Accuracy Assessment of RTK, PPK, and PPP-AR Techniques for Direct Georeferencing in UAV-Based Photogrammetric Mapping

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Abstract

In the fields of mapping, surveying, and three-dimensional (3D) modeling, unmanned aerial vehicle (UAV) systems have become essential equipment in recent times. UAVs are increasingly widely used, especially in the field of photogrammetry. The integration of technologies such as digital cameras, inertial measurement unit (IMU), and Global Navigation Satellite System (GNSS) has improved the quality and accuracy of photogrammetric products. In comparison to conventional methodologies, UAVs present a cost-effective alternative to traditional aerial photogrammetry. Recent advancements in technology substantiate their efficacy across a variety of applications. The utilization of direct georeferencing minimizes the reliance on ground control points (GCP). With the advancements in positioning techniques, the accuracy of the products is concurrently improving. Real-Time Kinematic (RTK) and Post-Processed Kinematic (PPK) techniques play a critical role in enhancing the accuracy of UAV-based photogrammetry. Both techniques are widely used in UAV-based photogrammetry. However, relative positioning poses limitations to the study in terms of infrastructure and cost. PPP (Precise Point Positioning), a specific form of absolute positioning, is utilized effectively across various applications. The PPP method, used globally with a single GNSS receiver, is more cost-effective than relative methods. In this study, the performance of the PPP-AR technique as an alternative to the relative methods RTK and PPK is evaluated. Thus, the applicability of the PPP technique, which has improved accuracy and precision with ambiguity resolution, in UAV-based photogrammetry is examined. RTK and PPK techniques achieve Root Mean Square Error (RMSE) values of less than 10 centimeters. In contrast, RMSE values at the decimeter level are observed in the PPP-AR technique.

1. Introduction

Unmanned Aerial Vehicles (UAVs) are an innovative technology utilized to collect geospatial data that makes it possible to map topography and infrastructure effectively. The capability to access remote and hard-to-reach areas, coupled with the ability to ascend to varying altitudes, enables UAV surveying to efficiently and accurately collect detailed, up-to-date data. This methodology facilitates a comprehensive examination of the various factors that define the environment, enabling the development of a detailed knowledge of the subject under study. Moreover, these devices can be equipped with a range of sensors to capture various types of information effectively. Commonly used sensors consist of high-resolution cameras, LiDAR (Light Detection and Ranging), thermal imaging devices, Inertial Measurement Units (IMU), multi-spectral sensors, and Global Navigation Satellite Systems (GNSS). By combining data from these various sensors, it is possible to obtain a thorough understanding of the surveyed region, which improves spatial planning, aids in natural resource management and structural monitoring, along with a wide array of other applications (Akbar et al., 2019; Mishra and Rai, 2021; Skondras et al., 2022).

In particular, UAVs have become increasingly important in remote sensing and photogrammetry research (Feng et al., 2015; Dönmez and Tunc, 2016; Šašak et al., 2019; Duran et al., 2021; Biyik et al., 2023; Atik and Arkali, 2025). UAVs play an essential role in the creation of high-accuracy products, including digital elevation models (DEMs), maps, orthophotos, and point clouds. These products are used effectively for different applications in various fields. Compared to terrestrial surveying techniques, UAV technology allows for the rapid and effective production of these products over large areas per unit of time. In aerial photogrammetry, there exist two methodologies for georeferencing: direct and indirect (Gabrlik et al., 2018). In direct georeferencing, lightweight GNSS receivers and IMUs for UAVs allow direct georeferencing of aerial imagery, reducing the need for ground control points. The technique uses feature-based computer vision algorithms for position and attitude refinement, necessitating precise calibration of the onboard sensors, especially for lever arm compensation and time synchronization. The methodology that utilises ground control points (GCPs) to aid in the georeferencing of aerial images is known as indirect georeferencing. Traditional georeferencing with GCPs ensures reliable positioning, but its geometrical accuracy depends on the number and spatial distribution of the GCPs, limiting time and cost efficiency. Considering the critical factors of cost and labour that influence the study's performance, the favour of direct georeferencing methods has increased in recent years. In UAV-based photogrammetry, positioning is a fundamental component of the spatial data. Improvements in GNSS positioning techniques integrated into UAV technology have especially increased the accuracy of photogrammetric products. During flight, GNSS offers consistent and accurate position information. The utilization of GNSS enables the precise correction of camera positions during the time of capture with centimeter-level accuracy, thereby reducing the necessity for GCPs in the georeferencing process of the photogrammetric model (Martínez-Carricondo et al., 2023). Direct georeferencing using GNSS offers an effective solution to the challenges of establishing ground control points in UAV-based photogrammetry, particularly in difficult and topographically complex environments. This methodology optimizes the process of data collection and significantly enhances the accuracy of mapping operations within challenging terrains. In UAV-based photogrammetry, GNSS positioning commonly employs real-time kinematic (RTK) and post-processing kinematic (PPK) techniques (Zhang et al., 2019; Štroner et al., 2021). The

