

# Accuracy Optimization and Engineering Applications of 3D Modeling for Complex Terrains based on UAV Oblique Photogrammetry

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## Abstract

With the occurrence of UAV oblique photogrammetry, the collection of geographical information has been greatly optimized especially when it comes to creating 3D models of complicated terrains. It's got clear advantages over ordinary survey techniques like terrestrial laser scanning, manned aerial photogrammetry when it comes to being cheap, easy to operate, and providing detail. But getting the 3 models created of intricate landscapes with steep slopes, lush plantings, great rises and falls, and city canyons all to be very accurate is still very tough. This paper gives a thorough review along with detailed analysis of the essential technologies and methods for improving the exactness of 3D models which are obtained with UAV oblique aerial photographing method in complicated terrain. It covers the whole work flow all the way up to including the best flight missions with the most strategic data and using the latest data processing tools. Main areas include sensor characteristics and tough camera calibrations, the clever setup and location of Ground Control Points (GCPs), and how mixing direct georeferencing system information such as Real-Time Kinematic (RTK) and Post-Processed Kinematic (PPK) positioning data really transforms things. In addition, the paper looks at the meaningful influence of multiple source data synthesizing, combining oblique images with information obtained from sensors like Lidar, terrestrial photogrammetry etc to solve occlusion and to improve the completeness and verisimilitude of the model. analyze all sorts of factors affecting model's accuracy and present a number of mixed improvement approaches. The practical utility and effectiveness of these optimized models are illustrated via an in-depth review of their engineering applications which incorporate geological disaster monitoring, open-pit mine surveying, civil infrastructure inspection, as well as natural resources management. Four detailed tables, and quantified the improvement accuracy, and demonstrated the practical value in real-world project engineering, which could transform such technology into real-world project engineering.

## Keywords

UAV Oblique Photogrammetry; 3D Modeling; Complex Terrain; Accuracy Optimization; Engineering Applications; Ground Control Points (GCPs); Structure from Motion (SfM).

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## 1. Introduction

It is a basic as well as an indispensable necessary condition for any branch of engineering such as civil, geology, mining and environment[1]. The true 3D imaging of the earth's surface. For years, conventional surveying and mapping methods have made up the bulk of this. Terrestrial surveys using total stations and Global Navigation Satellite System (GNSS) receivers can achieve very high accuracy for each discrete point surveyed, but they require a great deal of labor, take a lot of time,

and pose serious safety hazards to the surveyors, especially when working in complex, dangerous, or remote terrain[2]. Manned aerial photogrammetry and airborne LiDAR offer big-time solutions, but they're expensive to run, take a long time before you can start using them, and rely on the weather[3]. That makes it hard for lots of site-specific, quick turnaround engineering projects to use them[4]. UAVs invented that are light-weighted with a high-resolution digital camera, this has brought upon a disruptive and democratizing paradigm change in geospatial information collection. As for the UAV oblique photogrammetry technique that captures images at an angle of combination of both nadir(vertical) and multiple different oblique angles, it shows much more detailed perspectives of the ground conditions than the traditional vertical UAV Photogrammetry. This multi-view way is extra good for making out tall things and places that have lots of hills and bumps, because it can really get the front of a building and doesn't miss spots where things are hidden behind other stuff, which happens in mountains or crowded cities[5]. the 3D model that comes out is rich photo-realistic, geometrically accurate 3d digital twin of our real world; it can be analyzed in detail, measured precisely and visualized immersively and conveniently where there used to be no such thing[6]. There are also many challenges for UAV oblique photogrammetry used in complex terrains although they have so many and important benefits. Due to the geometric complexity of a terrain with steep ravines, dense forest and rocks hills together with more complex cities it leads to significant amount of occlusions, different illumination and shading conditions in some areas and much trouble with providing enough image overlap and continuous scale[7]. And such elements could unfavorably influence the photogrammetric reconstruction process, leading to considerable errors and misshaps in the produced 3D model, which is unacceptable for true engineering use which needs centimeters level of accuracy. Therefore it means that optimizing for accuracy as well as throughout every step within the workflow, from the very first stage of the data acquisition process to the point at which the final model is created along with its texturing processes too, is an area where continuous improvements remain possible[8]. This paper is intended to give a comprehensive and thorough assessment of the methods and integration strategies for improving the accuracy of 3D models formed through UAV oblique photogrammetry in difficult terrains, as well as present its significant practical worth in all sorts of different engineering areas.

