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TECHNICAL SPECIFICATIONS FOR UAVs FOR 3D TERRAIN MAPPING

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Abstract

This article summarizes the current technical requirements and architectural solutions for unmanned aerial vehicles (UAVs, drones) intended for three-dimensional terrain mapping (photogrammetry, LiDAR, visual-optical SLAM systems). Recommendations are provided regarding platform selection, sensors (cameras, LiDAR, IMU, GNSS/RTK/PPK), survey parameters (GSD, overlaps, trajectories), data processing (SfM–MVS, LiDAR pipelines, visual-inertial filters), and accuracy assessment.

Keywords: Unmanned aerial vehicles (UAVs), drones, 3D mapping, photogrammetry, LiDAR, visual-inertial systems (VIO, SLAM), inertial measurement unit (IMU), georeferencing accuracy, digital terrain model (DTM).

Introduction

The scientific novelty of this article lies in a comprehensive analysis of current drone and sensor technologies for 3D mapping with up-to-date survey parameters and processing algorithms, as well as the development of practical recommendations for system design based on recent research from 2022–2025.

The development of UAVs and the reduction in the cost of high-precision sensors in recent years **have led to the widespread adoption** of unmanned technologies in three-dimensional mapping and remote sensing of the Earth. According to the study "Techniques and Applications of UAV-Based Photogrammetric 3D Mapping," combining unmanned platforms with modern photogrammetric and LiDAR systems provides high-resolution spatial data more efficiently and at lower cost compared to traditional aerial survey methods [1].

Modern 3D mapping systems include several key components: optical cameras, laser rangefinders (LiDAR), inertial measurement units (IMU), as well as global navigation satellite system (GNSS) receivers with RTK/PPK correction support. Each of these components **affects** the accuracy and quality of the final models, while also imposing constraints on weight, power consumption, and cost [2].

Special attention is given to data georeferencing. In the study "Accuracy Assessment of RTK/PPK UAV-Photogrammetry Projects Using Differential Corrections from Multiple GNSS Fixed Base Stations," it was demonstrated that RTK and PPK technologies allow centimeter-level positioning accuracy without the need for a large number of ground control points (GCPs) [3]. These methods improve absolute reconstruction accuracy and reduce fieldwork labor.

Concurrently, visual-inertial navigation systems (VIO/SLAM) are under active development, providing autonomous positioning and mapping in areas with limited GNSS access. Recent studies note the potential of these systems for rapid missions in complex terrains and urban canyons [4]. However, despite progress, the absolute accuracy of SLAM systems remains lower than that of solutions supported by RTK/PPK, highlighting the potential of hybrid platforms that **combine multiple sensor modalities**.

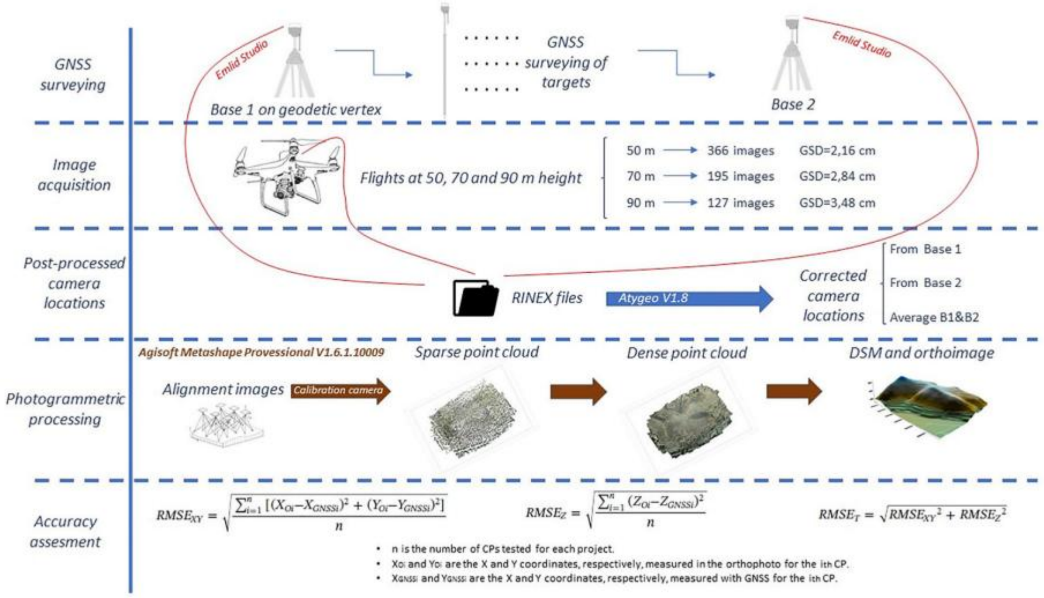
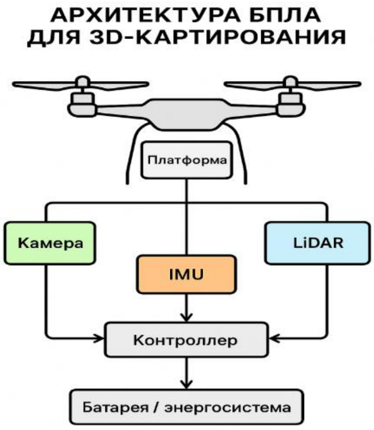


