Concept for System Performance Verification of INS/GNSS Solutions within GNSS denied Environments

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Inertial Sensors and Applications 2024
Braunschweig, Germany

Abstract

The validation or qualification of navigation and localization systems with respect to position and velocity accuracy requires a precise reference called “ground truth”. Obtaining such a ground truth for a given local environment can be very challenging especially when GNSS is fully or partially denied due to spoofing, jamming, multi-path or other disturbances. This paper proposes a method for ground truth generation by combining LiDAR, inertial measurement technology and GNSS.

The method is based on a two-step process. In the first step, the test area is precisely and automatically surveyed with an accurate LiDAR / INS / GNSS measurement setup (creation of a reference map). The second step is the verification, where the performance of the Device under Test (DUT) will be verified under difficult GNSS environment, the position and movement of the DUT can then be referenced independently of GNSS using the LiDAR / INS setup (now without GNSS) as reference, also called “Ground Truth”. Challenges raised in the paper are for instance the demand on excellent time synchronization, outlier handling and geo referencing of the INS / LiDAR data fusion.

Experimental results of the verification method are presented, using a highly accurate DUT of the type iPRENA-M, an inertial navigation system, which is mostly used in defence applications where GNSS availability is restricted. The test trajectory extends to 40 km and includes significant sections where reliable GNSS is not available. The demonstrated performance is in the area of a few decimeters.

1. Introduction

Deploying localization systems in so-called GNSS-denied environments with high accuracy and availability is becoming increasingly important in the light of today's geopolitical situation. This increases the demands on inertial measurement systems and also brings the proof of achievable accuracy more into focus. The state-of-the-art of accuracy verification is based on discrete geodetic landmarks whose positions are well-known. The verification of the device under test’s (DUT) positioning performance can then be compared to these landmark-positions. The major disadvantages of this method are:

1. This comparison is only possible at these discrete landmarks and not between them, which means that the position accuracy of the DUT between the landmarks is not sufficiently observable. Missing this information is a significant problem for all applications where continuous motion accuracy is safety-relevant.

2. The method requires typically a standstill of the vehicle at the landmark in order to achieve a position accuracy in decimeter range, which itself may cause e.g. an unwanted zero velocity aiding or may restrict the desired test procedure.

3. The determination of landmarks in GNSS denied regions like tunnels within a reasonable accuracy is only achievable with complex, time consuming geodetic methods. Consequently, the verification process is only possible on special prepared tracks, which will not represent all corner cases in a broad authentic verification procedure.

Therefore, in this paper we present our approach to overcome these disadvantages by proposing an INS/LiDAR based solution. This allows to determine the true position (so-called Ground Truth) and hence the position accuracy of the DUT over the whole trajectory at every data sample (up to 400 Hz), even on tracks where GNSS is partially or fully not available.

In the following chapters we give a justification of the method and we present the architecture of the verification procedure. Additionally, we demonstrate the performance of the GNSS-independent Ground Truth by comparing it with an INS/RTK-GNSS solution. Finally, we discuss the results and give an outlook to the further development activities.

2. Method Justification and Setup

The upcoming sections will describe the principle of our method. First, we will introduce the hardware setup and relevant components of the system. Then we present the architecture and the verification process, followed by experimental results by evaluation data obtained from specific trials.

2.1. Why LiDAR?

Using GNSS data to aid inertial measurement systems has been being state of the art for many decades so far. The GNSS receiver provides raw data or position and velocity and standard deviation together with a highly accurate time-stamp within a dedicated coordinate system (e.g. WGS84) and these data are used to aid the inertial measurement system. This process of sensor data fusion combines data from different, complementary sensor sources, i.e. on the one side data which are always available and self-sufficient, but which are highly accurate only over a short duration of unaided measurement (here the inertial data) and on the other side GNSS data with long-time stability (no drift), but with a high potential to be corrupted by multi-path, weather conditions, sun activities, spoofing, jamming etc. For the sake of brevity and a clear focus we are ignoring all other aiding sources like odometry, RF based localization etc. within this paper.

As explained above, we want to verify the performance, i.e. the **position accuracy of a DUT under real conditions in the field where GNSS is corrupted as a significant feature of such a test** (e.g. due to multi-path, caused by the environment like in urban canyons, or due to induced spoofing attacks etc.) or where GNSS is not available (e.g. in tunnels or during induced heavy jamming attacks).

So, for the verification step of the DUT (in the following called "Step 2"), we need a precise and reliable Ground Truth reference, which is able to cover all these conditions, which works without any GNSS aiding, which can be easily mounted on the DUT's carrier vehicle and which does not have any impact on the DUT itself (reaction-free operation).

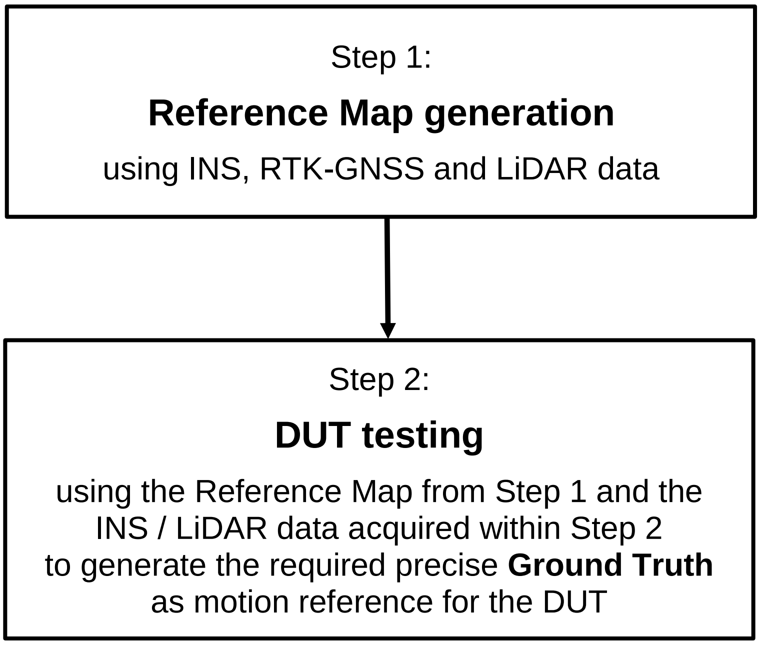

Figure 1: Ground Truth generation process

Here we use the latest imaging LiDAR technology as a well-known method for localization and mapping. SLAM (simultaneous localization and mapping) is a usual method to build up a point-cloud based map and to perform localization afterwards inside this point-cloud map. But this method has its limitations if we operate within the real world: There are surrounding areas that do not provide any textures (e.g. a small highway bridge), but which are required for relocalization in a point-cloud map. There are also scenarios where the surrounding area does not have any unique features to correlate (e.g. alley streets). These are scenarios where scan matching could converge into a local minimum instead of the global minimum, which is hard to detect. Furthermore, the environment can change after the map has been generated (e.g. vehicles had left a parking garage as region of interest) and then significant localization artifacts would occur during the verification trial with the DUT, if we want to reach decimeter accuracy. Such artifacts can lead to position errors in the range of even 10 meters and more. To overcome these limitations, we use a setup as described in the following.

