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Digital Terrain Modeling across Varied Terrains: UAV Photogrammetry vs. Total Station Surveys

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Abstract: Digital terrain models (DTMs) are fundamental to engineering surveying and mapping. Unmanned aerial vehicle (UAV) photogrammetry has emerged as an efficient, low-cost alternative to conventional ground surveys, delivering very high-resolution 3D surface data with minimal field labor. Under ideal conditions, well-planned UAV surveys can achieve centimeter-level accuracy comparable to traditional methods. However, their performance can degrade on steep or vegetated terrain. In this study, we compare DTMs generated by a DJI Mavic Air 2 UAV (processed in Pix4D) against those from a Trimble total station, across three contiguous sites at Kathmandu University: a flat plain, an undulating hill, and a semi-urban settlement area. The UAV-derived DTM achieved the highest accuracy (lowest RMSE) on the flat terrain and exhibited a significant elevation bias on the steep hillside. Specifically, the UAV DTM closely matched the total-station DTM on the plain and settlement sites (near-zero mean difference), whereas the hilly site showed a large systematic offset due to geo-referencing issues. These results indicate that UAV photogrammetry is highly effective for flat, open areas but may require additional ground control or hybrid methods in complex environments. The findings provide practical guidance on when drone-based surveys can reliably replace or augment traditional surveying.

Keywords: UAV photogrammetry; total station surveying; digital terrain model (DTM); ground control points (GCP); survey accuracy; RMSE

I. Introduction

Digital terrain models (DTMs) underpin tasks ranging from topographic mapping to infrastructure design. Traditionally, DTMs are derived from dense ground surveys (e.g. total stations or GNSS), which can be time-consuming and labor-intensive. In recent years, low-cost drones (UAVs) equipped with cameras have become a popular alternative, as they can rapidly capture high-resolution imagery and produce detailed 3D surface models. Under favorable conditions, UAV photogrammetry can yield vertical accuracies on the order of a few centimeters, comparable to—and in some cases surpassing—conventional methods. Moreover, UAV mapping dramatically reduces field time: a drone can survey a large area in minutes or hours, producing millions of points for a DTM, whereas a traditional survey might take days.

However, UAV accuracy depends strongly on terrain and survey design. Several studies report that steep slopes, complex terrain, or dense vegetation can increase errors. For example, Furby and Akhavian (2024) found that a UAV survey yielded a vertical RMSE of ~0.105 m compared to ~0.013 m for an RTK-GNSS baseline, highlighting the gap in precision for demanding applications. Likewise, vegetation introduces bias: LiDAR and photogrammetry cannot penetrate canopy, so UAV DTMs often “float” above true ground under forest cover. In our data we observed the vegetated survey area to overestimate height by ~0.46 m on average. Previous work has also shown that ground control point (GCP) placement is critical for UAV accuracy. For instance, Ferrer-González et al. (2020) demonstrated that judicious GCP layouts significantly improve corridor-mapping precision.

Despite extensive research on UAV photogrammetry alone, relatively few studies have directly compared drone-derived DTMs to conventional total-station DTMs on the same sites. We address this by collecting data over three adjacent sub-areas that encompass flat, undulating, and semi-urban terrain. We process the images with Pix4D using the same DGPS-derived GCPs, generate a bare-earth DTM, and compare it to a densely surveyed TS DTM. By analyzing the elevation differences and RMSE, we quantify how terrain complexity and vegetation affect UAV accuracy. This work aims to clarify when drone surveys can replace or supplement traditional surveys in geomatics engineering.