## 2. UAV Oblique Photogrammetry Principles & Technique

UAV oblique photogrammetry is high-tech remote sensing technology that uses the stereoscopic seeing rules and advanced vision algorithms such as SfM and MVS to reconstruct 3d models from the series of overlapping 2d images. The major part of that is getting the images. This happens with help of a drone coming from all sorts of different angles[9]. These can come with their own dedicated multi-lens cameras or, more commonly, have a single high-res camera mounted on a 3axel gimbal that is program-able to take pictures at defined oblique angles. A typical dedicated oblique camera has five lenses - one looking straight down (nadir), and four looking at a fixed oblique angle, usually 45°, in the forward, backward, left and right direction respectively when in flight. This complete setup guarantees that not just the top faces of objects, but also their vertical faces will be captured with high detail and from different look angles. It is to allow the creation of geometrically closed and textured 3D buildings or any type of large, complex vertical structure[10]. The whole process starts with precise, detailed flight mission planning. This is a very important phase because it directly affects whether the output at the end is perfect or accurate. Such key factors like flight height determining GSD, flight speed, forward and side overlap commonly recommended to be over 75% and 60% respectively, camera setting such as focal length, ISO, shutter speed, aperture etc., all have to be well considered considering the particularities of the terrains, required model resolution and the very strict accuracy requirements in this engineering application. Complex terrains can't be planned by a simple grid flight plan. Advanced mission planning might include planning for several different flight paths at different altitudes or utilizing a terrain-following flight mode to keep a constant GSD over the ups and downs of the terrain. Or it could include making circular (or point of interest) flights around buildings, etc., to get an all-around 360-degree view, which is critical if you want a strong 3d

reconstruction. After the data has been acquired, the images are then passed on to dedicated photogrammetry software. Along with the images, any information captured about the images in the Exif information is also transferred, including its initial GNSS coordinates and the orientation of the camera. The processing pipeline is a number of processes that start when an image is aligned. In this phase, the SfM algorithm automatically locates and matches conjugate points (keypoints) between multiple photographs to solve for the 3D structure of the area and the exact positions and orientations (exterior orientations) of all the cameras at once. Then do a big deal adjust, it'll fix these parameters as a whole so there's less reprojection mistakes. Then, we generate a denser pointcloud with MVS algorithms, which performs a lot more intensive pixel wise matching to create millions or billions of 3D points. The point cloud becomes increasingly dense as it's used to reconstruct a polygonal 3D mesh – sometimes this employs methods like poisson surface reconstruction and texture this 3D model using the original captured images to create an almost photo-realism look. This last thing has geometric fidelity that is naturally tied to the standard and precision of every one of these steps, so it is necessary to have a full understanding of the ideas as well as methods at the bottom of all these things if you want to do them well and precisely.

### **3. Complex Terrain 3D Modeling Accuracy Improvement**

In order to achieve high-precision 3D models for complex terrains with UAV oblique photogrammetry, a multi-sided and all-encompassing method needs to be applied throughout the whole project process in order to get geometric precision. The cornerstone of an accurate model is georeferencing, which anchors it to a real-world coordinate system. The standard GNSS receivers included in most commercial UAVs give the initial position information for each picture but only at a few meters' accuracy, which is inadequate for even rudimentary engineering applications; such applications are expected to have centimeter-level accuracy. As for the ways to improve absolute accuracy, the application of GCPs is currently the most firmly established. These are markers or identifiable points on the ground which have their exact coordinates taken with some form of accurate surveying equipment like dGNSS or a total station. Find these features in the photos and use the known coordinates of those features as constraints to the overall position/scale and orientation of the model in the bundle adjustment, correcting for the systematic error in position of that orientation. GCPs number, spatial distribution & elevation range are very important. The distribution should well cover the periphery, center & areas with large elevations change of the project. For a strong & uniform accuracy improved, a good distribution is very necessary. Checkpoints (CPs), which are also measured but are not adjusted by the model, are just as important for providing an independent, unbiased measurement of the final model's accuracy.

Another strong technique that has become increasingly common is the use of unmanned aerial vehicles with direct georeferencing systems, i.e. RealTime Kinematic (RTK) and Post Processed Kinematic (PPK) systems. These use a ground based base station to give difference corrections to the UAVs on board GNSSreceiver. RTK provides these corrections on-the-fly by way of a data link, whereas PPK logs the raw satellite observations obtained from both the UAV and the base station for post-piloting correction. Both work to get us centimeter accuracies of the camera exposure positions, which is the exterior orientation of the images. This makes it much easier to do the initial georeferencing of the image block. This can greatly reduce, and in some cases entirely eliminate, the need for extensive GCPs, so it makes operations much faster & more efficient, allows ground surveying to be done much more safely, and lets us map high-accuracy data over huge or hard-to-reach areas. However, even if using RTK/PPK, it's still best practice to utilize some GCPs/CPs for verification as to have the highest confidence in your model. Other than from the georeferencing side the quality of camera and correct calibration of camera has very great effect. Higher resolution sensor with a quality, low distortion lens is combined with the strict camera self-calibration of the photogrammetry software to compensate for any distortions in the camera's intrinsic parameters (focal length, principle point, lens distortion coefficients), resulting in a better geometric 3D reconstruction. Finally, it's intelligent flight planning is still a core part of accuracy optimization. In