2.2. Hardware setup

For a fast and reliable acquisition of high-density point-cloud maps and for execution of real-time LiDAR processing, iMAR Navigation GmbH recently has developed iLIANE (inertial Lidar Aided Navigation Equipment), which enables us to generate high density and geo-referenced point-cloud maps in various scenarios of interest. The system's part on the roof of our test vehicle consists of an OUSTER OS1-128 rev.7 and an iNAT-M300/TLD MEMS-based INS/GNSS solution, which is responsible for the time synchronization of the sensor suite, the removing of ego-motion during a LiDAR scan and the initialization of the LiDAR-Odometry optimization (see Figure 2 and Figure 3).

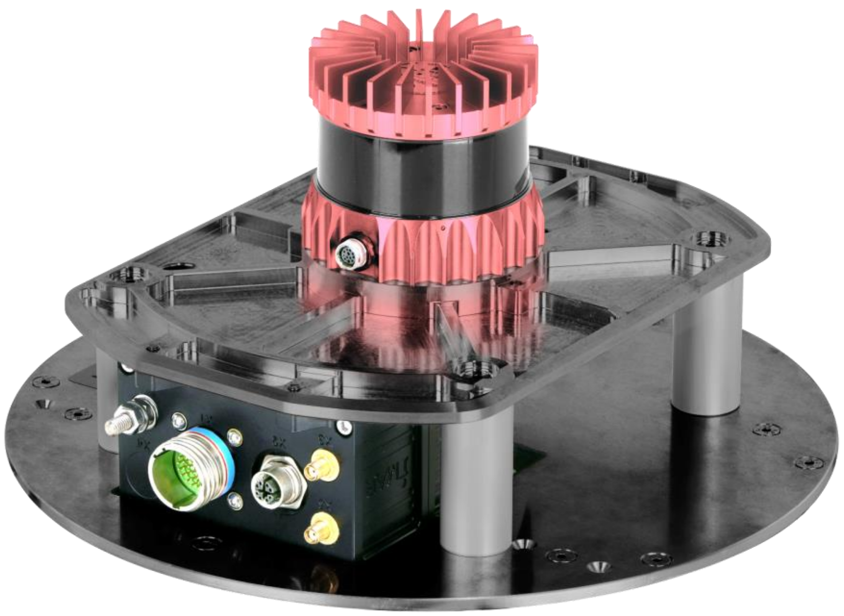

Figure 2: iLIANE: LiDAR based navigation equipment. The iNAT-M300/TLD in the black enclosure is stiff mounted at the bottom plate of the LiDAR and also provides timing information within Step 1.

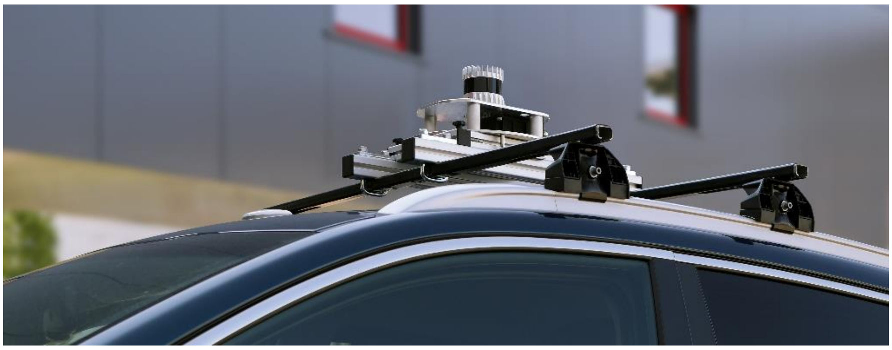

Figure 3: iLIANE: LiDAR based navigation equipment mounted on the roof of the test vehicle (car).

For data recording and map generation, we mounted the iLIANE host computer on the right mounting place in the trunk of the test vehicle, see Figure 4. The DUT for these tests is a high-performance INS/GNSS with ring laser gyro technology (ARW < 0.002 deg/sqrt(hr)) of type iPRENA-M, manufactured by iMAR Navigation and used also in challenging defence applications, which is mounted on the left side of the trunk.

2.3. Mapping Process

The mapping process (Step 1) can be seen as a preparation step for the subsequent verification process in the following section. During this process, we use another high performance INS/GNSS of type iNAT-RQT, which is a ring laser gyro based inertial navigation system for land, rail, marine and airborne applications with integrated all-frequencies / all-constellation GNSS engine and RTK capability, to build up and geo-reference the LiDAR based point-cloud map (see Figure 6). RTK GNSS aiding is enabled to achieve typically centimeter level accuracy, whenever accessible under sufficient conditions. The time synchronization between the LiDAR sensor and the INS/GNSS system is of highest importance – as an example, e.g. an unknown time delay of 10 ms between both sensors at a speed of 30 m/s would just lead to a position error in the map of 0.3 m! Therefore, the system is designed to meet a time synchronization accuracy of << 1 ms.

In areas where RTK is not available for a longer time or where multipath effects are significant, robust positioning is nevertheless achievable due to the LiDAR Odometry of the SLAM component, or even using post-processing with iPosCAL-SURV (not used for the data presented in this paper). In general and if needed, step 1 of the proposed method can also be performed completely without GNSS by using sporadically surveyed landmarks.

