Performance Assessment of a Mini Mobile Mapping System: iPhone 14 Pro Installed on a E-Scooter

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ABSTRACT:

In this study, we investigate the feasibility of using an iPhone 14 Pro's camera and LiDAR sensors to collect high-accuracy spatial data on a mobile e-scooter. Given the widespread availability of e-scooters in urban areas, they present an ideal platform for creating a compact mobile mapping system. The iPhone is securely mounted on the e-scooter and paired with a viDoc RTK Rover, which offers real-time kinematic (RTK) positioning accuracy in open sky areas. As the e-scooter traverses the area of interest, data is collected using the LiDAR sensor, while images are captured using the camera. The collected data is then processed using Pix4Dmatic software, enabling the generation of a fused point cloud and a detailed digital model of the surveyed area. In situations where the Global Navigation Satellite System (GNSS) signal is compromised or unavailable, such as indoor environments or urban canyons, alternative methods like Simultaneous Localization and Mapping (SLAM) can be employed. Additionally, Total Stations can be utilized to track the entire system's movement in GNSS-denied environments and provide accurate georeferencing for the acquired data. Control and check points throughout the area of interest are established using the Total Station as well. This approach offers a flexible and cost-effective means of collecting high-accuracy spatial data in small areas across a variety of environments, leveraging the readily available e-scooters for public use. The results of various experiments conducted using an iPhone 14 Pro and viDoc RTK on an e-scooter are thoroughly analyzed and reported in this paper.

1. INTRODUCTION

Electric scooters (e-scooters) have gained significant popularity in large cities due to their ease of use and accessibility. Leveraging the widespread availability of these e-scooters presents an opportunity to make mobile mapping more approachable and engage a wider range of users. By incorporating the necessary sensors for mobile mapping onto e-scooters, we can streamline the mapping process and tap into the vast potential of e-scooter riders to collect valuable spatial data in urban areas, such as bustling cities and college campuses.

Traditional mobile mapping systems have long been recognized for their data collection capabilities, but their operational costs can be significant. However, recent research conducted by (Ilci and Toth, 2020) highlights how the accuracy of more affordable sensors used in autonomous vehicles can rival that of traditional mobile mapping vehicles equipped with professional-grade sensors such as GNSS, Inertial Measurement Unit (IMU), mobile LiDAR, and metric cameras, which generate solutions through post-processing. In contrast to mobile mapping systems, autonomous vehicles employ simpler and more cost-effective sensors and require real-time processing.

The study specifically focuses on evaluating the performance potential of autonomous vehicle sensor systems in creating high-definition maps by solely relying on affordable sensor data to generate precise point clouds, without considering additional sensor inputs. The results confirm that these autonomous vehicle sensor systems can achieve centimeter-level accuracy, showcasing their promising capabilities in mobile mapping applications. Calibration and synchronization of sensors are crucial for optimal performance in both mobile mapping and autonomous vehicle systems. Performance assessment of autonomous vehicle systems can be challenging without a reference solution or suitable ground control. This investigation focuses on evaluating the performance of a LiDAR sensor in normal operations using a high-end georeferencing system. The study aims to determine the feasibility of creating accurate high-definition maps using mobile LiDAR sensors deployed on autonomous vehicles. The sensor installation included various GNSS antennas, IMUs, and multiple LiDAR sensors. The data acquisition was performed in a mixed-urban area with varying platform speeds and complex surroundings. The collected sensor data was integrated and transformed into a global coordinate system to create a 3D point cloud. Benchmark ground control data was collected for quality assessment, which showed mean differences of 6 cm for horizontal direction and 11 cm for vertical direction. These results demonstrate that using highly accurate georeferencing, the LiDAR sensor-based point cloud achieved centimeter-level absolute accuracy within a 50-meter range from a moving platform under normal traffic conditions. This performance level is comparable to that of modern mobile mapping systems, highlighting the potential of automotive-grade sensors for creating high-definition maps.

(Chiang et al., 2020) have explored the benefits and advancements of multisensor fusion in automated driving systems, focusing on self-driving cars. Their proposed multisensor fusion design combines an INS, a GNSS receiver, and LiDAR technology to implement 3D SLAM (INS/GNSS/3D LiDAR-SLAM). The method demonstrated significant improvements compared to the conventional INS/GNSS/odometer integration, especially in highly urbanized areas with signal blockage and multipath interference. In scenario 1, the proposed method achieved positioning accuracy of less than 1 meter in all three dimensions, with substantial enhancements in various directions. Scenario 2 involved highway driving with long-term GNSS outages and high-speed movement, yet the proposed method maintained a 1-meter accuracy, outperforming the conventional method. The statistical analysis confirms the superior performance of the proposed method in both scenarios.

In the realm of mobile mapping, (Room and Ahmad, 2023) conducted a recent study focusing on the generation of precise 3D building models. Their approach integrated point cloud data obtained from both UAV-based LiDAR and mobile laser scanning (MLS) LiDAR systems. The study area encompassed UTM's Ring Road, which presented a diverse range of complex buildings and surroundings. Through merging, processing, and classifying the point clouds into ground, tree, and building categories, the researchers achieved remarkable accuracy in their 3D models. Evaluation using the Root Mean Squared Error (RMSE) equation indicated an error rate of approximately ±0.015 meters in the horizontal direction and ±0.009 meters in the vertical direction, suggesting relatively low error levels according to the available data. However, it is important to consider potential limitations such as the assumption of ideal geometric conditions and the presence of surface irregularities in real-world structures. Therefore, caution should be exercised when interpreting these results. This successful integration of different LiDAR systems proved highly effective in capturing the complete structures of buildings, making the resulting 3D models invaluable for development management and planning purposes.