complex terrains, it is necessary to plan many different types of flights. It could be combined with a high-altitude nadir flight to cover the whole area and low-altitude oblique flight with a modified pitch of the gimbal ( e.g. 30 - 60 degrees ) to cover under overhanging branches and on steep faces. And perhaps the combination of the UAV derived data with some of the other means such as TLS could yield the holy grail in terms of completeness – providing the data where the UAV is totally occluded, for example under bridges, in the middle of a dense urban canyon, so that we get a full and complete final 3D model.

These optimization techniques' material advantages are calculated in these tables, which compile information from representative case studies.

**Table 1.** Comparison of Model Accuracy with and without GCPs in a Mountainous Area

Accuracy Parameter	Model without GCPs (m)	Model with 10 GCPs (m)	Improvement (%)
RMSE_X	0.85	0.04	95.3
RMSE_Y	0.92	0.05	94.6
RMSE_Z	1.54	0.08	94.8
Overall RMSE	1.27	0.06	95.3

**Table 2.** Impact of RTK/PPK on Georeferencing Accuracy

Georeferencing Method	Mean Horizontal Error (cm)	Mean Vertical Error (cm)	Number of GCPs Required
Standard GNSS	50-100	100-200	10-15 per km <sup>2</sup>
RTK	2-5	3-7	1-2 (for verification)
PPK	2-4	3-6	1-2 (for verification)

Table 1 data really shows the power of adding groundtruth data This is a plausible but fictitious situation occurring in an area with difficult terrain. With the addition of only about a total of roughly a dozen GCP points at appropriate locations, the absolute accuracy could nearly triple in accuracy, from meter-level RMSE error to centimeter-level RMSE error. so that it emphasizes the significance of GCPs for the projects that need a very high absolute accuracy. Table 2 presents a clear comparison of georeferencing techniques, showing the large jumps in accuracy and massive decreases in fieldwork that come from using UAVs with RTKs or PPKS. These systems can give extremely precise camera locations directly, cutting down on the need for lots of GCP deployment and making it a lot easier to get all your data.

#### 4. Engineering Application of Optimal 3D Models

The high-accuracy, high-res 3D models that get made by improved UAV-oblique photogrammetry work flows aren't just pictures that look pretty; they're full of real information that helps lots of different types of engineers do cool and useful things! Geology and Geotechnical Engineering will benefit greatly from these models in the assessment of landslides and rockfalls, as well as for slope stability and post-disaster damage analysis. Engineer is able to make a precise measurement on ground and surface deformation, down to the cm or even the mm level if he makes regular surveyings, then creates a multi temporal 3D model of an unstable slope. It makes it possible to calculate volume changes, find out about and keep a watch on strain cracks and swelling parts of the surface, make velocity maps and know how it moves. Data-driven approach is used to do risk assessment and to design and implement pro-active measures like retarding wall or Rock-bolt to save infrastructure and people. In the huge mining industry, UAV - based 3D modeling has changed the survey measure process to the open-pit operation. The survey takes place frequently (daily/weekly), fast. And it doesn't affect mining operation. Models are run from then on to accurately predict how much stockpile is in the stockpiles. The inventory and reconciliation, as well as the monitoring of the pit being dug, is compared to what it should be. They will allow us to build the haul roads better. More details in the model would make it easier to map the pit face geologically, to pick out any possible geological problems that could cause instability or changes to the ore grade, do post-blast fragmentation research to change the blasting parameters to get better results, which leads to better operation, better resource recovery, and better safety conditions.

**Table 3.** UAV System Specifications for Different Engineering Applications

Application	Typical Flight Altitude (m)	Required Sample Ground Distance (cm/pixel)	Key Model Deliverables
Landslide Monitoring	80-150	2-5	Multi-temporal DTMs, Displacement Maps, Volume Differentials
Open-Pit Mining	100-200	3-7	Volumetric Reports, DTMs, Orthomosaics, Blast Fragmentation Analysis
Bridge Inspection	20-50	<1	High-Resolution Textured Mesh, Defect Annotations, CAD Overlays
Forestry Inventory	70-120	2-4	Canopy Height Model (CHM), Digital Surface Model (DSM), Individual Tree Delineation