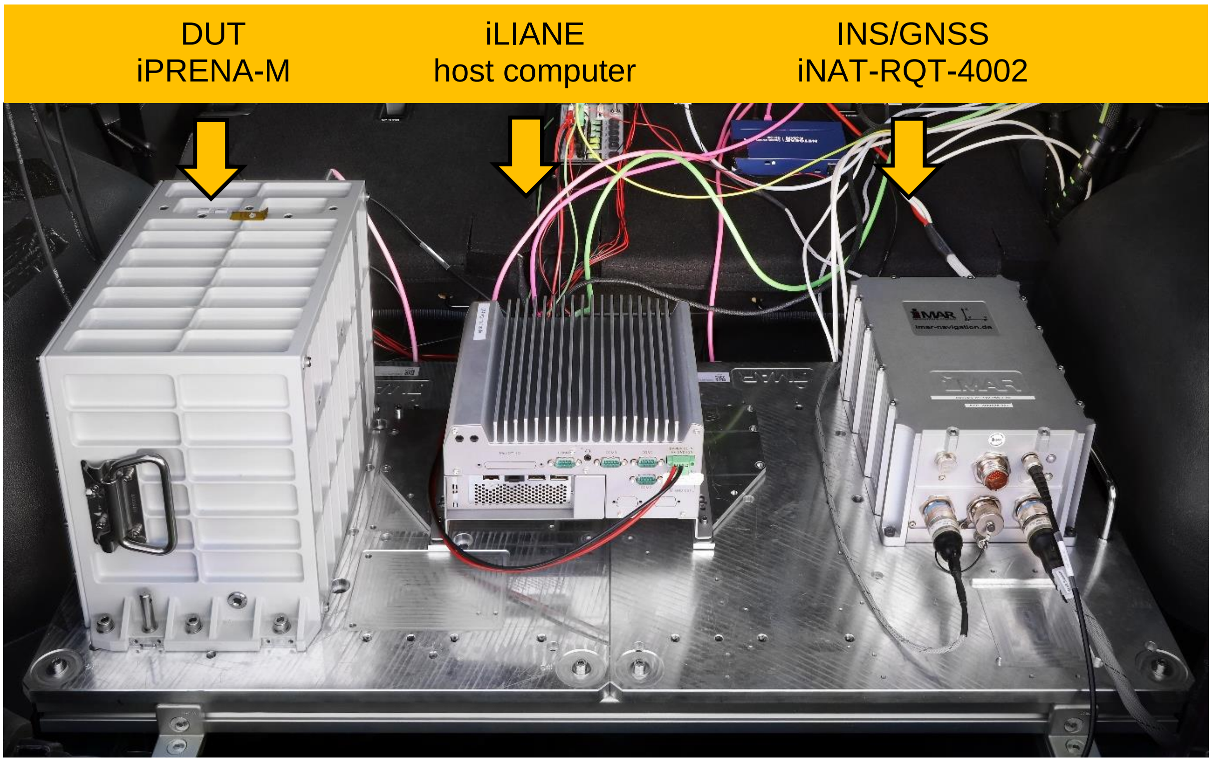

Figure 4: Device under Test iPRENA-M (left) and iLIANE host computer (middle) and reference INS iNAT-RQT-4002 (right) in the trunk of the test vehicle

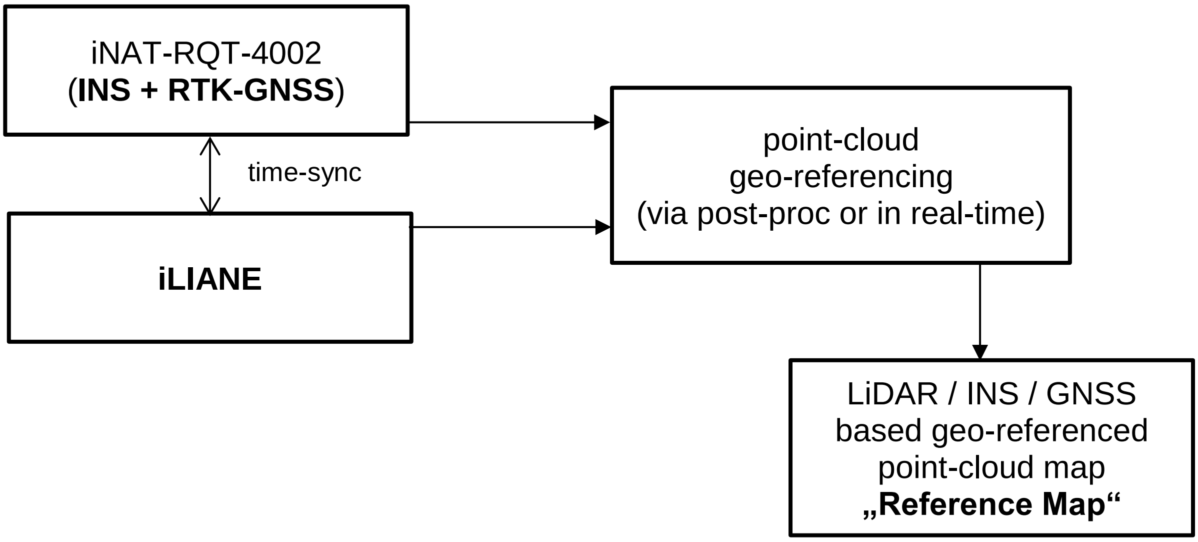

*Figure 5: **Step 1 of the method:** Generation of the LiDAR / INS / GNSS based Reference Map*