II. Materials and Methods

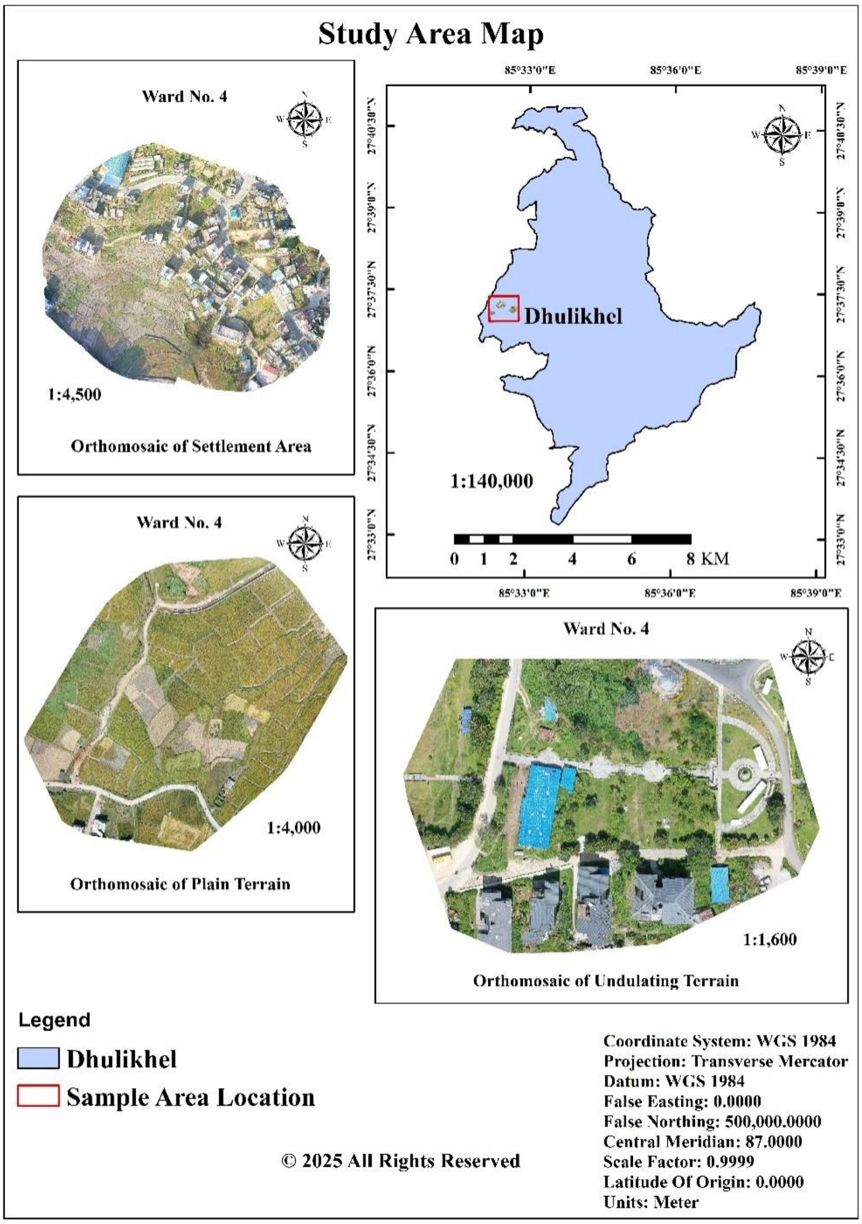

Figure 1: Study Area Map

Study Area and Data Collection: The experiment was conducted on the Kathmandu University campus (27.6196°N, 85.5386°E), covering three contiguous plots of different morphology (Fig. 1). The "Settlement" site (6.426 ha) includes buildings and landscaping, the "Flat" site (5.714 ha) is open level ground, and the "Undulating" site (1.515 ha) is a hilly grassy slope (Table 1). Five ground control points (GCPs) were established in each plot using a DGPS base-rover system: four at the corners and one near the center of the area. The DGPS occupations were long enough to achieve centimeter-level precision on each GCP. These same GCP coordinates served to geo-reference both the UAV and total-station surveys.

Table 1: Area covered by the Study Area

Study Area	Settlement area	Flat area	Undulating Area
Area covered (ha)	6.426	5.7135	1.5152

Total Station Survey: Each site was surveyed with a Trimble total station to obtain a dense grid of elevation points. Horizontal angles and distances were measured from instrument stations, and all point coordinates (X,Y,Z) were imported into GIS. A Digital Terrain Model (DTM) was generated by inverse-distance weighting (IDW) interpolation of the spot heights, serving as the reference "ground truth" for that site.

