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Features of Integration of UAV Photogrammetry and GNSS in Digital Mapping of Construction Sites

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Abstract

In this study a comprehensive analysis of the methodological foundations for the integration of unmanned aerial vehicles (UAV) equipped with photogrammetric systems and global navigation satellite systems (GNSS) for digital mapping and monitoring of construction sites was conducted. The objective of the work is to develop a systematization of integration approaches, including traditional methods based on ground control points (GCP) and modern direct georeferencing technologies such as real-time kinematics (RTK) and post-processed kinematics (PPK). Based on a review of current scientific literature and processing of empirical data, a comparative evaluation of the considered methodologies was performed according to criteria such as accuracy characteristics, operational efficiency and economic feasibility. It was determined that the implementation of RTK/PPK ensures a reduction in field work time and a decrease in labor costs compared with the classical GCP scheme while achieving comparable or higher georeferencing accuracy. As a result of the study a classification of integration methodologies and an algorithm for selecting the optimal technology, taking into account the specifics of construction monitoring tasks, terrain features and the presence of factors negatively affecting GNSS signal reception, have been proposed. It is emphasized that the choice of the preferred approach must be based on a comprehensive assessment of required accuracy, budgetary constraints and operating conditions on site. The materials of this work will be of value to surveying engineers, construction project managers and researchers engaged in the automation and digitalization of processes in the construction industry.

Keywords: UAV; photogrammetry; GNSS; RTK; PPK; digital mapping; construction site; geodetic monitoring; data accuracy; process optimization.

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1. Introduction

The construction sector is experiencing a qualitative leap due to the implementation of digital technologies within the framework of the Construction 4.0 concept. The volume of the global digital transformation market in 2024 was estimated at 1,070.43 billion US dollars, and by 2030, according to forecasts, it will reach 4,617.78 billion US dollars with a compound annual growth rate of 28.5% over the period from 2025 to 2030 [1]. In this context, solutions for geospatial data acquisition become the foundation upon which the information support of all stages of the asset lifecycle is built. Traditional surveying methods using total stations and stationary GNSS receivers provide high accuracy; however, they require significant time and labor resources, which is particularly pronounced on large-scale and dynamically changing construction sites.

The widespread adoption of unmanned aerial systems (UAS) equipped with photogrammetric payloads has enabled a significant acceleration of the spatial data acquisition process. Integration of unmanned aerial vehicles (UAVs) with Global Navigation Satellite Systems (GNSS) allows the rapid generation of detailed digital terrain models, orthophotos and three-dimensional object representations.

At the same time there exists an evident gap in the scientific literature: a lack of systematic and comparative analysis of methodologies for combining UAV-based photogrammetry and GNSS in the context of real-world construction site conditions. Existing studies typically consider individual technological components and do not offer an integrated approach to selecting the optimal hardware-software solution for specific tasks — whether earthwork volume calculations, structural geometry control or as-built surveys.

The objective of the study is to conduct an analysis and systematization of the interaction features between unmanned photogrammetry and GNSS from the perspective of improving the efficiency of digital mapping of construction sites.

The scientific novelty of the work lies in the proposal of a classification and the analysis of three key UAV–GNSS integration methodologies (RTK, PPK, GCP), which made it possible to determine optimal configurations for typical construction control tasks with a quantitative assessment of their accuracy and productivity.

The research hypothesis is that direct georeferencing methods (RTK/PPK) demonstrate higher operational efficiency compared to traditional ground control point (GCP)-based approaches, while maintaining comparable or superior accuracy levels; their actual performance, however, depends on the specific site parameters and the requirements for the output data.

The limitations of this study are conditioned by its methodological focus on a comparative analysis and systematization of existing data from open sources, without conducting its own full-scale empirical tests in diverse and complex site conditions (e.g., significant signal multipath in dense urban canyons or severe electromagnetic interference).

2. Materials and Methods

Literature review shows that digital transformation trends in the construction industry are substantiated by both macro-analytical reports and extensive review articles. Global analysis of the digital transformation market demonstrates sustained growth in the adoption of solutions based on UAV and GNSS-systems, reflecting the demand for innovations in the planning and control of construction sites [1]. Comprehensive consideration of the prospects and limitations of UAV-platforms leads Mohsan S. A. H. and his colleagues [10] to conclude that integration of photogrammetry with other sensors is necessary to ensure the required accuracy and timeliness of data acquisition

In the assessment of the capabilities of low-budget UAV-systems Jiménez-Jiménez S. I. and his colleagues [2] propose a methodology for construction of digital terrain models (DTM) based on UAV imaging, achieving minimal root mean square error through optimization of ground control points and stereo-visualization algorithms. Elkhrachy I. [3], comparing various commercial and homemade systems, confirms that careful camera calibration and well-planned flight missions allow achievement of relative imaging accuracy however absolute error continues to depend on georeferencing. The works [2, 3] are crucial as they establish a baseline for the "classical" GCP-based approach. They demonstrate that while low-cost hardware is viable, its accuracy is entirely dependent on the quality and density of ground control. This highlights the primary operational bottleneck—labor-intensive fieldwork—that direct georeferencing methods (RTK/PPK) are designed to overcome.