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application of these techniques involves certain requirements, including infrastructure and costs. For example, the implementation of RTK positioning necessitates at least one additional GNSS receiver. Furthermore, it is essential to maintain continuous communication between the rover and the base station to receive correction data throughout the duration of the UAV flight. In PPK mode, as an alternative to RTK, all calculations required for position correction are performed after the flight using global navigation satellite system (GNSS) data (Eker et al., 2021). The baseline between the base and the rover limits both positioning techniques. Therefore, it may not be possible to apply these techniques in UAV-based photogrammetry studies carried out in places beyond this baseline.

In recent years, the Precise Point Positioning (PPP) technique, which is absolute positioning, has been used in UAV-based photogrammetry as an alternative to relative positioning techniques such as RTK and PPP (Kim et al., 2023; Makineci et al., 2024). The PPP technique utilizes data from a single receiver collected in single or multifrequency GNSS to determine the 3D coordinates, precise orbit and clock products, and code/phase biases in post-processing or real-time. The implementation of a single GNSS receiver not only reduces costs but also minimizes the infrastructure requirements associated with reference stations. This study investigated the potential of the PPP method as an alternative in situations where the application of RTK and PPK methods is not feasible. In addition, it examined the contribution of ambiguity resolution in the PPP technique to the position accuracy in the photogrammetric study.

The known coordinates of the ground control points (GCPs) established in the field were compared with the results obtained from RTK, PPK, and PPP-AR methods. In other words, the horizontal, vertical, and 3D spatial information of the control points was analyzed. As a result, the applicability of the PPP technique as an alternative method, considering the cost, labor, and infrastructure requirements, has been investigated.

2. Material and Methods

2.1 Study Area

The study area is situated within a segment of the Istanbul Technical University Ayazaga Campus in İstanbul, Türkiye. This region encompasses a diverse landscape characterized by a combination of infrastructure, including roads and buildings, along with green spaces featuring trees and adjacent residential zones. UAV flights were carried out over a total area of roughly 10 hectares, allowing for data collection and observations. A map illustrating the specific boundaries and features of the study area is presented in Figure 1.

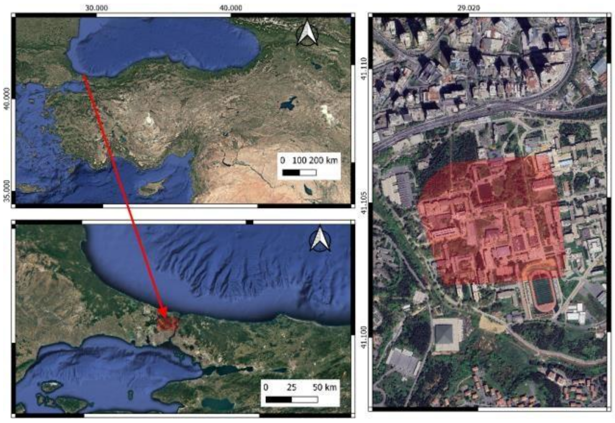

Figure 1. Study area.

2.2 Positioning Techniques

2.2.1 Real-Time Kinematik (RTK): Since the late 1990s, RTK technology utilizing GNSS has become the preferred method for surveying worldwide. This approach achieves centimetre-level precision within seconds over distances of several kilometres. RTK surveying functions through a base station that transmits correction data to rovers, which then computes the baseline between them almost immediately. The accuracy relies on the baseline length and is affected by orbital errors and atmospheric conditions. Correction data is transmitted via radio waves or satellite communications, ensuring reliable, precise results (Aykut et al., 2015).