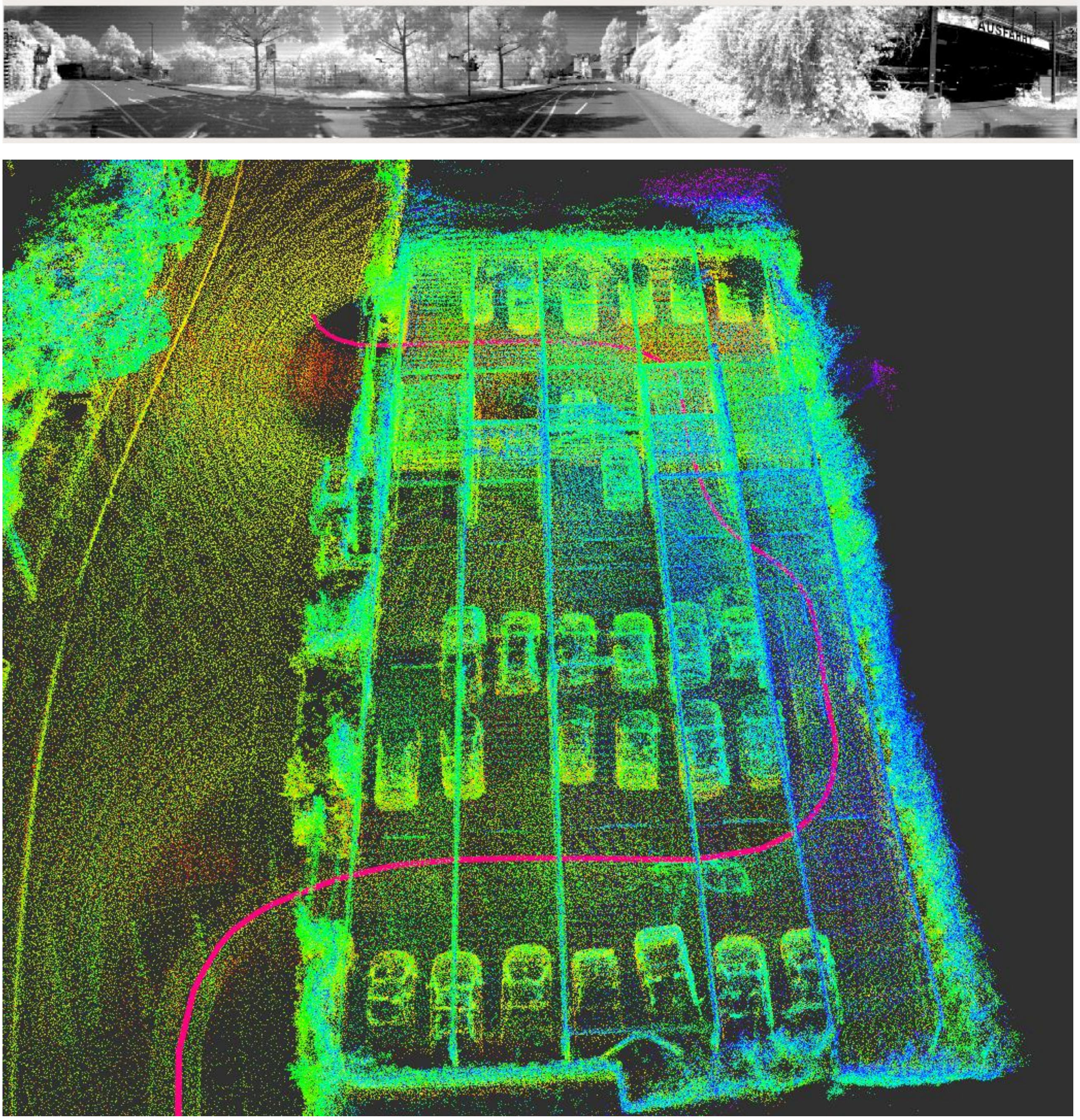

Figure 6: Process of point-cloud map generation while driving through a parking garage. The upper image shows the 2D ambient image projection of a LiDAR scan (360° view), which has currently no influence on the mapping process itself, but generates useful information for documentation purposes. The lower image represents a part of the generated point-cloud map from a bird view perspective. The red line represents the driven trajectory during the map generation process.

2.4. Verification process

Then, in Step 2 (see Figure 7), when testing the DUT under real-world GNSS denied conditions and where consequently no GNSS is available to build a trajectory reference, the same INS of type iNAT-RQT as used during the previous mapping process in Step 1, is used as Ground Truth, but now aided by the acquired LiDAR data, instead of RTK measurements. In theory it seems obvious to use just the position of the LiDAR system as Ground

Truth directly, but in reality artifacts in the map or unsuccessful scan matches, reasoned by a unstructured environment (e.g. a straight alley passage) could degrade the map matching solution significantly – furthermore, pure LiDAR data are available only with a relatively low data rate while the INS/LiDAR solution provides output data with up to 400 Hz, giving the ability to verify the DUT also during high dynamics.

A key requirement also during this Step 2 is a good time synchronization between the components, as mentioned before. Typically, a hardware trigger signal (pulse per time, similar to the PPS / pulse per second known from GNSS) is used, but here generated from the high precision internal clock of the iNAT-RQT (0.2 ppm OTR), because no GNSS is available during the test of the DUT.