This study represents a continuation of our previous research efforts. In a recent publication (Süleymanoğlu and Tamimi et al., 2023), we employed the iPhone 14 Pro with the viDoc RTK Rover and conducted a comparative analysis with mobile mapping and UAV LiDAR systems. The investigation unveiled that the relative positions of the point cloud generated by the iPhone-viDoc system exhibited errors that were comparable to those observed in the mobile mapping system and UAV LiDAR, with an RMSE of three centimeters. Based on our findings, we recommend employing the iPhone-viDoc system for smaller projects, highlighting its efficiency when compared to larger mapping systems.

Although there is currently no specific research on using e-scooters for mobile mapping, previous work by (Siddhant et al. 2020) discussed the integration of e-scooters into safety systems that analyze and predict object movements on the road. To achieve comprehensive reconstruction of driving scenarios, a proposed data collection and processing system incorporates various perception sensors, such as cameras, 3D LIDAR, and IMU, mounted on an e-scooter. While this thesis primarily focuses on the safety aspect of utilizing sensors on an e-scooter, considering their integration into a mini mobile mapping system could offer an excellent opportunity to gather large quantities of data.

For this study, we utilized a TurboAnt e-scooter and the iPhone 14 Pro in conjunction with the viDoc RTK Rover. The choice of the iPhone as a mapping tool was motivated by its ubiquity and user-friendly nature. With its built-in camera, LiDAR sensor, and IMU, the iPhone offers a powerful suite of sensors that can be leveraged for smartphone mapping. By integrating the viDoc RTK Rover, we were able to access network RTK corrections to enhance the accuracy of the system's trajectories.

To validate the accuracy of the trajectory data, we employed two different ground truthing (GT) systems: a Leica GS18 I GNSS receiver and a Leica TS16 Total Station. Figure 1 shows the mini mobile mapping system with the GS18 I attached as the GT system. These systems provide reference data against which we can compare and assess the accuracy of the mini mobile mapping system's trajectories. The aim of this research is to investigate the performance and accuracy of the iPhone 14 Pro with the viDoc RTK Rover as a mini mobile mapping system and to evaluate the effectiveness of the chosen GT systems. By analyzing the collected data and comparing it with the ground truth, we can gain insights into the reliability and limitations of the system, as well as identify areas for potential improvement. We can then harmonize the data to improve its quality.

Figure 1: Mini Mobile Mapping System with the TurboAnt e-scooter, iPhone 14 Pro with the viDoc RTK Rover, and a *Leica GS18 I GNSS receiver for GT. *(Leica 360 prism for Total Station GT)

2. METHODS

2.1 Equipment and Setup

2.1.1 Study Area and Reference Data

The study area chosen for this research is a 320-meter long residential drive located in a subdivision in Sterling Heights, MI. This specific area was intentionally selected to provide a realistic and suitable environment for demonstrating the practical application of an e-scooter with a mini mobile mapping system in various scenarios.

To validate the accuracy of all scenarios, we used single point positioning with a total station and a 360-degree reflective prism to survey the study area. A total of 43 checkpoints with XY&Z coordinates were captured, creating a reference dataset for comparing scenario runs on the e-scooter. These checkpoints serve as benchmarks to assess the accuracy and reliability of the mini mobile mapping system and ensure that the collected data closely aligns with GT measurements. Figure 2 depicts an aerial image of the study area with the 43 checkpoints.

Figure 2: Aerial Image of the Study Area and the 43 checkpoints.

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2.1.2 iPhone 14 Pro with viDoc RTK Rover

The iPhone 14 Pro is securely mounted at the front of the e-scooter, providing optimal visibility for forward-looking data collection. The integration of the iPhone's camera and LiDAR sensors enables us to capture comprehensive ground data. To ensure accurate positioning and trajectory information, we utilize the viDoc RTK Rover. When paired with the iPhone 14 Pro, the viDoc RTK Rover provides RTK corrections for enhanced trajectory accuracy. This integration allows us to collect spatial data with precise georeferencing, particularly in open sky areas where satellite visibility is maximized. Figure 3 illustrates the implementation of the iPhone-viDoc system on the front of the e-scooter.

Figure 3: iPhone-viDoc at the front of the e-scooter.

However, in GNSS-denied environments, such as under tree canopies, we utilize SLAM. SLAM enables us to estimate the trajectory and position of the e-scooter by leveraging sensor data, including the LiDAR and IMU sensors. This ensures the continuity of data collection even in the absence of GNSS corrections. It is essential to acknowledge that this mini mobile mapping system serves as an initial proof of concept, providing a foundation for conducting future tests with future sensors that can be seamlessly integrated into the e-scooter platform.

2.1.3 Leica GS18 I GNSS Receiver

To ensure accurate ground truth measurements and assess the reliability of our mini mobile mapping system, we installed the Leica GS18 I GNSS receiver at the back of the e-scooter as the initial iteration of our GT system. Figure 4 illustrates how the GS181 was mounted over the rear wheel.

Figure 4: GS18 I GNSS Receiver attached at the back of the e-scooter for ground truthing.

The GS18 I offers precise GNSS positioning but also integrates an IMU for tilt compensation. Since the GS18 I was aligned to the platform, this feature compensates for any tilt or inclination of the e-scooter during data collection, ensuring accurate and reliable measurements. We configured the GS18 I receiver using the Leica Captivate software to collect single positions at a set interval of 1 meter, allowing us to capture frequent and precise updates for the GT data.