2.2.2 Post-Processing Kinematic (PPK): PPK positioning is a relative positioning technique commonly used in UAV-based photogrammetry (Türk et al., 2022). This method requires at least two GNSS receivers: a stationary reference station (base station) and a mobile rover. PPK operates by post-processing the gathered data, eliminating the need for real-time corrections. Access to precise ephemeris and clock products for GNSS satellites during post-processing improves the accuracy of positioning solutions.

2.2.3 Precise Point Positioning (PPP): The PPP technique is a type of absolute positioning that does not depend on infrastructure, network, or additional GNSS receivers. The PPP technique was established through Anderle's publication (Anderle, 1976). The background theory of PPP was initially presented by Zumberge et al. in 1997 (Zumberge et al., 1997). The main PPP technique and correction models were developed by Héroux and Kouba using the International GNSS Service's (IGS) precise orbit and clock products (Héroux and Kouba, 2001). The PPP technique has the capability to consistently attain accurate 3D point positioning at the cm- to dm-level, demonstrating effectiveness, efficiency, and cost-effectiveness (Alkan et al., 2024). The PPP technique has been widely used in a variety of fields, including atmospheric investigations (Li et al., 2024), seismic activity (Jin and Su, 2019), and structure health monitoring (Ju et al., 2022).

2.3 Data Acquisition Processing Strategy

In the study, two flights were executed within the study area at a flight altitude of 70 meters and a speed of 15 meters per second, employing a DJI Mavic 3E UAV. RTK positioning was implemented during the first flight and was not activated during the second flight. In both missions, GNSS data were acquired at intervals of 0.2 seconds. A total of 1,053 images have been

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collected, consisting of 529 images acquired in RTK mode and 524 images captured in non-RTK mode.

Equipment	Category	Specification
UAV	Model	DJI Mavic 3E
	Speed	15 m/s
	Altitude	70 m
	Data interval	0.2 second
	GNSS	G+ R+E+C
	Max Takeoff Weight	1050 g

Table 1. Flight specifications.

The work planning was conducted in accordance with the process illustrated in Figure 2. Each step is complementary until the final product is obtained.

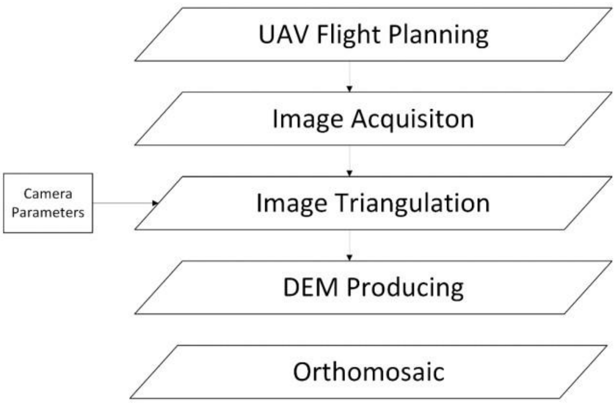

Figure 2. Workflow of study.

The RTK processing was conducted utilizing the correction data obtained from the ISKI-UKBS network. The UAV completed the process connected to the internet throughout the flight with RTK active.

The Rinex data obtained from the non-RTK flight was used for PPK. PPK technology effectively addresses limitations related to temporary signal interruptions and coverage gaps caused by distance from the base. The PPK method was performed in the Redtoolbox program. A trial version of Redtoolbox, a commercial software, was used. ISTA, included in the IGS network, was used as the base station. ISTA station is located within the study area. Precision orbit and clock products were used in the PPK technique.

PPP-AR (Precise Point Positioning with Ambiguity Resolution) is an advanced technique that enhances the speed and accuracy of position determination over conventional PPP by resolving carrier phase ambiguities in GNSS signals. PPP-AR enhances GPS positioning by mitigating equipment delays, improving accuracy, reducing convergence time, and stabilizing solutions in kinematic PPP studies (Ocalan et al., 2022). Ambiguity resolution for the PPP technique was undertaken utilizing the web-based Canadian Spatial Reference System-Precise Point Positioning Service (CSRS-PPP) software. This service is provided by Natural Resources Canada's (NRCan) Geodetic Survey Division. The CSRS-PPP service was introduced in 2003 (Mireault et al., 2008). GNSS users can upload field data to NRCan and receive accurate position estimates, quality assessments, and a visual control report within minutes. Clock corrections, equipment delay bias estimations, precise satellite orbits, and Earth orientation parameters obtained from a global network of GNSS receivers are all used by CSRS-PPP to calculate user's accurate position (Banville et al., 2021). This software analyzed the Rinex data obtained from the non-RTK flight in a kinematic mode. Position information was obtained according to each epoch.
The positioning techniques mentioned above were employed to ascertain the coordinates of the camera center. The operational principles of these techniques directly impact the precision of the resulting photogrammetric products.