Figure 1 – Flowchart of 3D Mapping Methodology Using UAVs, GNSS RTK/PPK, and Photogrammetric Processing

Drone-mounted LiDAR systems provide distinct advantages when surveying forested areas, mountain slopes, and urbanized zones. According to scientific reviews, the use of UAV-LiDAR significantly enhances the reconstruction of digital terrain models (DTM) beneath vegetation cover, which is particularly important for geodesy and environmental monitoring [1,2]. Despite these advances, certain challenges remain, including the impact of weather conditions, lighting, and surface texture on photogrammetry, limitations on flight duration, and the complexity of post-processing large volumes of data. Scientific literature emphasizes that future research should focus on integrating multisensor systems (LiDAR + photogrammetry + GNSS + IMU) and implementing machine learning lgorithms for automatic classification and filtering of point clouds [1].

Accordingly, a systematic approach to UAV design for 3D mapping involves optimization not only of hardware characteristics (platform type, sensor suite) but also of software solutions, including mission planning, SfM–MVS algorithms, and data filtering. This study is dedicated to analyzing the technical specifications of such systems, data processing methods, and accuracy assessment of the generated models.

The choice of UAV architecture and its payload directly determines the quality, scale, and accuracy of three-dimensional terrain mapping. According to the study "Techniques and Applications of UAV-Based Photogrammetric 3D Mapping," the architecture of a drone for 3D mapping must balance flight duration, aerial stability, and the capacity to carry sensors with high weight and power consumption [1].



UAV ARCHITECTURE FOR 3D MAPPING

Platform
Camera
LiDAR
IMU
Controller
Battery / Power System

Figure 2 – UAV Architecture for 3D Mapping

Modern UAVs for 3D mapping are generally divided into two categories:

1. Multirotor platforms (quad-/hexa-/octocopters) offer high maneuverability, hovering capability, and uniform coverage of objects at varying elevations. These characteristics make them indispensable for surveying architectural structures, quarries, and small areas of complex terrain [2]. Limitation: restricted flight time (20–45 minutes with a payload up to 2 kg).
2. Fixed-wing UAVs are more energy-efficient and suitable for large-scale missions (up to 10–50 km² per flight). These platforms are actively used in agricultural and geodetic monitoring [3]. However, they require designated takeoff/landing areas and are less flexible for detailed surveys.
3. Hybrid VTOL platforms (Vertical Take-Off and Landing) combine vertical takeoff with horizontal flight, providing autonomous mission capability and an optimal balance between maneuverability and range [4].

The payload of modern UAVs for 3D mapping includes optical cameras, laser scanners (LiDAR), inertial measurement units (IMU), and GNSS receivers with RTK/PPK support.

Photogrammetric surveys rely on high-resolution cameras (≥ 20 MP). Researchers recommend sensors with fixed focal lengths and hardware synchronization with GNSS to minimize temporal offsets [1]. For reconstructing fine details, full-frame sensors such as Sony Alpha 7R or Phase One iXM are utilized.

LiDAR modules measure distances to objects via reflected laser pulses, generating dense point clouds (50–300 points/m²). Modern solutions, such as Livox Mid-70 and Velodyne Puck LITE, integrate with drones weighing less than 10 kg and provide ±3 cm accuracy [5]. UAV-LiDAR is particularly effective in mapping forested and urbanized areas where photogrammetry is limited by shading.