We conducted a comparative analysis between the iPhone-viDoc system and the GS18 I GNSS receiver to evaluate the absolute trajectories obtained from both systems and identify any discrepancies or variations. The precise trajectories derived from the GNSS GT data served as a benchmark for assessing the accuracy and reliability of our mobile mapping system. This comparison helped validate the system's performance and ensured that the collected data closely aligned with the GT. In areas where the viDoc RTK Rover encountered challenges in RTK corrections, the GS18 I GNSS receiver provided an alternative solution for correcting the e-scooter's trajectory data. Due to its robustness, the GS18 I receiver maintained accurate trajectory information even in compromised signal environments where the viDoc RTK Rover was unable to provide RTK corrections.

Finally, we harmonized the trajectory data from the GS18 I GNSS receiver with the iPhone-viDoc system and compared the results to the reference data. This comparison allowed us to evaluate the accuracy and reliability of our mini mobile mapping system, providing valuable insights into its performance and effectiveness.

2.1.4 Leica TS16 Total Station

A second iteration of the GT system involved using the Leica TS16 Total Station to validate the accuracy and reliability of our mini mobile mapping system's data. The Leica TS16 Total Station offers higher precision data compared to satellite-based positioning systems by utilizing relative positioning based on angles and distances between the Total Station and a 360-degree reflective prism. This approach provides a robust alternative for achieving precise measurements. Figure 5 illustrates how the reflective prism was attached to the back of the e-scooter.

Figure 5: Leica 360 degree reflective prism attached at the back of the e-scooter for clear visibility to the TS16 total station.

By utilizing the advanced capabilities of the Total Station, we achieved exceptional accuracy in measuring trajectories if there was a clear line of sight between the reflective prism and the e-scooter. We employed Leica Captivate software to capture positions at intervals of 1 meter. To maintain the visual line of sight, we set up two separate Total Station configurations on each side of the road for each scenario. The data collected from these two runs were combined to create a single dataset for each scenario.

In scenarios where the viDoc RTK was unable to receive RTK corrections, we relied on the trajectories calculated by the Total Station. We harmonized the data from the Total Station with the rest of the dataset. The results were then compared to similar scenarios conducted using the GS18 I GNSS receiver as the GT method, as well as to the reference data.

2.2 Methodology

2.2.1 Data Collection Parameters

We utilized the Pix4Dcatch app, which enabled us to capture images and LiDAR scans of the road. This app played a critical role in acquiring the necessary data for our study. Moreover, it facilitated a seamless connection to network RTK using the viDoc, ensuring real-time corrections for the trajectories of the entire system. Following data collection, the captured data was exported and processed using Pix4Dmatic to generate point cloud datasets for each scenario. These point cloud datasets formed the basis for our analysis and evaluation of the mini mobile mapping system's performance across various scenarios.

2.2.2 Impact of Speed on Data Quality

To assess the impact of different speeds on data quality, we conducted experiments using three speed settings for the e-scooter: 10, 20, and 30 km/h. This approach enabled us to evaluate the potential degradation of data quality as the e-scooter operated at higher speeds. By doing so, we could comprehensively assess the resolution, accuracy, and reliability of the trajectories obtained from the mini mobile mapping system. The variation in speeds also allowed us to examine the performance of the GT systems under different conditions. This analysis helped us understand if the reliability and effectiveness of these systems varied at different speeds, providing valuable insights into the trade-offs between data quality and speed. Ultimately, it helped identify the most suitable operational conditions for optimal results. With these three speeds, we conducted a total of six scenarios, combining different speeds with different GT systems.

For scenarios 1, 2, and 3, the e-scooter was driven at speeds of 10, 20, and 30 kilometers per hour, respectively, with the GNSS receiver serving as the reference for GT data. This setup allowed us to evaluate the system's accuracy and reliability in real-time positioning under varying speeds. In scenarios 4, 5, and 6, the total station was utilized as the GT system. Like the previous set of scenarios, the e-scooter was driven at speeds of 10, 20, and 30 kilometers per hour, respectively. The total station provided precise and relative positioning data, enabling us to validate the system's performance in areas with limited satellite visibility.

2.2.3 Time Synchronization of Ground Truth Trajectories

After acquiring the six scenarios, our next step was to harmonize the trajectory data obtained from the GT systems with the data collected by the iPhone-viDoc. This process is crucial for achieving precise and accurate trajectories of the mini mobile mapping system. To accomplish this, we synchronized the timestamps of the images taken by the iPhone-viDoc with the corresponding timestamps on the GT system. By aligning the timestamps, we can accurately associate the positions recorded by the GT system with the entire mini mobile mapping system. This synchronization ensures that the trajectories of the collected data are updated and refined.

The harmonized trajectories derived from this synchronization process will then be compared to the reference data acquired from independent observations. This comparison allows us to assess whether there is an improvement in accuracy through the additional incorporation the trajectory data collected by both the GNSS receiver and the Total Station. By analysing the results, we can gauge the effectiveness and reliability of the mini mobile mapping system and identify any potential improvement that can be made.

3. RESULTS

3.1 Without GT Trajectory Harmonization

3.1.1 GNSS GT Trajectory

Scenario 1 involved the e-scooter traveling at a speed of 10 km/h. During data collection by the iPhone-viDoc and the GNSS receiver, Figure 6 illustrates the trajectories recorded by both systems. Analysis of the results reveals that the GS18 I GNSS receiver encountered challenges in areas with dense tree coverage, leading to standard deviations ranging from three to five meters. In contrast, the iPhone-viDoc system leveraged SLAM techniques to estimate and maintain accurate trajectories of the mini mobile mapping system.