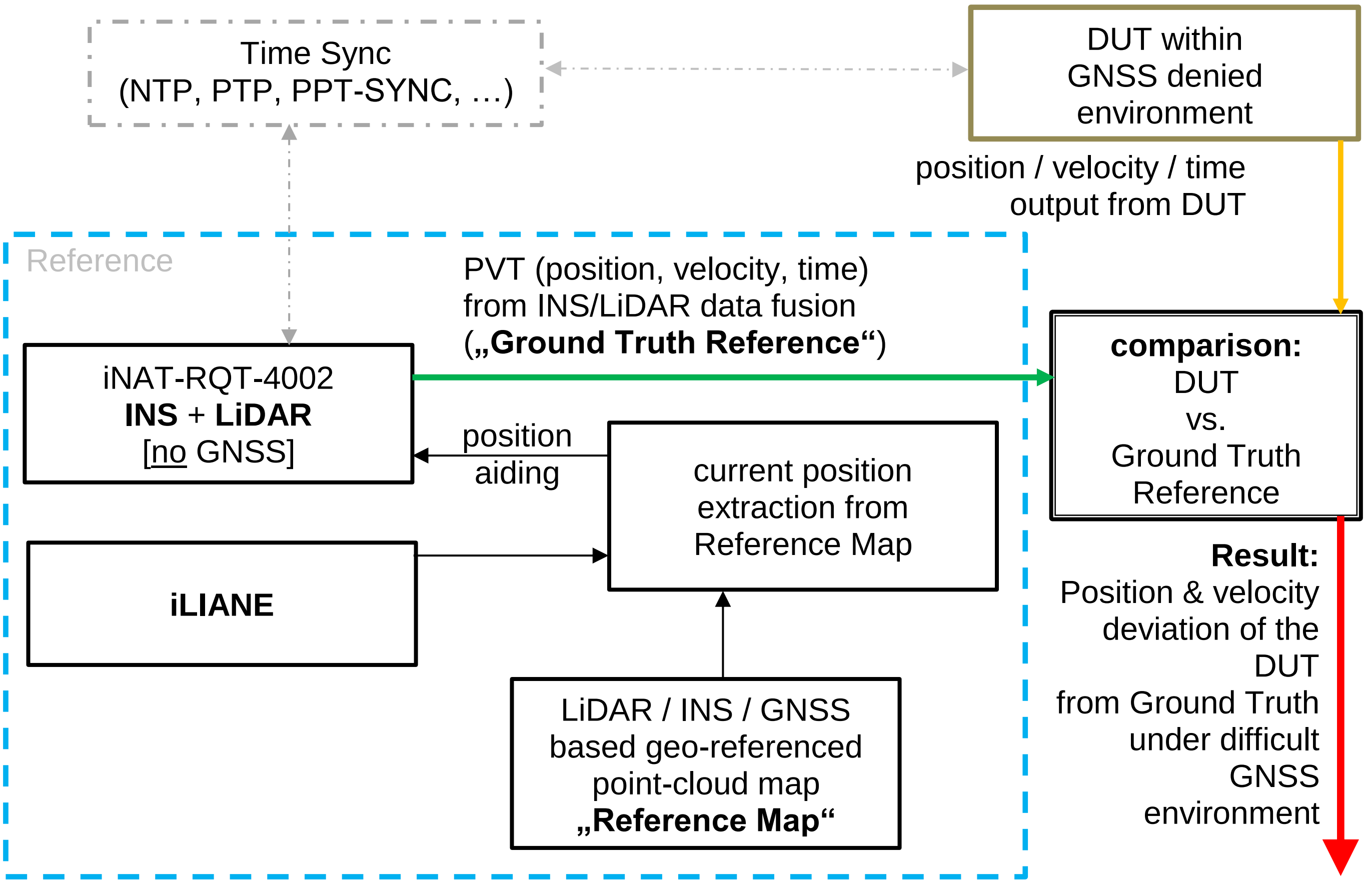

*Figure 7: **Step 2 of the Method: Verification of the DUT's position accuracy** within GNSS denied environment by providing a Ground Truth, based on the previously generated LiDAR/INS/GNSS Reference Map*

Therefore, a sophisticated real-time process of LiDAR map data processing outlier detection and isolation is implemented, based on the inertial data of the reference INS and the previous INS/LiDAR data processing, to use only those aiding data from the LiDAR for the INS which pass a certain accuracy criterion. This process is partially similar to the process, which we are using to eliminate e.g. GNSS artifacts in corrupted GNSS data or to eliminate corrupted wheel sensor data inside of our INS/GNSS/ODO system solutions.

The described process to generate the Ground Truth with the INS/LiDAR/MAP reference system can be performed in real-time or in post-processing. The generated Ground Truth is then used to determine the position and velocity deviation of the DUT, if desired for every data sample up to 400 Hz.

3. Experimental Results

To evaluate our method, we chose a heterogenous route beginning with sections through residential areas, rural areas, a tunnel and parking garages and the return path over a highway, also covering a wide range of speed up to about 140 km/h.

As already mentioned, the LiDAR based map generation depends on many external impacts. It can be announced as a measurement process with uncertainties, which cannot be fully detected during map generation. In Figure 10 we show the results if we would only use the LiDAR obtained position (without INS data fusion).

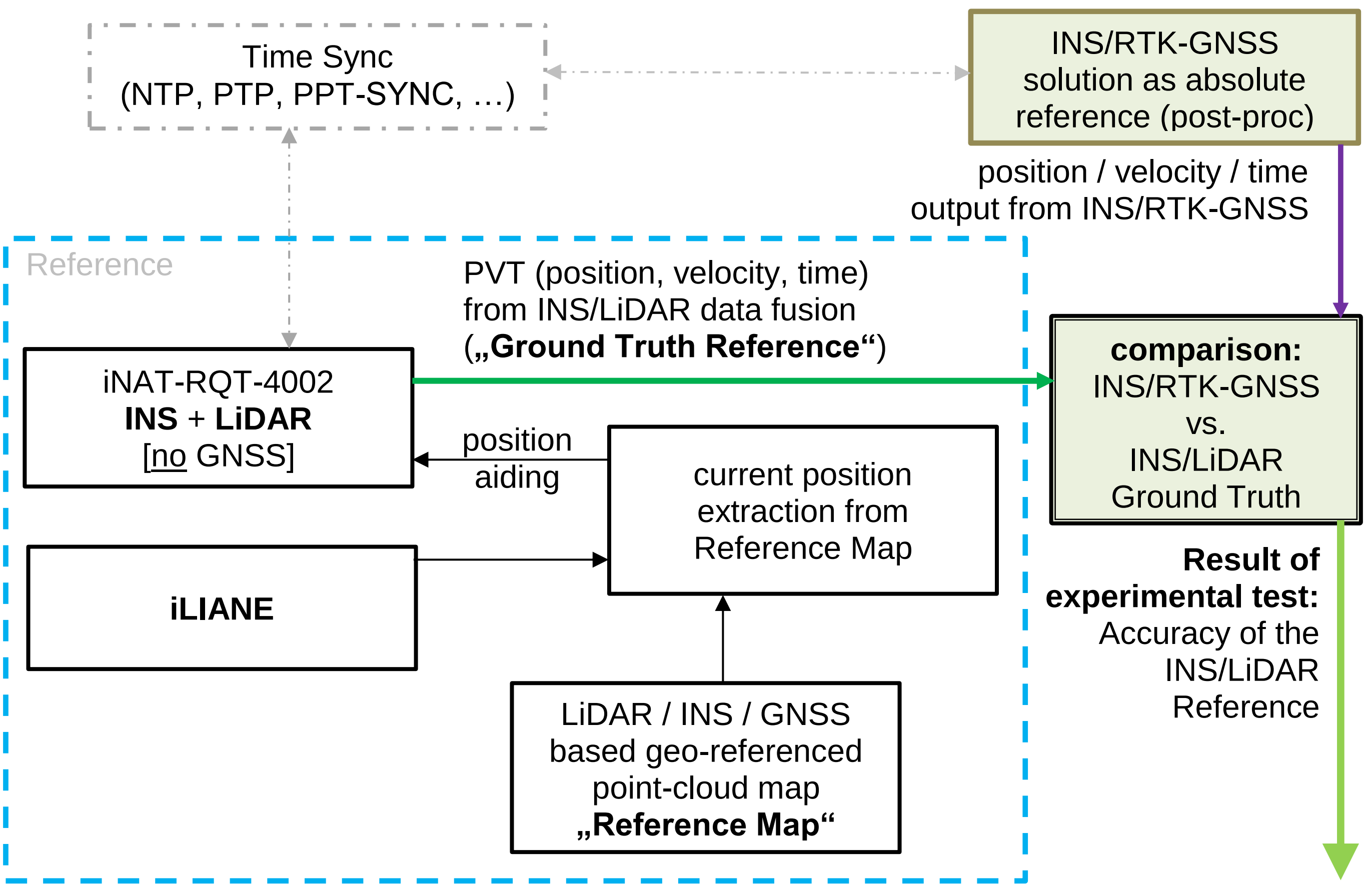

*Figure 8: **Setup for the experimental result verification:** Comparing the "LiDAR/INS Ground Truth" against the "INS/RTK-GNSS Ground Truth" solution with data acquired during the same track test.*