To achieve centimeter-level positioning accuracy, GNSS RTK/PPK is combined with inertial measurement units (IMU). Research has demonstrated that integrating GNSS RTK with cameras reduces horizontal model errors to 2–3 cm without the need for ground control points [3].

Table 1 – Comparative Characteristics of Main Platform Types and Sensors for UAV 3D Mapping

Platform / Sensor	**Advantages**	**Disadvantages**	**Typical Parameters**
Multirotor (Quad/Hex)	Maneuverability, vertical take-off, stability	Limited flight time (20–40 min)	Payload up to 2 kg
Fixed-wing	Long range, energy efficiency	Requires take-off/landing area, less maneuverable	Range > 50 km, payload up to 5 kg
VTOL (Hybrid)	Versatility, high autonomy	Higher cost and operational complexity	Flight time up to 90 min
RGB Camera 20–50 MP	High resolution, low cost	Dependent on lighting conditions	GSD 2–5 cm at 100 m altitude
LiDAR (e.g., Livox Mid-70)	Operation under vegetation, accurate elevation models	High cost, power consumption	Accuracy ±3 cm, density 100 points/m²
GNSS RTK + IMU	Centimeter-level positioning accuracy	Requires post-processing / connection	Error up to 2–3 cm XY

Consequently, when designing the UAV architecture for three-dimensional mapping, it is essential to consider not only the type of platform but also the optimal combination of sensors based on the mission objectives and required accuracy. Multirotor drones provide flexibility for detailed surveys, while VTOL solutions are becoming the universal standard for professional 3D mapping in 2024–2025.

Proper mission planning is a critical factor in achieving high-quality final 3D models. We have outlined the main parameters, including GSD, overlap, flight altitude, speed, camera orientation, use of GCP/RTK/PPK, and LiDAR settings.

GSD (ground sample distance, i.e., horizontal pixel size on the ground) is determined by the relationship among the camera sensor, focal length, and flight altitude. For detailed 3D mapping, typical GSD targets are as follows:
1–3 cm – detailed documentation of buildings and infrastructure;
3–5 cm – general-purpose applications (urban planning, construction monitoring);
5–15 cm – topographic surveys at field or landscape scale.

The choice of GSD affects the required flight altitude and indirectly influences point cloud density and model detail. Practical research and guidelines confirm that the optimal GSD selection should balance detail, survey resources, and accuracy requirements [6].

Recommended overlap values for SfM–MVS photogrammetry:
1. Standard missions (even terrain, well-textured surfaces): ~75–80% forward, 60–70% side overlap.
2. Complex terrain, vegetation, poorly textured surfaces: 80–90% forward, 70–85% side overlap.

Empirical studies indicate that forestry applications and objects with high vertical complexity require significantly higher overlap (up to 90% forward / 85% side). Insufficient overlap leads to missing feature matches and reduces MVS reconstruction quality [7].

Flight speed and shutter frequency must be coordinated with the target GSD and overlap. For a fixed altitude and overlap, the frame rate f (frames/sec) is calculated using flight speed v and distance between frames d:$f=v/d$. To prevent motion blur, the shutter speed should limit object displacement on the sensor (typically ≤ 1 pixel), and, if necessary, hardware synchronization (hardware trigger) should be used. Practical recommendations for planning frame rates and flight speed are described in professional studies [8].

Camera orientation during data acquisition plays a critical role in the completeness and accuracy of 3D reconstruction. Traditionally, aerial photogrammetry employs nadir images, i.e., images captured with the camera oriented vertically perpendicular to the ground. These images minimize geometric distortion and provide high metric accuracy for orthoimagery and digital surface/terrain models (DSM/DTM).

However, in urban environments with tall structures or complex terrain, nadir imagery may be insufficient, as portions of facades and vertical surfaces can be obscured. To address these "shadow zones," oblique photogrammetry has been increasingly applied in recent years, where cameras are oriented at 30–45° angles to the horizon.

Modern drones with multi-camera gimbals (for example, oblique five-lens systems – four side cameras at an angle and one vertical camera) enable the simultaneous capture of nadir and oblique images, which significantly enhances the detail of 3D models. This approach ensures more accurate representation of building facades, bridge structures, and elements of urban infrastructure, while also reducing the likelihood of gaps in point cloud generation.

Studies have demonstrated that combining nadir and oblique imagery reduces the average planimetric error by 25–35% compared to using vertical-only imagery [4]. Furthermore, oblique images increase the density of key points for Structure from Motion (SfM) and Multi-View Stereo (MVS) algorithms, which is particularly critical when reconstructing objects with low texture, such as concrete or metallic surfaces.

