demanding task since mostly there is no possible to install ground truth data source. Each experiment is rather difficult to repeat assuming similar conditions. For this reason we claim the satisfactory qualitative results. Resulting point clouds are sufficient since cumulative LiDAR odometry error is minimized by the loop closure and the final refinement procedures.

9. Conclusion

This paper presents a novel low cost 3D mapping system. It is designed for fulfilling the gap between existing solutions and constantly growing end-users' expectations. We provided an

Figure 5. Configuration 5: Construction site survey with device on the long stick.

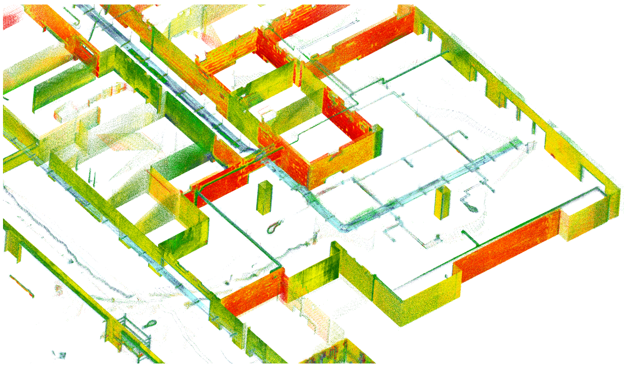

Figure 6. Result of construction site survey - it is showing installations such as pipes etc. (perspective view)

open-source and open-hardware projects. The ergonomic, light weight, reconfigurable approach enables a wearable equipment. It allows among other things the freedom to walk, crawl and climb. Those are necessities in extreme mobile mapping applications such as cave mapping, construction site survey, search and rescue missions and other unexplored yet applications such as mobile mapping with K9s (trained dogs equipped with 3D mobile mapping systems). We provided cost effective mobile mapping solution. Our software is constantly improved for covering more applications e.g. air + ground + underground mapping.

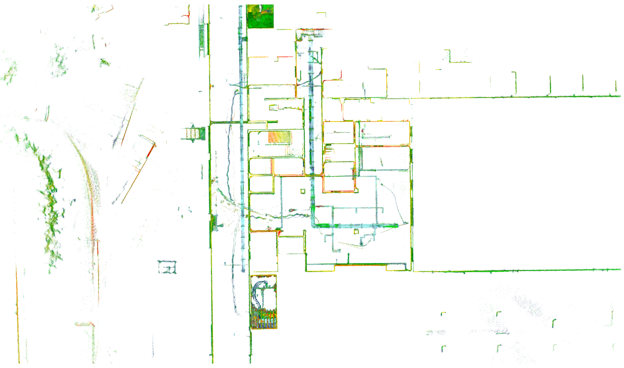

Figure 7. Result of construction site survey - it is showing installations such as pipes etc. (top view)

Figure 8. Crawling scenario.

10. Future work

The system does not have camera yet, thus future work will be related with adding affordable solution for 360 images. Two main challenges are not yet solved: long tunnels and extremely narrow spaces. The problem with luck of LiDAR intrinsic calibration yields banana shape of long trajectories, thus intrinsic parameters' calibration will be investigated. Finally, qualitative and quantitative measures have to be done for estimating the accuracy and precision of our solution. It would be beneficial providing ground truth order of magnitude more accurate and precise than our mobile mapping system.

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Figure 9. Climbing scenario.

Figure 10. Typical scenario - layout generation.

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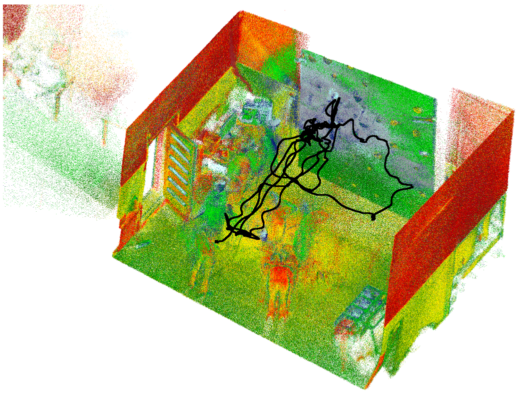

Figure 11. Extreme mapping scenario - climbing (see photo 9). Trajectory is marked by black color, point cloud is reconstructed using this trajectory.

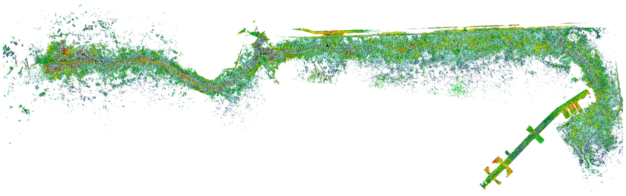

Figure 12. Extreme mapping scenario - search and rescue simulation with canine: Point cloud.

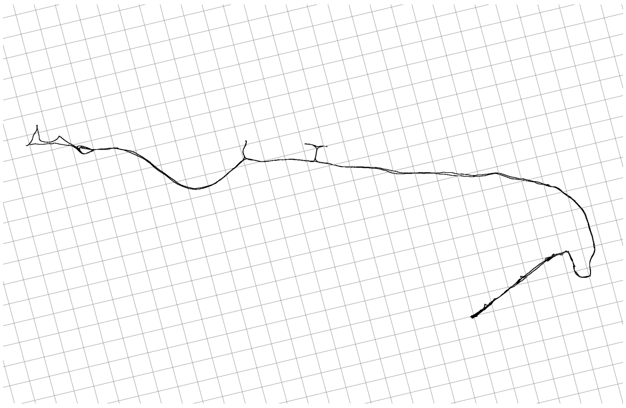

Figure 13. Extreme mapping scenario - search and rescue simulation: trajectory of the canine from photo 3. Grid 10m x 10m.

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Figure 14. Extreme mapping scenario - cave survey.

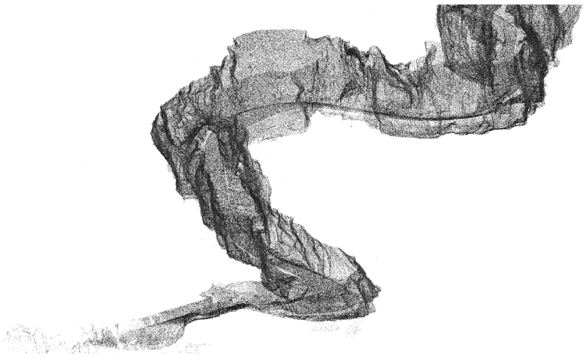

Figure 15. Extreme mapping scenario - cave survey.

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