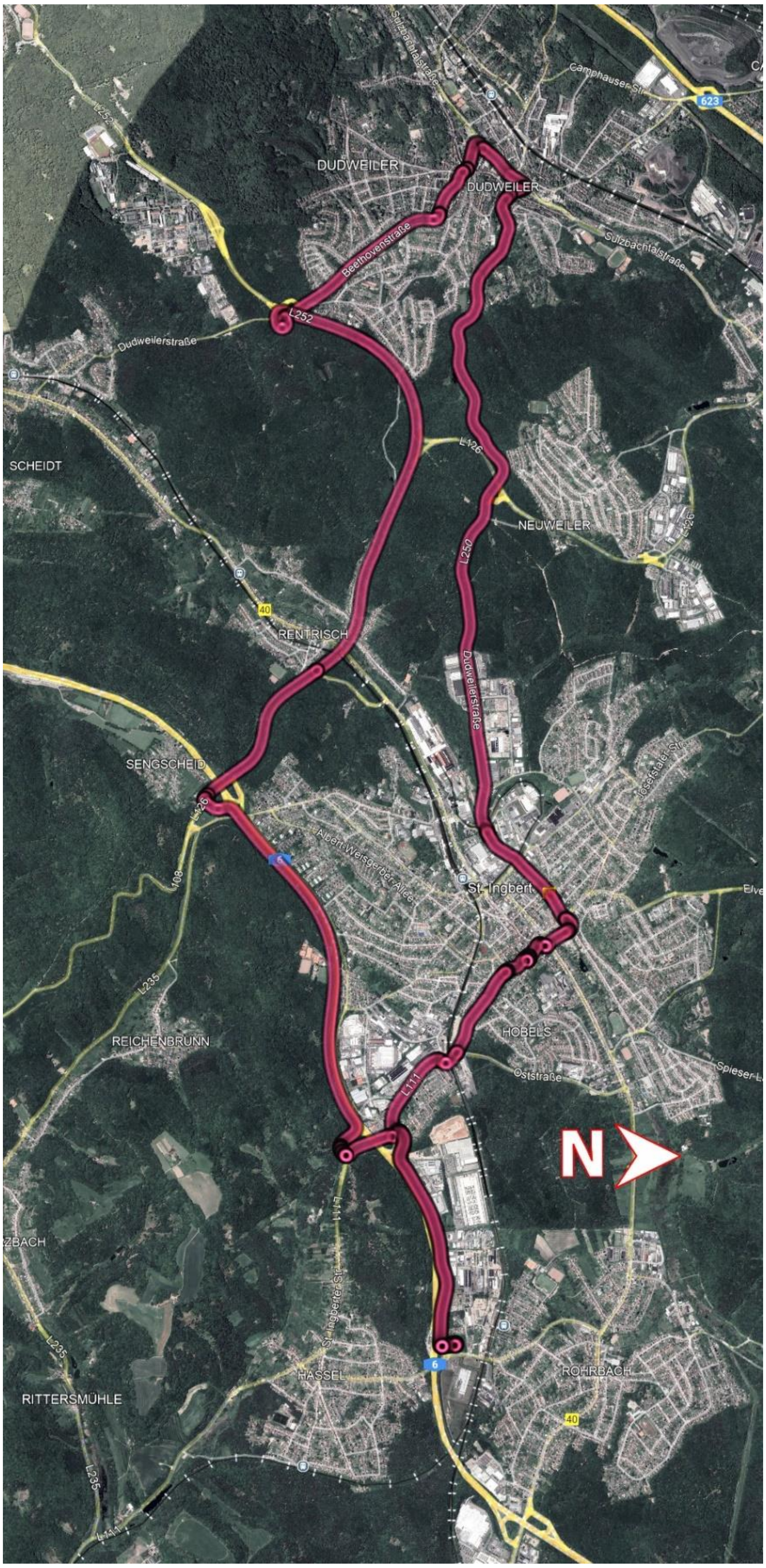

Figure 9: Satellite view on the heterogeneous route we used to evaluate our method. The route started at the campus of iMAR Navigation GmbH (St. Ingbert / Germany) in western direction through a residential area. After passing a rural area in the west, the return path went over a highway in in the south in east direction. All rights reserved by Google Earth.

We quantified these effects by comparing the raw LiDAR position solution (without GNSS) against the results of an RTK based reference trajectory, obtained in post-processing by using the iNAT-RQT-4002 INS/GNSS. Here it is important to emphasize that the RTK-aided reference trajectory in use is completely independent and is only used to verify the achievable accuracy of the GNSS-denied LiDAR aided Ground Truth.

The results confirmed the expectation: The assumed uncertainty of the zero-mean LiDAR system aiding information shows a standard deviation $\sigma_{LiDAR,hor} \approx 2.0\ m, \sigma_{LiDAR,vert} \approx 0.5m$, represented by the dashed lines in Figure 10. The peak error at about 1'800 s can be ascribed to mismatches of LiDAR scans to the point-cloud map.

Figure 10: Difference between the LiDAR system positions and a RTK-aided iNAT-RQT-4002 trajectory during the verification process. The blue shaded period marks valid LiDAR system positions. Color coding for position error graphs: blue – error in north direction, orange – error in east direction, green – down error. The dashed lines represent the standard deviation of the LiDAR position aiding in particular directions.

So, these uncertainties are handled in the sensor data fusion process to generate a reliable GNSS-denied Ground Truth.

Figure 11 shows the DUT performance in absence of any aiding information. The position error of the DUT (pure free inertial operated high performance INS of type iPRENA-M on the test vehicle) is relative to the RTK reference trajectory on the test vehicle.