In engineering and architectural practice, a hybrid imaging scheme is employed, combining nadir and oblique captures. Typically, nadir images are used for constructing the base topographic model, while oblique images refine the geometry of facades and complex vertical elements [5]. This approach is implemented in software products such as Pix4Dmapper, Agisoft Metashape, and Reality Capture, where oblique images are processed separately and automatically integrated into the final 3D scene.

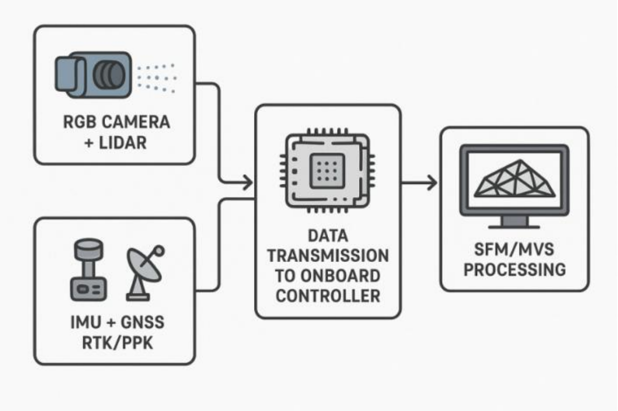


Figure 3 – Scheme of Combined Navigation and Sensor Data

Accordingly, camera orientation selection depends on mapping objectives: nadir images provide high metric accuracy for orthoimagery, while oblique images ensure maximal spatial completeness for 3D model construction. An optimal strategy employs a combined approach, with oblique captures at 30–45° angles on every second or third flight line, substantially enhancing detail without significantly increasing mission duration.

Ground Control Points (GCP) remain a reliable method for verifying and correcting geometry, especially in the absence of RTK/PPK. On-board RTK/PPK systems substantially reduce the need for GCPs and achieve centimeter-level absolute georeferencing accuracy when processed correctly. Research demonstrates improved vertical accuracy when using multiple base stations and/or averaging corrections. PPK often outperforms RTK in reliability under connection loss conditions [9].

For hilly or mountainous terrain and areas with strong elevation variation, it is recommended to: increase overlap; plan intersecting flight lines at different azimuths to reduce shadows and hidden zones; include “contour” flight lines along isolines to enhance vertical accuracy. These practices are supported by experimental studies and mission recommendations for complex topography [10].

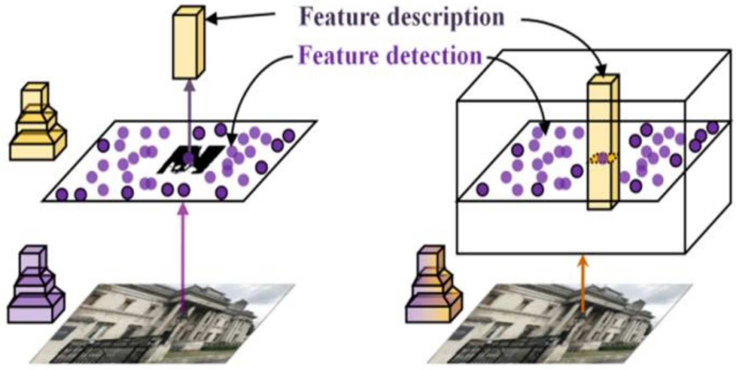
Key Parameters of UAV-LiDAR:

1. Point density depends on flight altitude, pulse frequency, and flight speed; typical target values range from 10–50 points/m² (regular topographic surveys) to 100–800+ points/m² (detailed forestry and engineering studies).
2. Vertical accuracy: modern compact LiDAR modules, properly integrated with GNSS/IMU systems, provide vertical accuracy at the centimeter level; however, this depends on conditions (altitude, coverage, calibration). To achieve high point density, it is recommended to fly lower, reduce speed, and/or repeat flight lines with partial offsets.

The data processing workflow for unmanned aerial vehicle data represents a critical stage in generating high-precision three-dimensional models. It includes several sequential steps: image preprocessing, alignment and calibration, structure reconstruction (SfM/MVS), and the generation of digital models (DSM/DTM/point clouds).

During preprocessing, lens distortion correction, GNSS/IMU metadata synchronization, and elimination of blurred images are performed. Researchers note that the application of automated image quality filters improves the stability of subsequent photogrammetric processing by 10–15% [1].