In the study area, a total of nine control points were utilised where photogrammetric results were applied (Figure 3).

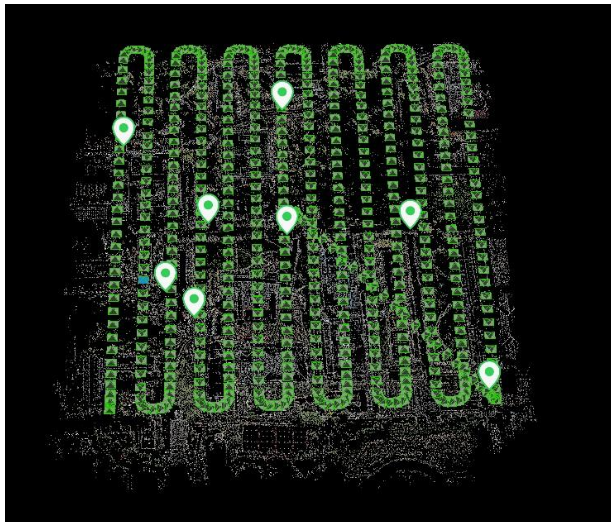

Figure 3. Check points distribution in study area.

3. Results and Discussion

In the UAV-based photogrammetric study conducted at the Ayaza Campus of Istanbul Technical University. This study evaluates the impact of different positioning techniques on the accuracy of photogrammetric products derived from UAVs. Relative positioning-based RTK, PPK and absolute positioningbased PPP-AR techniques are used in the application. These methods were implemented to ensure precise geospatial data collection and mapping of the selected study area, enhancing the accuracy and reliability of the gathered imagery and measurements. The Structure from Motion (SfM) technique was used with the DJI Terra program to generate a DEM and a georeferenced orthomosaic (Figure 4, Figure 5).

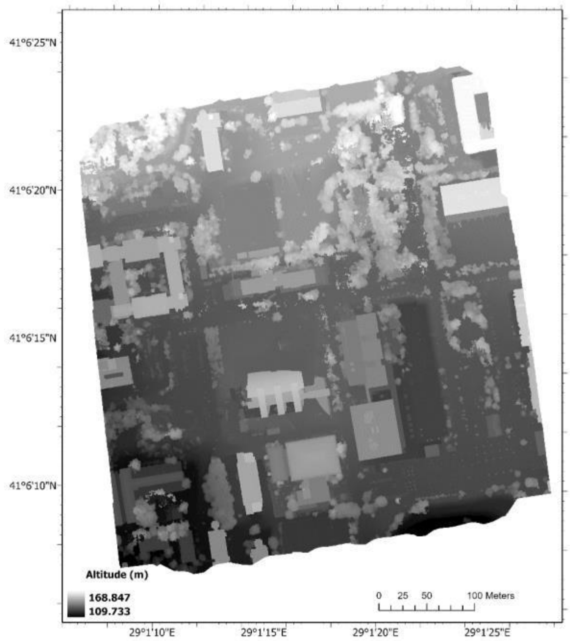

Figure 4. DEM of the study area.

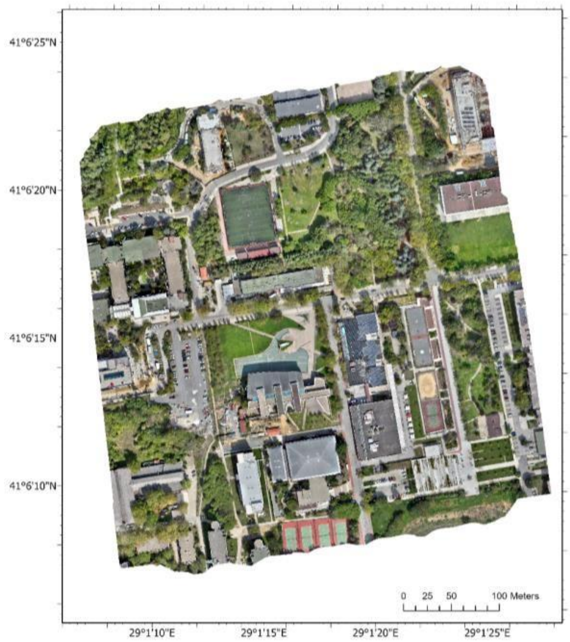

Figure 5. Orthomosaic of the study area.

