EVALUATING THE PERFORMANCE OF GNSS RTK AND UAV (DRONE) TECHNOLOGIES UNDER VRS MODE IN CHALLENGING ENVIRONMENTS

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ABSTRACT

The advancement of modern geospatial technologies has significantly improved the efficiency and accuracy of engineering surveying through the integration of Global Navigation Satellite System Real-Time Kinematic (GNSS RTK), Unmanned Aerial Vehicle Real-Time Kinematic (UAV RTK), and Simultaneous Localization and Mapping Real-Time Kinematic (SLAM RTK) systems. However, their performance under challenging environmental conditions remains a critical concern due to signal obstruction, canopy interference, multipath effects, and operational limitations. This study evaluates and compares the performance of GNSS RTK, UAV RTK, and SLAM RTK technologies operating under Virtual Reference Station (VRS) mode across urban, forested, mixed-use, and semi-urban environments. Field surveys were conducted using a TOKNAV T5Lite GNSS RTK receiver, static GNSS observations, Total Station traverse surveys, a DJI Matrice 350 RTK UAV equipped with a Zenmuse L2 LiDAR sensor, and a GoSLAM M40 handheld mobile mapping system. Positional accuracy was assessed through coordinate comparison and Root Mean Square Error (RMSE) analysis using adjusted reference coordinates established from the control network. GNSS RTK achieved the highest positional accuracy, recording horizontal RMSE values of 0.064 m, 0.079 m, 0.074 m, and 0.121 m in urban, forested, mixed-use, and semi-urban environments, respectively. UAV RTK recorded an RMSE of 0.106 m in urban areas, while SLAM RTK recorded RMSE values of 0.160 m and 0.299 m in forested and mixed-use environments. The findings demonstrate that GNSS RTK provides the highest positioning accuracy under favorable satellite visibility conditions, whereas UAV RTK and SLAM RTK offer significant operational advantages for rapid mapping and surveying within large-scale or obstructed environments.

Keywords: Geospatial Analysis, GNSS RTK, SLAM RTK, UAV LiDAR, Virtual Reference Station

1. INTRODUCTION

Modern geospatial technologies have significantly improved the efficiency and accuracy of engineering surveying and spatial data acquisition. Among these technologies, Global Navigation Satellite System Real-Time Kinematic (GNSS RTK), Unmanned Aerial Vehicle Real-Time Kinematic (UAV RTK), and Simultaneous Localization and Mapping Real-Time Kinematic (SLAM RTK) systems are widely used for positioning and mapping applications. However, their performance can be affected by environmental conditions such as dense vegetation, urban obstructions, terrain variability, and multipath interference.

Understanding the strengths and limitations of these technologies under different environmental conditions is essential for selecting appropriate surveying methods. Therefore, this study evaluates and compares the performance of GNSS RTK, UAV RTK, and SLAM RTK technologies operating under Virtual Reference Station (VRS) mode across urban, forested, mixed-use, and semi-urban environments. The assessment focuses on positional accuracy, operational feasibility, and environmental sensitivity to support technology selection for engineering surveying applications.

2. LITERATURE REVIEW

Recent advancements in geospatial surveying have increased the use of Global Navigation Satellite System Real-Time Kinematic (GNSS RTK), Unmanned Aerial Vehicle Real-Time Kinematic (UAV RTK), and Simultaneous Localization and Mapping (SLAM) technologies for high-accuracy spatial data acquisition. GNSS RTK is widely used in engineering surveys due to its ability to provide centimeter-level positioning accuracy through real-time correction services such as Virtual Reference Stations (VRS). However, its performance is strongly influenced by environmental conditions, particularly signal obstruction, multipath effects, and limited satellite visibility in urban and forested environments (Aldibaja et al., 2022).

Network-based RTK systems improve operational efficiency by eliminating the need for local base stations, although atmospheric disturbances may still affect positioning accuracy (Bae & Kim, 2018). UAV RTK systems have emerged as efficient tools for rapid mapping and high-resolution data collection. Studies have shown that RTK-enabled UAVs can achieve reliable georeferencing accuracy and significantly reduce field survey time (Tavasci et al., 2024; Dlamini & Ouma, 2025).

In GNSS-challenging environments, alternative approaches such as SLAM-based mobile mapping have gained attention due to their ability to provide continuous spatial data acquisition under dense vegetation and obstructed conditions. Furthermore, LiDAR-assisted positioning techniques have been shown to improve reliability in environments affected by multipath and non-line-of-sight errors (Liu et al., 2022). These findings highlight the need for comparative evaluations of GNSS RTK, UAV RTK, and SLAM technologies across different environmental conditions.

3. METHOD

This study evaluated the performance of GNSS RTK, UAV RTK, and SLAM RTK technologies operating under Virtual Reference Station (VRS) mode in urban, forested, mixed-use, and semi-urban environments. Positional accuracy, operational feasibility, and environmental sensitivity were assessed under varying levels of signal obstruction and canopy cover.

3.1. Data Collection

GNSS RTK observations were conducted using a TOKNAV T5Lite receiver under VRS mode. Static GNSS observations and Total Station traverse surveys were used to establish the reference control network. UAV data were acquired using a DJI Matrice 350 RTK equipped with a Zenmuse L2 LiDAR sensor, while SLAM surveys were performed using a GoSLAM M40 handheld mobile mapping system.