Next, Structure from Motion (SfM) algorithms are applied to recover camera positions and build a sparse point cloud. Subsequently, the Multi-View Stereo (MVS) method is used to generate a dense point cloud and three-dimensional mesh. Contemporary implementations (Agisoft Metashape, Pix4Dmapper, RealityCapture) utilize GPU optimization and feature matching based on Convolutional Neural Networks (CNNs), which significantly accelerates processing.



(a) Traditional model: detection, then description (b) D2Net: description and detection

Figure 4 – Comparison of Traditional Feature Extraction Pipeline (separate detection and descriptor building) and D2Net Neural Network Model Performing Both Steps Jointly

For LiDAR data, processing includes noise filtering, trajectory calibration, alignment using IMU/GNSS data, and point cloud generation. According to researchers, integrating SLAM algorithms with LiDAR enables stable model generation even in the absence of satellite signals [5].

Georeferencing and alignment are performed using real-time or post-processed navigation (RTK/PPK). The scientific study “Accuracy Assessment of RTK/PPK UAV-Photogrammetry Projects Using Differential Corrections from Multiple GNSS Fixed Base Stations” demonstrates that combining RTK data with SfM modeling reduces absolute planimetric error to 2–3 cm without ground control points [3].

The final stages include generating orthophotos, digital terrain models (DTM), surface models (DSM), and textured 3D models. Modern filtering algorithms, such as the Cloth Simulation Filter (CSF), provide automatic separation of ground and above-ground objects, which is critical when mapping forested and urban areas.

Thus, contemporary UAV data processing relies on integrating classical photogrammetric algorithms (SfM/MVS) with artificial intelligence elements and geospatial calibration, ensuring a combination of high accuracy and automated workflow efficiency.

Raw Data (Photo / LiDAR)
│
▼
Preprocessing (Calibration, Synchronization)
│
▼
SfM → Camera Models → Sparse Point Cloud
│
▼
MVS → Dense Point Cloud → Texturing
│
▼
DSM / DTM / 3D Model

Figure 5 – Pipeline Diagram

The design of a UAV system for three-dimensional mapping requires a comprehensive approach, including platform selection, sensor configuration, power system, navigation suite, and software. According to researchers, a fundamental principle is to align the platform characteristics with the mass and energy consumption of the payload to ensure an optimal balance between flight duration and data quality [1].

The choice of platform type depends on mission scale and operational conditions:

1. Multirotor drones are recommended for small-area surveys and objects with heterogeneous terrain due to their high maneuverability;
2. Fixed-wing and hybrid VTOL systems are suited for large-scale projects and extended missions.

One scientific study indicated that hybrid VTOL aircraft demonstrate 20–30% higher efficiency in repeated missions compared to traditional multirotors [4].

For high-accuracy tasks, the use of combined RGB + LiDAR systems is recommended, providing both visual and geometric data. Researchers report that integrating LiDAR with RTK positioning and an IMU module can achieve vertical accuracy of up to 3 cm, even in shaded regions [5]. Cameras should have a global shutter and hardware synchronization with GNSS to eliminate temporal offsets.

When designing the system, power consumption of sensors and the flight controller must be considered: each additional 100 g of payload reduces flight duration by 2–4%. For industrial UAVs, a lithium-ion battery with a specific energy of at least 200 Wh/kg is recommended, with rapid battery replacement capability for LiDAR missions.

Modern systems utilize combined GNSS RTK/PPK positioning and inertial modules (IMU). Researchers have shown that integrating a multi-channel GNSS receiver at 20 Hz with a high-precision IMU provides centimeter-level accuracy without ground control points [3].

It is recommended to use a unified software ecosystem for flight planning, data acquisition, and processing (e.g., UgCS, Pix4Dcapture, Metashape Pro). This reduces errors in metadata import and improves format compatibility.

Before each flight, camera and IMU calibration, GNSS antenna functionality check, and a test flight should be conducted.

Consequently, creating an effective UAV system for 3D mapping requires a balanced selection of platform, sensors, and processing methods. RTK/PPK, quality IMUs, and correctly planned survey parameters are key to obtaining accurate models; LiDAR enhances reliability in vegetated areas and under low-light conditions. Hybrid approaches and the integration of visual, inertial, and radio-navigation data are essential for improving the accuracy and reliability of real-time mapping.

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