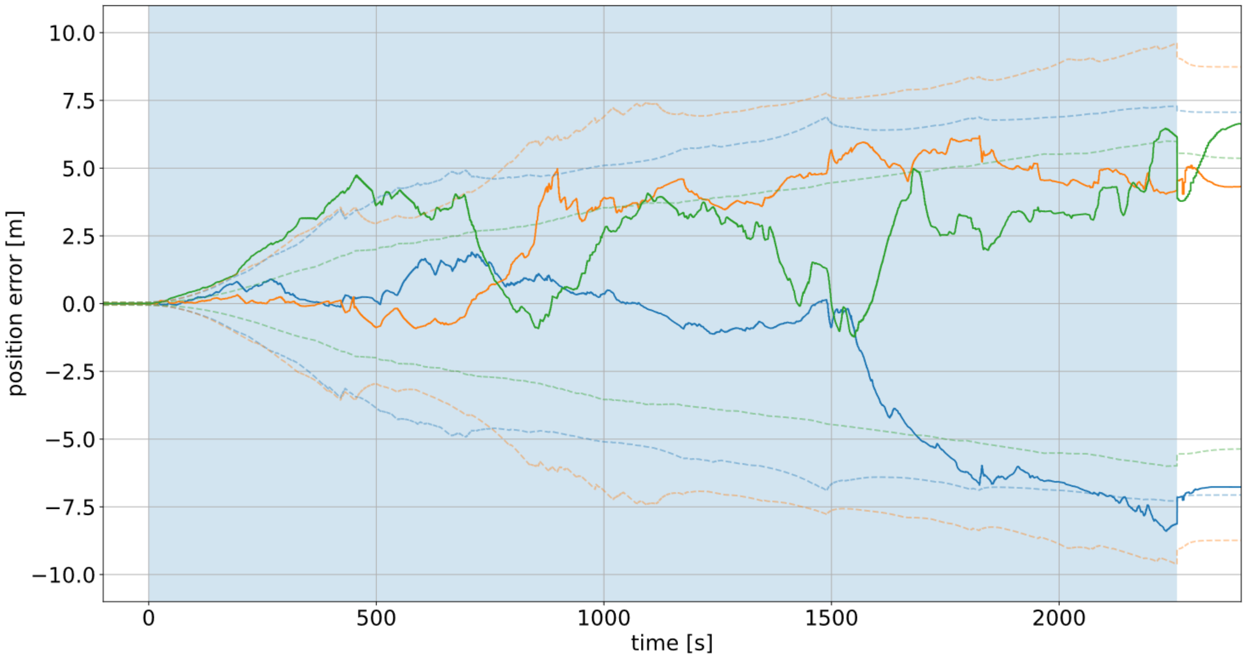

Figure 11:. Position error evolution of the DUT relative to a RTK aided trajectory for our method: Reference positions diverge in absence of any aiding information. In the period where the LiDAR system aiding could be possible (blue shaded), the absolute error in north direction diverges up to 8 m. Color coding for position errors graphs: blue – north error, orange – east error, green – down error. The dotted lines represent the estimated standard deviation of the particular axis.

Now we look to the Ground Truth reference, built up as explained in section 2: The LiDAR with the geo-referenced map aids the INS with a LiDAR data update frequency of 2 Hz, performing internally our sensor data fusion with integrated extended outlier detection. With this setup we demonstrate the reduction of the **absolute maximum error** in horizontal direction down to about 1.10 m, see Figure 12. The standard deviation of the Ground Truth position accuracy is now about 0.21 m in north and east direction, and about 0.1 m in altitude, see Figure 12.

It can be seen, that map and scan matching artifacts now have minor influence on our Ground Truth trajectory, damped by a factor of about 2 in rms and even a factor of 4 for the maximum deviation, compared to the results without INS, i.e. if referencing just only to the LiDAR system position directly. A summary of all relevant error measurements can be found in Table 1.

In summary, Figure 13 illustrates the final result of the DUT's verification process against the LiDAR/INS Ground Truth: It can be seen, that the position error of the DUT against the INS/GNSS-RTK based Ground Truth (see Figure 10) is nearly the same as the comparison against our here presented LiDAR/INS based GNSS-denied Ground Truth – so a reliable verification and qualification of land based navigation and localization systems can be performed in GNSS denied environment with the solution proposed in this paper.

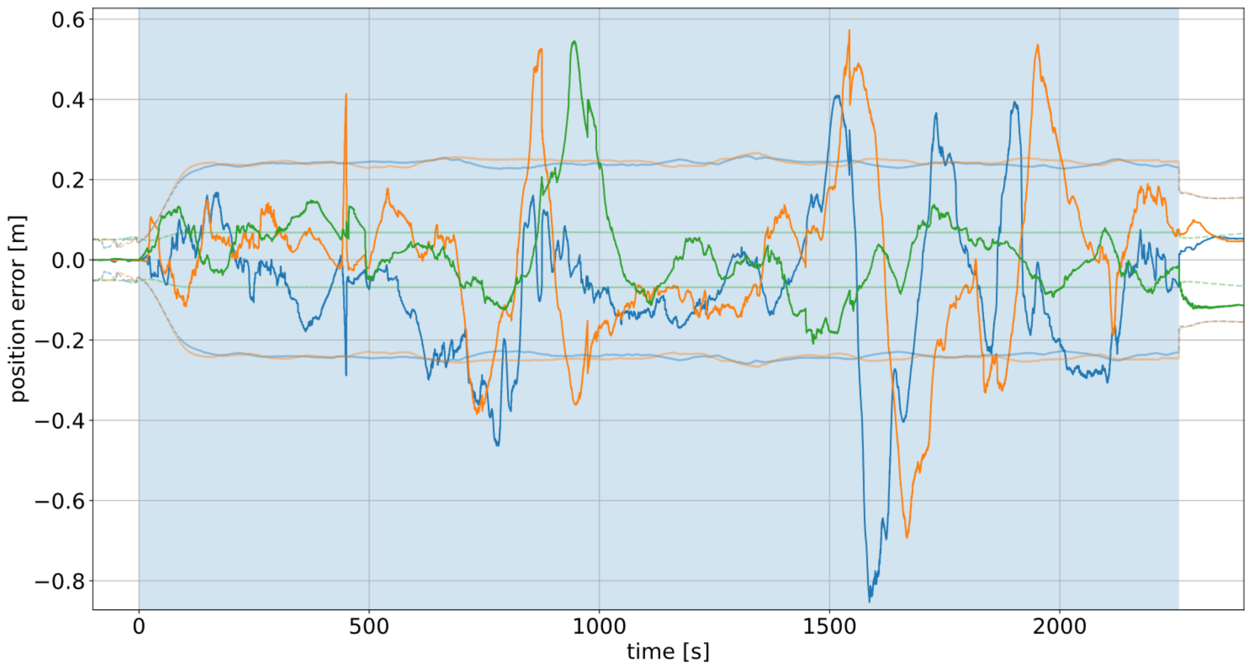

Figure 12: Position error of the Ground Truth (INS/LiDAR) relative to the INS/RTK-GNSS trajectory. Color coding for position error graphs: blue – north error, orange – east error, green – down error. The dotted lines represent the estimated standard deviation of the particular axes.