3.2. Data Processing and Analysis

Survey datasets were processed using 3Dsurvey software. Positional accuracy was evaluated through coordinate comparison and Root Mean Square Error (RMSE) analysis using adjusted reference coordinates derived from the control network. Comparative analysis was then performed to assess technology performance across the selected environments.

4. RESULTS AND DISCUSSION

Environmental conditions significantly influenced the performance of GNSS RTK, UAV RTK, and SLAM RTK technologies operating under VRS mode. The locations of the selected study environments are shown in Figure 2.

GNSS RTK consistently achieved the highest positional accuracy across most environments. In the urban environment, GNSS RTK recorded a horizontal RMSE of 0.064 m compared to 0.106 m for UAV RTK. In the forest environment, GNSS RTK achieved an RMSE of 0.079 m, while SLAM RTK recorded 0.160 m. In the mixed-use environment, GNSS RTK achieved an RMSE of 0.074 m compared to 0.299 m for SLAM RTK.

A summary of positioning performance is presented in Table 1. The results indicate that GNSS RTK consistently achieved the lowest RMSE values, confirming its suitability for high-precision engineering surveys.

Figure 1 illustrates the variation of horizontal RMSE across the evaluated technologies and environments. Positioning accuracy generally decreased with increasing environmental complexity due to canopy cover, signal obstruction, and multipath effects. However, UAV RTK and SLAM RTK provided operational advantages for rapid mapping and surveying in areas where conventional GNSS observations were constrained.

Overall, GNSS RTK delivered the highest positioning accuracy, while UAV RTK and SLAM RTK offered greater flexibility for large-scale and obstructed environments.

Table 1. Comparative Summary of Positioning Performance

Environment	Technology	RMSE Horizontal Error (m)
Urban	GNSS RTK	0.064
Urban	UAV RTK	0.106
Forest	GNSS RTK	0.079
Forest	SLAM RTK	0.160
Mixed Use	GNSS RTK	0.074
Mixed Use	SLAM RTK	0.299
Semi-Urban	GNSS RTK	0.121

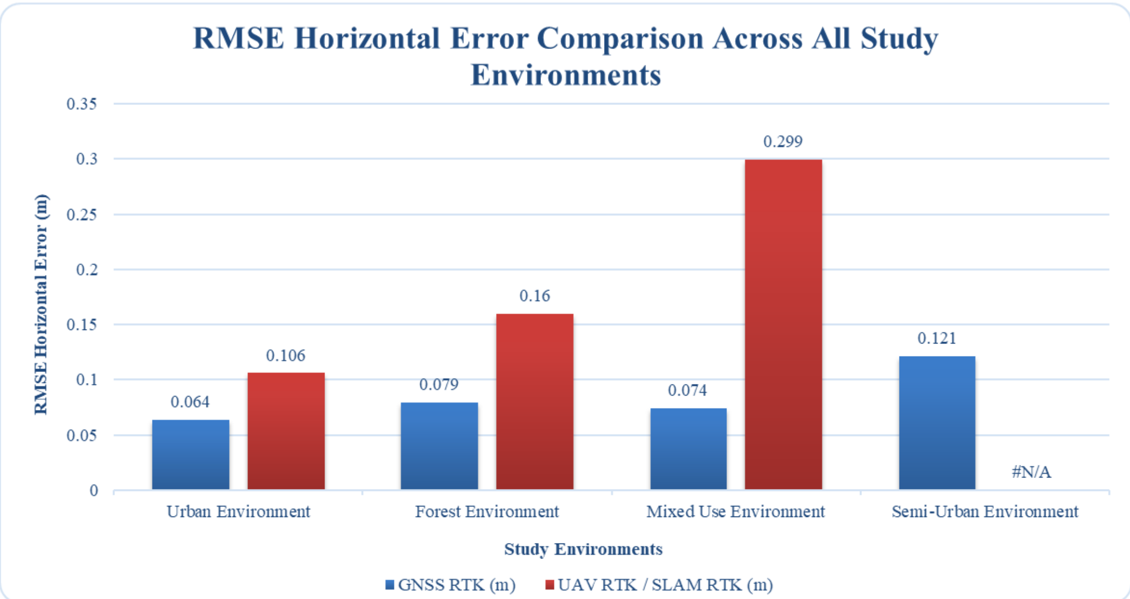

Figure 1. RMSE Horizontal Error Comparison Across Study Environments

Figure 2. Study Area Locations and Survey Points of the Selected Areas (Urban Area | Forest Area | Mixed Use Area | Semi-Urban Area)

5. CONCLUSION

This study evaluated the performance of GNSS RTK, UAV RTK, and SLAM RTK technologies operating under Virtual Reference Station (VRS) mode across urban, forested, mixed-use, and semi-urban environments. The results showed that environmental conditions, including canopy cover, building obstruction, and multipath interference, significantly affect positioning accuracy and operational performance.

GNSS RTK consistently achieved the highest positional accuracy, making it suitable for precision engineering surveys and control establishment. UAV RTK provided efficient large-area mapping capabilities, while SLAM RTK demonstrated effective performance in obstructed environments where GNSS observations and UAV operations were limited.

The findings indicate that no single technology is optimal for all environments. Therefore, technology selection should consider required accuracy, environmental conditions, accessibility, and operational requirements. Future research should investigate performance in mountainous terrain and explore advanced sensor integration techniques to further improve positioning reliability.

6. REFERENCES

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