The root mean square error (RMSE) analysis is the most widely used statistical technique for assessing accuracy. The root mean squared error (RMSE) for each positioning technique has been calculated across horizontal, vertical, and three-dimensional components. This approach assesses the variation between ground points that have established coordinates (χ_G) and those derived from the orthomosaic or 3D model (χ_M).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(\chi_{M_i} - \chi_{G_i})}{n-1}} \qquad (1)$$

Table 1 shows the RMSE values for various techniques. According to Table 1, the RMSE values of positioning techniques are all sub-metre values. The RMSE of the horizontal component is 0.037 m for the RTK technique, 0.035 m for the PPP technique, and 0.629 m for the PPP-AR technique. The values for the vertical component error are 0.075 m and 0.071 m for RTK and PPK, respectively. For PPP-AR, this value was calculated to be 0.659 m. As a result of all three techniques, the vertical component has a more significant error result than the horizontal component. The RMSE values for the 3D component were calculated at 0.84 m for RTK and 0.079 m for PPK. As a result of the analyses performed with PPP-AR, this value was found to be 0.911.

Method	RMSE (m)		
	Horizontal	Vertical	Total
RTK	0.037	0.075	0.084
PPK	0.035	0.071	0.079
PPP-AR	0.629	0.659	0.911

Table 1. RMSE errors of the check points.

The RMSE values calculated by relative positioning techniques are at the cm level for each component, but this is not the case for PPP-AR. PPK showed better performance than RTK. Relative positioning is generally observed to have better performance compared to absolute positioning. In relative positioning, the position is determined by taking the differences between two or more receivers (e.g., a base station and a mobile receiver).

Consequently, systematic errors such as atmospheric errors (ionosphere and troposphere delays), satellite clock errors, and satellite orbit errors are essentially eliminated.

The PPP-AR technique produced dm-level results for all three components. To achieve centimeter-level positioning precision, the conventional float PPP requires an initialization time of over thirty minutes (Li et al., 2018). PPP-AR may improve the precision of positioning and reduce the convergence time. However, in roughly ten minutes, precision in the study was below what was expected.

4. Conclusion

The effectiveness of UAVs in the domain of photogrammetric studies has been demonstrating a significant upward trend in recent times. The advanced solutions offered by UAV enable a more extensive area to be scanned in a reduced timeframe when compared to conventional measurements. This efficiency not only enhances productivity but also allows for more thorough data collection and analysis, contributing to overall project effectiveness. A review of the literature indicates that unmanned aerial vehicles (UAVs) have been increasingly employed in recent years for the production of high-accuracy products across various fields.

Through direct georeferencing, the number of ground control points (GCPs), which is a crucial aspect of fieldwork, can be minimized. In UAV-based photogrammetry, GNSS positioning techniques can produce cm-level products. In this study, relative positioning techniques provided cm-level results. In the analysis of kinematic GNSS data, the principle of relative positioning necessitates the use of a GNSS receiver (base) with known coordinates to function as a reference station. Previous research indicates that the cost and workforce requirements associated with the relative positioning techniques can impose limitations on photogrammetric studies. In applications utilizing UAV-based photogrammetry, the use of absolute positioning methods is increasingly popular due to the advantages it offers in time efficiency, cost savings, accuracy, and reductions in labor.

However, employing the PPP technique using a single GNSS receiver can enhance the efficiency of these studies. Furthermore, this approach facilitates project execution in challenging and rugged terrains without the dependence on ground control points. Furthermore, Rinex data collected by GNSS can be analyzed using the PPP method in web-based or open-source data processing software. This analysis does not require advanced GNSS knowledge from the user.

The analysis of the absolute positioning-based PPP-AR technique shows that the error remains at the decimetre level in all three components.

The products derived from the precise positional data obtained through ambiguity resolution utilizing the PPP technique have the potential to contribute significantly to future interdisciplinary studies.

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