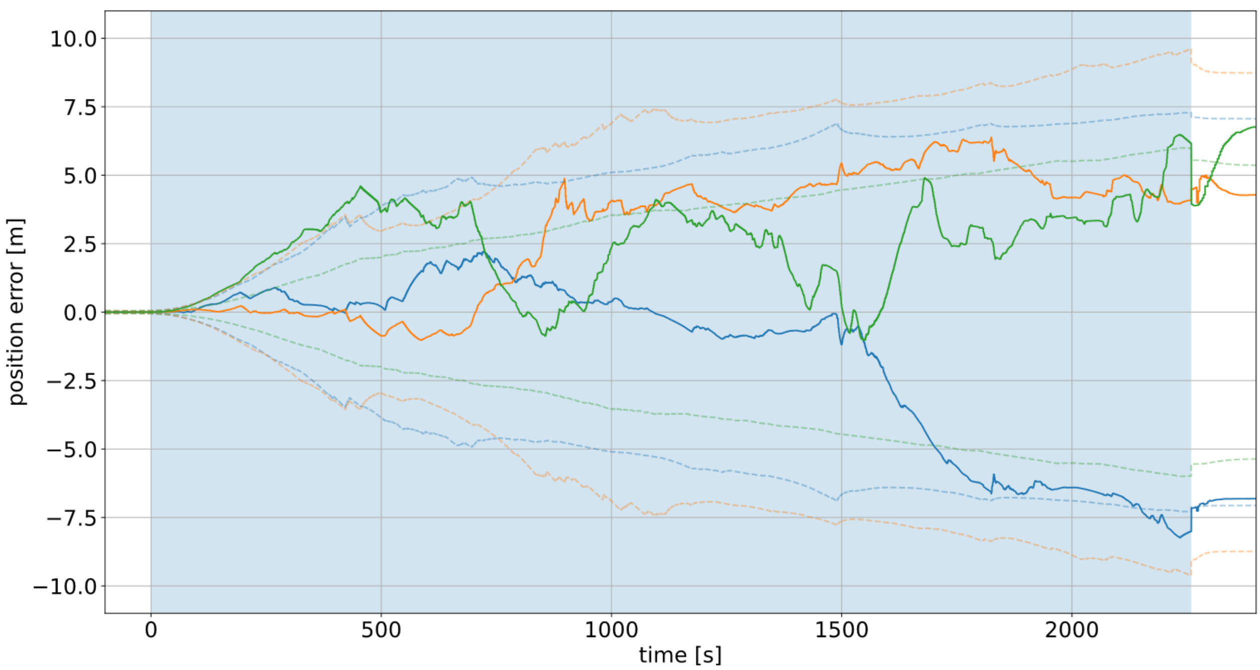

Figure 13: Final result of the verification process: The plot shows the positional error of the free inertial running DUT against our LiDAR/INS based GNSS-denied Ground Truth. Color coding for position error graphs: blue – north error, orange – east error, green – down error. The dotted lines represent the estimated standard deviation of the particular axes.

Table 1: Summary of error measurements relative to the RTK-GNSS aided trajectory; trajectory distance is 40 km and lasted approx. 40 minutes. It can be seen that the maximum error of the INS/LiDAR Ground Truth solution compared to a "LiDAR only" solution is smaller by a factor of 3.2 and compared to an excellent unaided INS (DUT) by round about a factor of 10.

Error quantum relative to a RTK GNSS aided trajectory	"LiDAR only" system position error (for information only)	Ground Truth accuracy: INS, aided by LiDAR	Position error of the DUT (all the time unaided INS)
Maximum error in north direction [m]	3.7312	0.853	8.402
Maximum error in east direction [m]	1.5256	0.693	6.191
Maximum error in down direction [m]	0.654	0.545	6.465
RMS error in north direction [m]	0.294	0.206	3.547
RMS error in east direction [m]	0.205	0.205	3.686
RMS error in down direction [m]	0.078	0.109	2.956
95.4 percentile in north direction [m]	0.604	**0.392**	7.452
95.4 percentile in east direction [m]	0.494	**0.476**	5.796
95.4 percentile in down direction [m]	0.126	0.211	4.521

4. Conclusion

In this paper we presented a method for the verification and qualification of localization systems in scenarios where GNSS can be absent or corrupted. The required Ground Truth within GNSS denied areas was generated by an INS, which is aided by a LiDAR system, which references itself to a pre-generated point-cloud map. Because the generation of an exact point-cloud map is not possible in certain corner cases, processes have been developed and discussed to eliminate erroneous parts of the map automatically during the verification step of the DUT with a dedicated outlier detection and isolation method. We can state an overall performance of the resulting LiDAR/INS based Ground Truth reference trajectory of about $\sigma_{refpos\,north/east} = 0.2\,m$, independent on the length and the duration of the trajectory.

In future investigations we will analyse whether we can achieve further improvements even to detect certain sporadic map degradation during the map generation process. The next development step is the industrialization of the product, comprising the following possible features:

- Ground Truth map generation without any GNSS, only by using landmarks (e.g. navigation in caves).
- Support of a mobile wide area (i.e. borders) jamming and spoofing detection, mapping and warning solution

The verification method for DUTs presented in this paper is based strictly on deterministic signal processing, i.e. it does not contain any AI methods and therefore the verification method is fully traceable and suitable to be used to qualify DUTs also for critical mission applications, where highest reliability is demanded. Therefore, the method proposed here can even be used to verify the accuracy of AI based sensor data fusion within GNSS denied environment, also in corner cases, which are not covered by trained memory of the AI model.

5. References

[1] T. Shan, “LIO-SAM: Tightly-coupled Lidar Inertial Odometry via Smoothing and Mapping”, IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2020