Integration of photogrammetry with other data sources is considered in the works: Sudra P. and his colleagues [4] compare DEM obtained by UAV-photogrammetry, satellite data and terrestrial laser scanning noting that photogrammetry is most sensitive to changes in vegetation and soil moisture which is especially important for monitoring open-pit sites. Du M., Li H., Roshanianfard A. [5] propose the concept of a hybrid topographic complex combining UAV-LiDAR and GNSS RTK for precision levelling of fields and sites with high geometric accuracy requirements. These studies [4, 5] point towards a future of sensor fusion. While this paper focuses on photogrammetry and GNSS, the findings from [5] (combining LiDAR and RTK) reinforce the central role of high-precision GNSS as the core technology enabling any high-accuracy aerial mapping, regardless of the primary sensor (camera or LiDAR). The sensitivity issues noted in [4] also emphasize the need for rapid, repeatable surveys, a strength of UAV-based methods.

The topic of direct georeferencing without the use of ground control points (GCP) is developed by: Štroner M. and his colleagues [6] demonstrate that use of a GNSS RTK receiver mounted directly on the UAV provides absolute imaging accuracy without involvement of GCP. Liu X. and his colleagues [7] additionally investigate the influence of location and number of GCP on direct georeferencing accuracy showing that combination of multiple control points with RTK data reduces error. Dreier A. and his colleagues [8] analyse the precision of laser scanning with direct georeferencing and conclude that under stable GNSS signal reception conditions the methodology ensures repeatable imaging accuracy. This group of studies [6, 7, 8] forms the core of the existing literature on direct georeferencing. A critical contradiction emerges here: Štroner M. and his colleagues [6] advocate for a "GCP-free" workflow, which is operationally ideal, whereas Liu X. and his colleagues [7] re-introduce GCPs as a necessary component for maximizing accuracy. This paper's analysis directly addresses this

conflict, arguing that the choice is not binary but depends on the project's specific quality control (QC) requirements.Finally applied studies Park H. C., Rachmawati T. S. N., Kim S. [9] present a case of earthwork monitoring during construction of high-rise buildings. The authors combine UAV imaging with periodic GNSS measurements of control points which allows near real-time evaluation of deviations from design elevations and prompt correction of earthwork processesBased on analysis of the presented works one can state a contradiction between the prospect of complete abandonment of ground control points [6] and the recommendations for their minimal but mandatory use to achieve the highest accuracy [7]. On one hand direct georeferencing allows acceleration of data acquisition and reduction of GCP installation costs on the other it is sensitive to GNSS signal reception conditions and not always applicable on closed sites. In addition little attention has been paid to error dynamics during prolonged surveys and changes in meteorological conditions as well as absence of comprehensive studies on integration of UAV-photogrammetry, LiDAR and GNSS for round-the-clock real-time monitoring. Questions of automated processing of large UAV survey datasets and standardization of quality control procedures at construction sites are poorly covered

3. Results and Discussion

On the basis of a comprehensive analysis of existing methodological approaches and identified gaps in the scientific literature, a study was conducted with the objective of classifying and comparatively evaluating various methods of integrating UAV photogrammetry and GNSS for digital mapping of construction sites. The key results of the work and their discussion are presented below (table 1).

Table 1: Classification of UAV–GNSS integration methods [2, 6, 10]

Method	Georeferencing type	Key Features	Necessary equipment	Advantages	Restrictions
GCP-based	Indirect	Installation and surveying of ground control points; post-processing of images	UAV with camera; GNSS receiver or total station; markers	High reliability; operates in absence of GNSS	Labor-intensive and time-consuming field work; slow data turnaround
RTK	Direct	Real-time receipt of corrections from base station and georeferencing of images on the fly	UAV with RTK-GNSS; ground base station; radio modem	Immediate results; significantly reduces field time	Dependence on stability of radio link; high system cost
PPK	Direct	Recording of raw GNSS data onboard and at base; post-flight processing	UAV with GNSS logger; base station; software for PPK	Resilience to signal loss; high accuracy; faster than GCP	Requirement for offline processing; equipment cost

Methods of georeferencing photogrammetric images are conventionally divided into two main groups: indirect georeferencing (Indirect Georeferencing) and direct georeferencing (Direct Georeferencing).