Scenario 2 involved the e-scooter traveling at a speed of 20 km/h with the GS18 I GNSS receiver as the GT system. This scenario exhibited similar outcomes to Scenario 1. Figure 7 shows that in regions where the GS18 I received RTK corrections, the trajectories closely aligned with those of the iPhone-viDoc, demonstrating consistent precision in the mini mobile mapping system. However, it is important to note that assessing this accuracy becomes challenging in areas with dense tree coverage, where the GNSS signal may be compromised and affect the reliability of the trajectories.

In Scenario 3, the e-scooter traveled at a speed of 30 km/h while utilizing the GS18 I GNSS receiver as the GT system, as shown in Figure 8. The findings in this scenario were consistent with Scenarios 1 and 2, showing a strong alignment between the trajectories of the GS18 I and the iPhone-viDoc in areas where RTK corrections were available. The speed of the e-scooter does not seem to impact the GT's abilities to collect trajectory data. However, these scenarios also highlighted the limitations of relying solely on GNSS positioning for GT, as the visibility of satellites played a critical role in the accuracy and reliability of the trajectories.

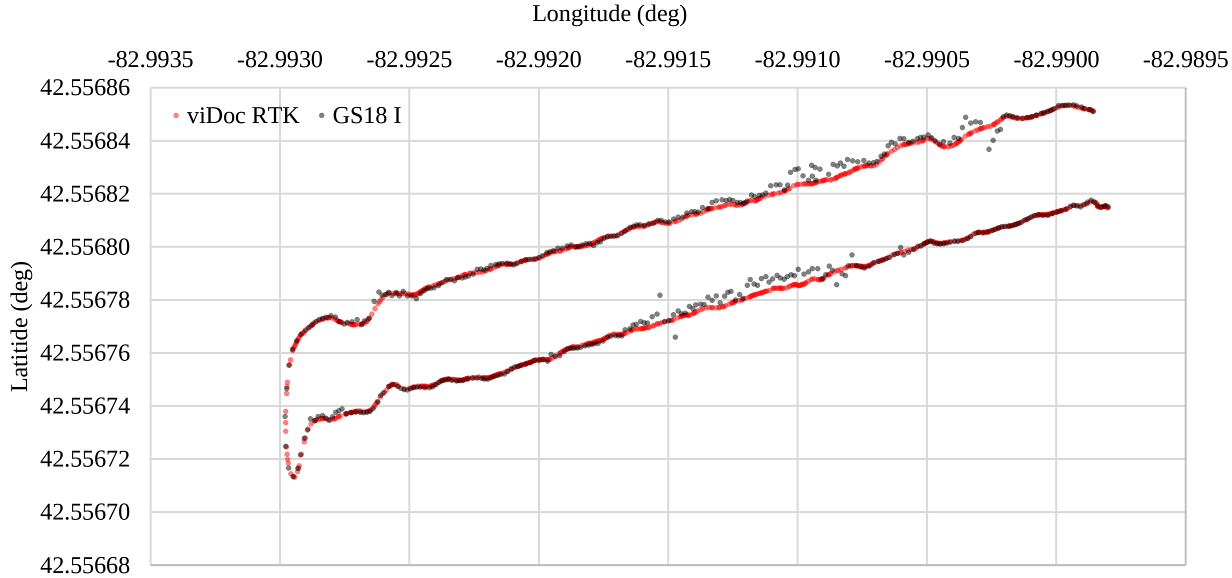

Figure 6: 10 km/h with GNSS for Ground Truthing

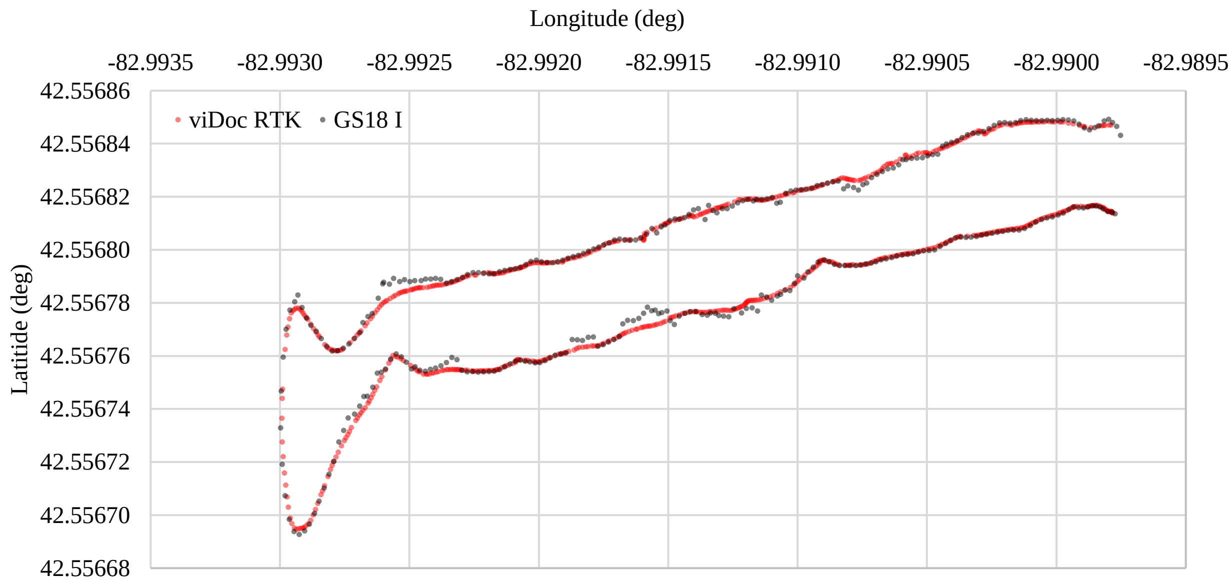