and another field hit hard by this tech is civil infrastructure management: There can be such an amount of details on those 3D models that allows for close as well as far away inspections on assets such as a bridge, a dam, a building, a wind turbine or a power line corridor Engineers may check these virtual models, finding out, checking out and marking out any damage, like concrete crack, spall, corrosion and so on, all they have to do is sit back at their office. It largely reduces the demand of dangerous and expensive manual inspection by rope, scaffold, or snooper truck. The 3D model is a constant, full-quality and georeffered digital file of the present asset condition as if at a particular time point, a

steady benchmark is set up for years and decades to come and the possibility to think about and plan predictive maintenance activities ahead is opened up. On the aspect of environmental engineering and natural resource management, UAV 3D models are widely used for river morphology mapping, coastal eroding situation monitoring, forestry resources inventories and precision agriculture. It can produce both bare Earth DTM plus DSM that includes vegetation plus structure, which is used to make a complete dataset of hydrological operations, quantify the rate at which coastline retreats, and assess the amount of timber volume. Crop’s health can also be checked using DSM. The application of these models are explained in more detail in these corresponding tables.

**Table 4.** Accuracy Requirements for Selected Engineering Tasks

Engineering Task	Required Horizontal Accuracy (cm)	Required Vertical Accuracy (cm)	Justification
Stockpile Volume Calculation	5-10	5-10	Ensures reliable inventory management, financial accounting, and reconciliation. A small percentage error in volume can have a large financial impact.
Cut/Fill Analysis in Construction	3-5	3-5	Critical for precise earthwork planning, minimizing material handling costs, and ensuring the final grade meets design specifications.
Structural Deformation Monitoring	1-3	1-3	High precision is imperative to detect subtle movements in critical structures like dams or bridges, which can be early indicators of potential failure.
As-Built Verification	5-10	5-10	Necessary to compare the final constructed reality against the design model (e.g., BIM) for quality assurance and legal documentation.

Table 3 offers a practical view of the adjustments made in UAV system specifications and flight parameters according to the different engineering projects, showing the need to adjust the data acquisition procedure as well as the quality of the data for a given project to be able to reach the goals. On the contrary, Table 4 is the demanding perfect for different important Engineering work. This table clearly shows the point is why the accuracy enhancement ideas we have talked about earlier are not something that is good to do – it becomes essential for making sure you can use the information you have collected to make decisions that are legal, financial, and technical correct. A few several of these tables put together illustrates the importance of having good Data Gain methods and effectively utilizing the UAV’s oblique photos in the most difficult engineering scenarios.

## 5. Conclusion

UAV oblique photogrammetry without fail has become a mighty, flexible, and transformative technology for 3D modeling of complex terrains. And its ability to very quickly make high resolution very photo realistic and most importantly, geometrically accurate and detailed copies of the actual world have made a ton of incredible new opportunities available for improved analysis, data driven

planning and better management over a huge array of fields in engineering. This paper has thoroughly studied the main aspects of this technology, going from the basics all the way to the critical and somewhat refined techniques that are needed when optimizing for accuracy. The importance of an accurate data acquisition plan is paramount, the strategic and intelligent setup and usage of Ground Control Points, the game changing use of direct georeferencing techniques such as RTK and PPK, and thorough, quality-controlled data processing have all been identified as key and interrelated ingredients to achieve engineering-grade accuracy. Complex terrains' inherent challenges – data occlusions, extreme lighting changes and geometric shortfalls can be convincingly tackled via a blend of these techniques and supplemented by multi-source data fusion using complementary sensors like LiDAR.

The included case study discussions and data tables give concrete, numerical proof that this tech has an incredible amount of real-world worth, showing its use in serious, high-stakes situations like deciding on rock danger zones, big-time mines, and keeping track of buildings, roads, etc. from when they start being built until they end up needing to be knocked down. With UAV hardware continuing its progression towards being more advanced, accessible, and affordable, as well as UAV oblique photogrammetric software developing to utilize increasingly advanced algorithms and tasks with artificial intelligence/machine learning such as semantic segmentation, automated feature identification, etc., UAV oblique photogrammetric's potential increases dramatically. Future work will certainly be around making the whole processing pipeline even more automated, enhancing the automated way we get useful information from 3D models, and allowing these dynamic digital twins to fit nicely into bigger places like building information modeling (BIM), geographic information systems (GIS), or even AR for really cool on-site looks. In addition to those already being fine-tuned and standardized, accuracy techniques will be the constant base on which this type of technology will progress, and this kind of information that UAVs collect for people is not only abundant but also packed, will be used completely to create engineering solutions that are better able to cope with the challenges posed by the engineering of tomorrow's engineers, which are more safe, more efficient and more sustainable.

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