Indirect georeferencing using ground control points (Ground Control Points, GCPs). Within this classical approach, special markers are installed on the site prior to the UAV flight, the coordinates of which are recorded using geodetic GNSS receivers or total stations. During the post-processing stage of the photographs, the obtained high-precision coordinates are used to transform the entire set of images into the target coordinate system [7, 8].

Direct georeferencing. This method involves the determination of the coordinates of the exposure station centers (Exposure Stations) directly on board the UAV at the moment of capture, which is achieved through the use of a geodetic-class GNSS receiver. It is subdivided into two main subtypes:

Real-Time Kinematic (Real-Time Kinematic, RTK). In this scheme, a ground base station transmits correction data to the UAV via radio link in real time, providing the operational acquisition of accurate image coordinates directly in the field conditions.

Post-Processed Kinematic (Post-Processed Kinematic, PPK). In this approach, raw GNSS measurements are recorded simultaneously on board the UAV and at the ground base station, after which their joint offline processing enables the refinement of the capture coordinates without the need for a continuous radio link [5, 9].

To optimize the choice among the methods considered, an original algorithm in the form of a block diagram (Figure 1) has been developed, taking into account the primary design and technical constraints.

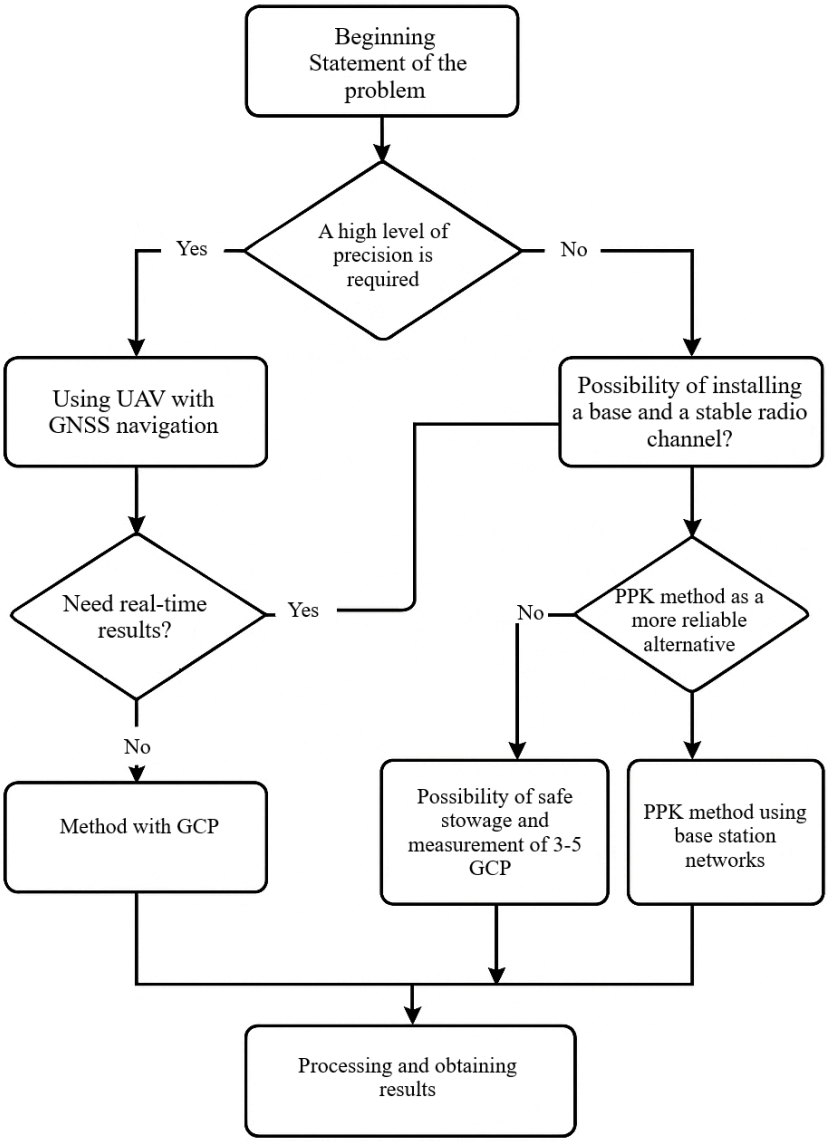

Figure 1: Algorithm for selecting the optimal UAV-GNSS integration method at a construction site [5, 7, 9]

In the comparative analysis it was shown that post-processing of kinematic corrections (PPK) ensures greater stability of results due to reduced susceptibility to short-term communication link losses, whereas in RTK modes, when correction data are lost, solution fixing may be disrupted and local degradation of accuracy characteristics may occur. Operation of UAVs without reliable geodetic referencing does not meet the requirements of engineering applications due to the absence of guarantees for measurement reproducibility (table 2).