Figure 7: 20 km/h with GNSS for Ground Truthing

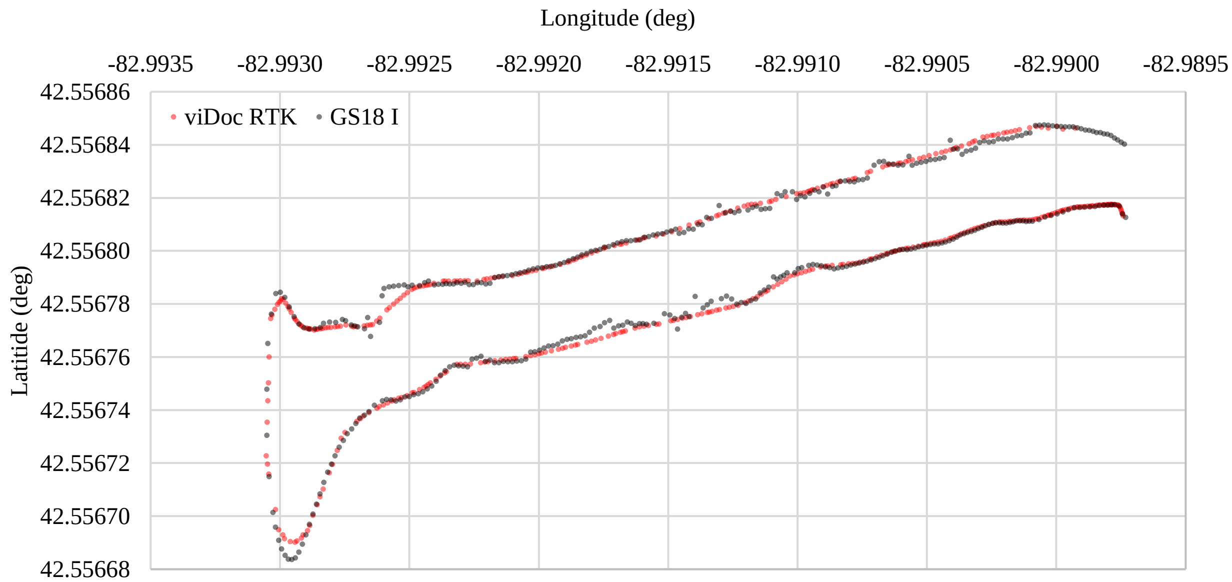

Figure 8: 30 km/h with GNSS for Ground Truthing

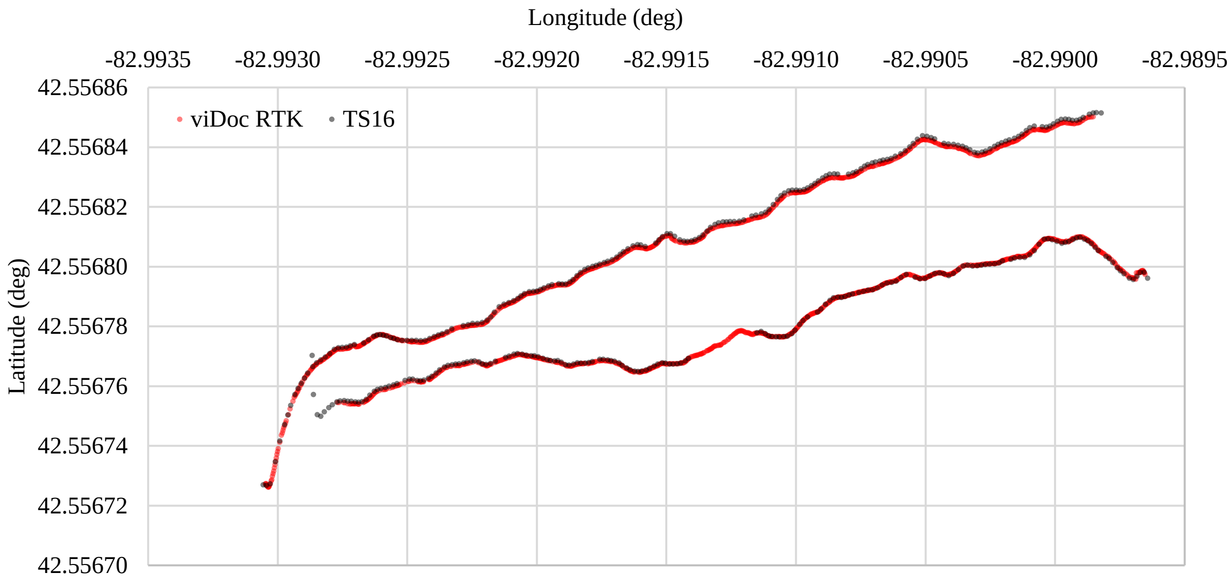

Figure 9: 10 km/h with Total Station for Ground Truthing

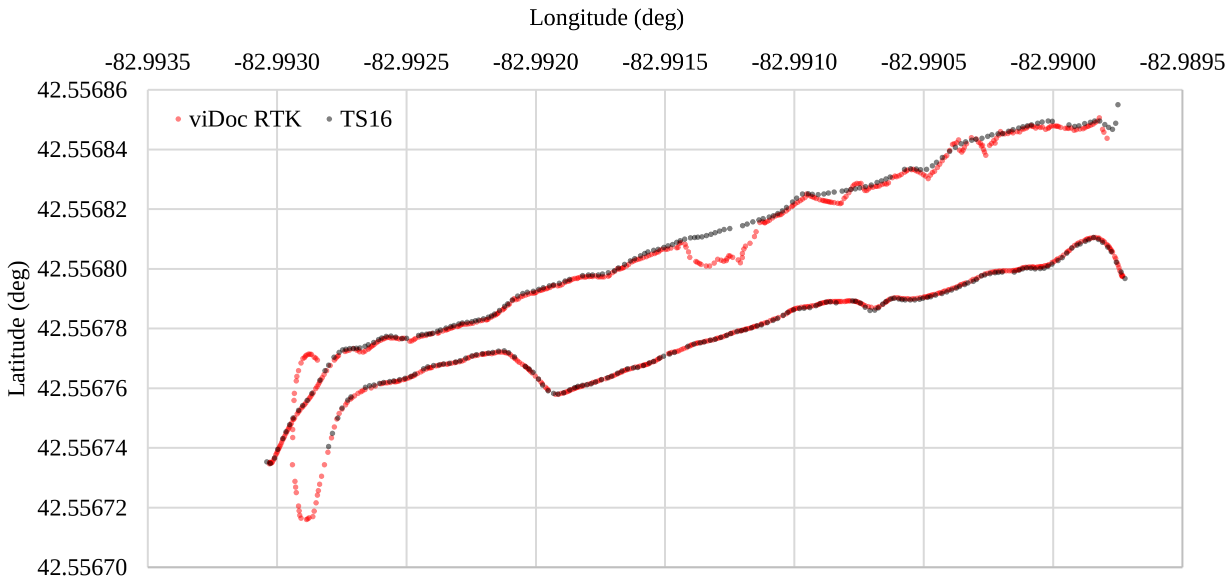

Figure 10: 20 km/h with Total Station for Ground Truthing

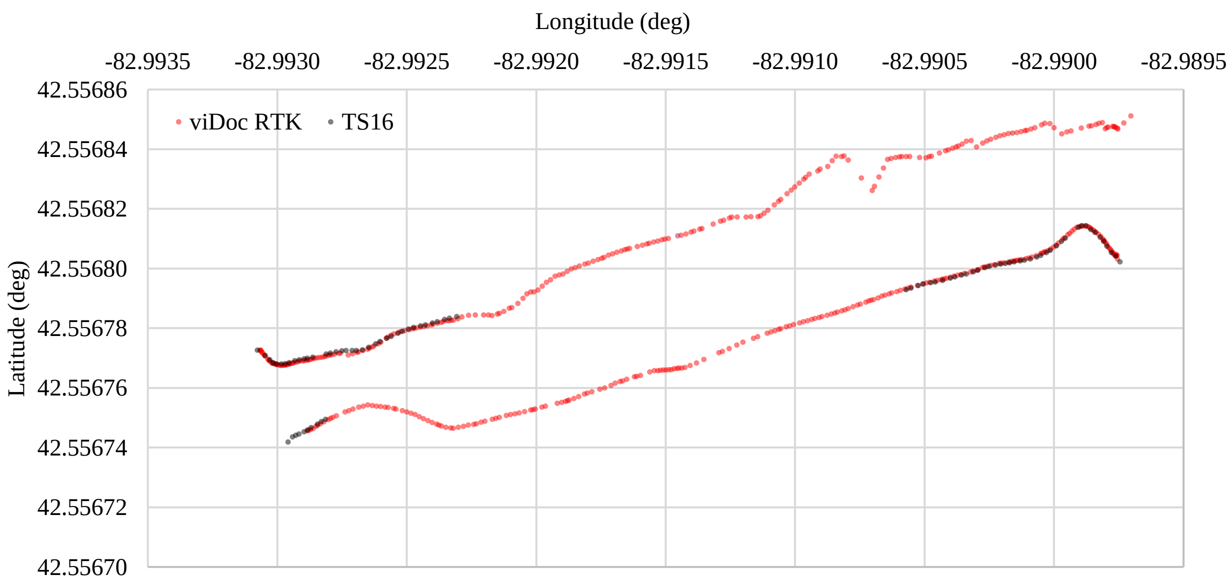

Figure 11: 30 km/h with Total Station for Ground Truthing

3.1.2 Total Station GT Trajectory Harmonization

In Scenario 4, the e-scooter traveled at a speed of 10 km/h, and data collection was conducted using the iPhone-viDoc and the TS16 total station as the GT system. Figure 9 depicts the trajectories recorded by both systems. The analysis of the results indicates that the TS16 total station consistently maintained trajectories that closely matched those of the mini mobile mapping system throughout most of the data collection. However, it should be noted that in one instance, no data was collected by the total station, which could be attributed to a loss of visual line of sight.

In Scenario 5, the e-scooter traveled at a speed of 20 km/h, and data collection involved the iPhone-viDoc and the TS16 total station as the GT system. Figure 10 illustrates the trajectories captured by both systems. Like Scenario 4, the utilization of a total station as the GT system proved to be highly effective in ensuring accurate GT if visual line of sight was maintained. However, during the second run of this test, it was observed that the iPhone-viDoc lost RTK corrections, resulting in an inaccurate estimation of the mini mobile mapping system's trajectories by the SLAM method. In contrast, the total station maintained its line of sight, resulting in a linear trajectory. This highlights the advantage of harmonizing the trajectory data from both systems to improve the accuracy and reliability of the overall dataset.

In Scenario 6, the e-scooter operated at a speed of 30 km/h, and both the iPhone-viDoc and the TS16 total station were employed for data collection and GT, respectively. Figure 11 showcases the trajectories recorded by both systems. Notably, the TS16 total station encountered significant challenges at this higher speed, resulting in a catastrophic failure. The trajectories exhibited a pattern where the total station initially captured data but lost visual line of sight shortly after, leading to a lack of data collection. While the line of sight briefly returned towards the end of the first run, it was lost again after starting the second run, resulting in no data being collected. Multiple repetitions of this scenario consistently yielded similar outcomes, suggesting that the speed of 30 km/h exceeded the capabilities of the total station to maintain reliable measurements.

3.1.3 Point Cloud Accuracy

When assessing the accuracy of the point cloud generated by the iPhone 14 Pro with the viDoc RTK Rover, we utilized 43 checkpoints from the reference data for analysis. By georeferencing the corresponding locations of the checkpoints to their position on the point cloud, we can find the differences in coordinates between what was measured with the GS18 I GNSS receiver, and the calculated positions in the point cloud. To quantify the accuracy, we calculated the root mean square error (RMSE) for the entire project. This measures the average difference between values calculated by a model and the actual values, providing an estimation of how well the model can predict the target value. The formula used to compute the RMSE is as follows:

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(\hat{x}_i - x)^2 + (\hat{y}_i - y_i)^2 + (\hat{z}_i - z)^2}{n}}$$

where $\hat{x}_i - x_i$, $\hat{y}_i - y_i$, and $\hat{z}_i - z_i$ are the differences between the calculated positions and the true positions in x, y, and z, respectively, n is the total number of observations taken.

After analyzing all 43 checkpoints during the 10, 20, and 30 km/h tests, the average errors obtained are presented in Table 1 and illustrated in Figure 12. The errors range between two and six centimeters, demonstrating accuracies that are consistent with handheld smartphone mapping. These results indicate that the mini mobile mapping system utilizing the iPhone 14 Pro and viDoc RTK Rover can achieve accurate spatial data collection comparable to other smartphone-based mapping methods at speeds of 10 km/h.

In the 20 km/h test, the errors observed in this scenario are approximately double those of the 10 km/h test, with values ranging between four and ten centimeters. Although there is a reduction in accuracy compared to the slower speed, the overall integrity of the data remains reasonably intact. The largest errors tend to occur in the X (long) coordinate direction, which aligns with the motion of the e-scooter during the tests. To further enhance the quality of this dataset, the inclusion of additional ground control points could significantly improve the accuracy and precision of the collected data.

In the 30 km/h test, the errors in these scenarios are notably higher, ranging between 10 and 30 centimeters. These results clearly indicate a significant degradation in data quality when the e-scooter operates at higher speeds. The increased errors emphasize the challenges of maintaining accuracy and reliability in data collection under such conditions. This reinforces the importance of carefully considering the operational speed of the mini mobile mapping system to ensure optimal data quality and integrity.

Table 1: X, Y, and Z differences of point cloud generated by iPhone-viDoc at 10, 20, and 30 km/h to reference data.

Speed	ΔX (cm)	ΔY (cm)	ΔZ (cm)	RMSE
10 km/h	3.2	2.1	4.5	5.9
20 km/h	4.0	5.8	7.7	10.4
30 km/h	10.1	13.5	19.3	25.6

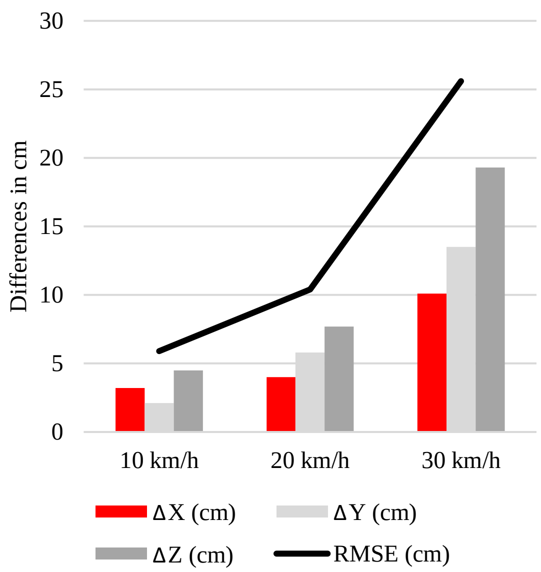

Figure 12: No trajectory harmonization

3.2 With GNSS Receiver GT Trajectories

By leveraging the timestamps of the observations, we synchronized the positions of the GS18 I GNSS receiver with the trajectory positions of the iPhone-viDoc captured during image acquisition. If the GT trajectories deviated by more than 1 centimeter, we updated the overall trajectories of the mini mobile mapping system using the positions from the GS18 I GNSS receiver.

Table 2 presents the relative differences between the extracted points from the point cloud with the updated trajectories from the GNSS receiver and the positions of the 43 checkpoints in the reference dataset. At speeds of 10 and 20 km/h, the results closely resemble those without trajectory harmonization. There is a slight reduction in differences in the vertical direction, but the overall RMSE is only marginally lower, with a decrease of two to three millimeters. This is illustrated in Figure 13.

At a speed of 30 km/h, the horizontal differences remain similar between the two datasets, while the vertical accuracy improves by approximately 9 centimeters, resulting in a lower RMSE. This demonstrates that incorporating a second high-precision GNSS receiver can enhance vertical accuracy, particularly at high speeds.

Table 2: X, Y, and Z differences of point cloud generated by iPhone-viDoc with the GNSS receiver GT trajectories harmonized at 10, 20, and 30 km/h to reference data.