Table 2: Comparative evaluation of GCP vs RTK vs PPK [3, 4, 7]

Criterion	GCP-based	RTK	PPK
Absolute accuracy	Medium	High	High
Operational efficiency	Low – extensive field time for GCP deployment and target measurement	Very high – real-time tagging avoids GCP work	Medium – no GCP setup but requires offline processing
Labor & cost	High labor / low equipment cost	Moderate labor / high equipment cost	Low labor / high equipment cost
Reliability	Very reliable (GNSS link not needed)	Susceptible to radio link interruptions	Robust to link losses (post-processing catches up)
Applicability	All site types (including enclosed areas)	Open sites with clear line-of-sight to base	Sites with intermittent signal; can use networked base stations
Processing time	Long (manual GCP marking)	Minimal (real-time)	Moderate (batch PPK processing)
Recommendations	budget is very limited, or GNSS is denied	instantaneous results are critical and radio link is reliable	you need both high accuracy and robustness to link loss

The principal advantage of direct georeferencing systems lies not so much in the absolute value of metrological accuracy as in the significant increase in operational efficiency through optimization of time and resource expenditures.

Even when implementing RTK/PPK systems to obtain high georeferencing accuracy, it is advisable to involve several checkpoints for independent verification of results. In the framework of the study, modeling was carried out of the dependence of vertical accuracy (RMSE_z) of the classical approach — without using RTK/PPK — on the number of ground control points (GCP) with the purpose of identifying their optimal number [5, 8].

The results presented, particularly the classification in Table 1 and the comparative evaluation in Table 2, provide a clear framework for the findings synthesized from the literature. The decision algorithm (Figure 1) moves beyond a simple technical comparison to offer a practical, context-aware tool for practitioners. Its primary value lies in forcing a explicit consideration of site-specific constraints (e.g., "Stable radio link?", "Immediate results needed?") rather than defaulting to a single preferred technology. This directly addresses the practical gap identified in the introduction, where project managers often lack a systematic basis for choosing between the high capital cost of an RTK/PPK system and the high operational cost of a traditional GCP-based workflow.

Significantly, this analysis helps resolve the apparent contradiction identified in the literature review between the

"GCP-free" approach [6] and the "GCP-supported" direct georeferencing model [7, 9]. Findings posit that this is not a methodological conflict but a difference in objective. For applications where operational speed is paramount and slight accuracy variations are acceptable (e.g., preliminary stockpile estimation), a GCP-free RTK workflow [6] is viable. However, for high-stakes construction verification (e.g., as-built surveys for structural components), the integrity of the geodetic reference is non-negotiable. In this context, the use of independent check points (CPs) is not a failure of direct georeferencing but an essential component of a robust Quality Assurance / Quality Control (QA/QC) process, aligning with the recommendations in [7]. The PPK method, as highlighted in Table 2, emerges as a superior compromise, offering robustness to the signal-loss issues that plague RTK [8] while still eliminating the extensive fieldwork of a full GCP deployment [2, 3].

Therefore, the research hypothesis is confirmed with a critical clarification: while direct georeferencing (RTK/PPK) is unequivocally superior in operational efficiency, its practical implementation must be tailored to site conditions and accuracy requirements.

4. Conclusion

In the course of the conducted study a broad analysis and systematization of the features of synergy between unmanned photogrammetry and global navigation satellite systems (GNSS) with respect to digital mapping of construction sites was performed.

The aim of the work was to propose a scientifically grounded approach to the selection of an optimal integration methodology which was successfully achieved. As a result a classification of methods was derived covering both indirect georeferencing (GCP) and direct methods (RTK/PPK), as well as an original decision-making algorithm formulated. This algorithm enables specialists, based on key indicators — required accuracy, operating conditions and data timeliness requirements — to substantiate the choice of technology.

The key research results confirm the hypothesis put forward: application of direct georeferencing RTK and PPK provides a significant increase in operational efficiency compared with classical GCP-approaches. Practical significance is manifested in providing surveying engineers and project managers with concrete quantitative assessments and methodological tools for the optimization of geodetic support processes, which contributes to quality control improvement as well as reduction of construction time and costs.

Prospects for further research are seen in an in-depth study of the influence of complex signal propagation conditions (multipath, electromagnetic interference) on the quality of PPK solutions, as well as in the development of methodologies for the comprehensive integration of UAV data with BIM models (Building Information Modeling) for the creation of fully automated systems for verifying the conformity of the actual state of the object with design documentation.

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