Speed	ΔX (cm)	ΔY (cm)	ΔZ (cm)	RMSE
10 km/h	3.5	2.4	3.7	5.6
20 km/h	4.8	6.5	6.3	10.2
30 km/h	9.9	13.1	10.5	19.5

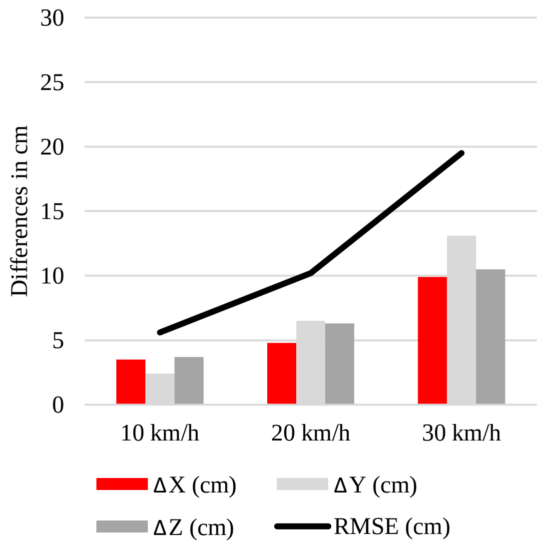

Figure 13: GNSS Receiver trajectory harmonization

3.3 With Total Station GT Trajectories

Table 3 presents the relative differences between the point cloud data, updated with trajectories from the total station, and the positions of the 43 checkpoints in the reference dataset. This is illustrated in Figure 14. Notably, at 10 and 20 km/h, there is a significant improvement in data accuracy, with an average reduction of two centimeters in the RMSE. This highlights the total station's ability to provide more precise trajectories, particularly in areas where SLAM-based estimation is required due to GNSS limitations.

However, at 30 km/h, errors return to a similar range as the dataset without trajectory harmonization, indicating the total station's failure at high speeds. Nonetheless, there is a slight advantage in the vertical direction, with a four-and-a-half centimeter reduction in differences. However, the RMSE remains in the 20 centimeter range. While this improvement may be minimal, it suggests that any sensor harmonization, irrespective of data collection limitations, can contribute to enhanced vertical positioning accuracy.

Table 3: X, Y, and Z differences of point cloud generated by iPhone-viDoc with the Total Station trajectories harmonized at 10, 20, and 30 km/h to reference data.

Speed	ΔX (cm)	ΔY (cm)	ΔZ (cm)	RMSE
10 km/h	2.0	2.7	2.5	4.2
20 km/h	2.2	3.7	2.8	5.1
30 km/h	9.7	12.8	15.7	22.5

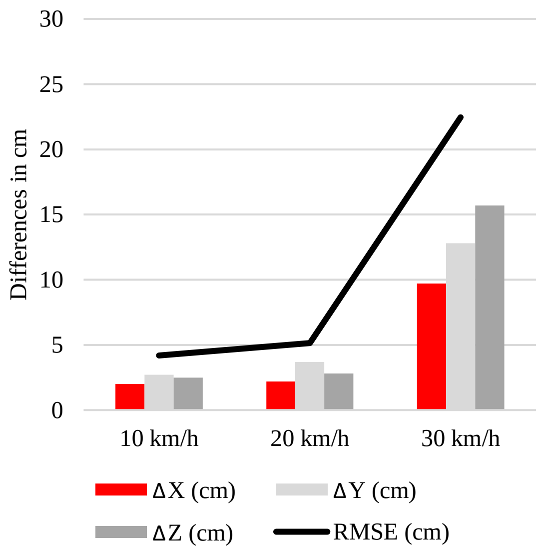

Figure 14: Total Station trajectory harmonization

4. DISCUSSION AND CONCLUSION

The experiments conducted in different scenarios using the iPhone-viDoc, GS18 I GNSS receiver, and TS16 total station for data collection and ground truthing have provided valuable insights into the capabilities and limitations of these systems in mini mobile mapping applications. The results have demonstrated the impact of factors such as speed, GNSS visibility, and environmental conditions on the accuracy and reliability of the collected data.

At lower speeds of 10 km/h and 20 km/h, the iPhone-viDoc system demonstrated its ability to leverage SLAM techniques and maintain accurate trajectories even in GNSS-challenged areas with dense tree coverage. As a GT system, the GS18 I GNSS receiver also performed well in areas where RTK corrections were available, exhibiting strong trajectory alignment with the iPhone-viDoc. However, limitations were observed in scenarios where GNSS visibility was compromised, resulting in decreased accuracy.

The use of a total station as the GT system demonstrated its effectiveness in maintaining accurate trajectories, particularly when visual line of sight was preserved. It consistently aligned with the mini mobile mapping system trajectories, demonstrating its suitability for ground truthing purposes, especially in situations where other systems may face limitations. However, using a total station involves field work with setting up a control network to maintain visual line of sight between the Total Station and the reflective prism, which may be less favorable in mobile mapping contexts. Nonetheless, the total station proved to be a valuable option in specific circumstances where it was feasible and affordable. It is essential to carefully consider the operational limitations, including speed constraints, when selecting an appropriate GT system.

The analysis of the point cloud accuracy revealed that the iPhone 14 Pro with the viDoc RTK Rover can achieve accuracies comparable to handheld smartphone mapping methods at speeds of 10 km/h and performs well on mobile platforms with moderate speeds. At higher speeds, the accuracy decreased, emphasizing the importance of ground control points to enhance data quality. The inclusion of diverse terrain, GNSS-denied environments, ground control points from the 43 checkpoints, and complex road networks in future studies will contribute to further improvements in accuracy and reliability. We may also analyze the time synchronization between the iPhone-viDoc and the GT systems at different speeds to see how the speed affects the synchronization accuracy.

This research has provided valuable insights into the performance of the iPhone 14 Pro with the viDoc RTK Rover in mini mobile mapping applications. The analysis of using different GT systems has also yielded significant insights into the advantages and limitations of each system. These findings can guide practitioners in selecting the most appropriate system for specific scenarios and highlight areas for further research and development to enhance data accuracy and reliability in challenging environments.

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