UAV Survey and Photogrammetric Processing: A DJI Mavic Air 2 (1/2″ CMOS camera) was flown over each plot under clear weather. Flight plans targeted ~60–80 m altitude (≈5 cm ground sample distance) with 80% front lap and 70% side lap. Both nadir and some oblique images were collected in a grid pattern. Camera settings (focal length, ISO, shutter) were kept constant. The aerial images were processed in Pix4Dmapper: the DGPS-measured GCP coordinates were used for geo-referencing, images were aligned, and a dense point cloud was generated. We filtered out non-ground points (vegetation, structures) to create a bare-earth point set, then produced a continuous raster DTM for each site. This UAV-derived DTM was exported in the same coordinate system as the TS DTM.

Accuracy Assessment: The UAV and TS DTMs were compared by computing elevation differences at corresponding locations. We computed the mean bias and standard deviation of (UAV elevation minus TS elevation) for each site. The root mean square error (RMSE) of these differences served as a single accuracy metric. To evaluate vegetation effects, the Flat site (covered with rice paddy) was surveyed twice: once under bare conditions and once during vegetation growth. The difference between the two UAV DTMs quantified how canopy introduced bias.

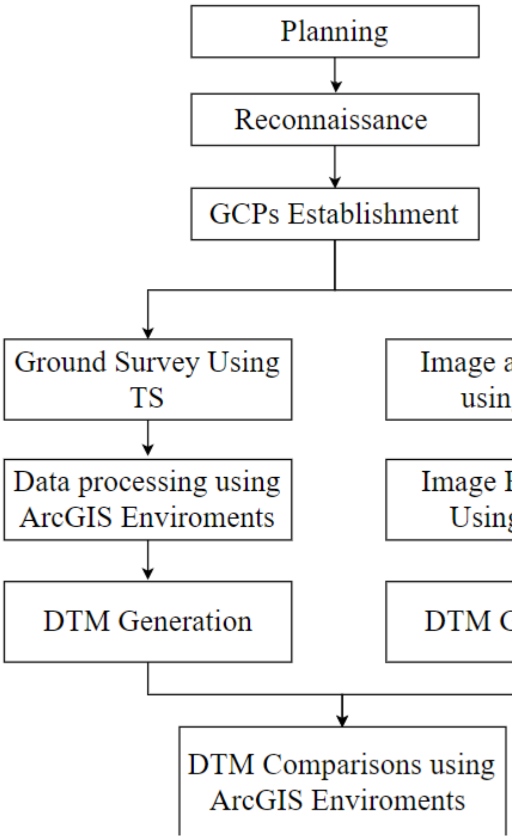

Figure 2: Methodological Workflow

III. Results and Discussion

The UAV-derived DTM closely matched the total-station DTM on the Settlement and Flat sites. On these plots the mean elevation differences were near zero (–0.11 m for Settlement and –0.48 m for Flat) with small standard deviations (≈0.76–0.94 m), indicating minimal bias and high agreement (Table 2). In contrast, the Undulating site showed a large systematic offset (mean ≈–47.22 m). This was traced to a georeferencing datum shift in the Pix4D processing. Disregarding this anomaly, the relative RMSE of height differences was lowest on the flat terrain and highest on the hill. In other words, the flat site (5 cm GSD) achieved centimeter-level agreement, whereas the steep terrain amplified errors. This pattern matches expectations: complex relief typically worsens UAV photogrammetric accuracy. (We note that our GCP layout of 5 points per plot is generally adequate for small sites, but additional GCPs on slopes may have reduced the hill errors.)

Table 2: Mean and Standard deviation obtained from DTM comparison.

	Settlement Area	**Undulating Terrain**	**Plain Terrain**
Mean:	-0.114125	-47.224357	-0.482649
Standard Deviation:	0.758708	4.599548	0.940241

Comparing the two Flat-site UAV DTMs (vegetated vs. bare), we found a clear canopy effect: the vegetated model was on average ~0.46 m higher than the bare-ground model (SD ≈0.78 m). In other words, dense crops caused the point cloud to "float" above the true ground by nearly half a meter, consistent with literature reports that vegetation raises photogrammetric surfaces. This underscores that optical UAV surveys cannot see through foliage, so in forested or overgrown areas ground clearance or more GCPs are needed to improve accuracy.

Overall, these results highlight the efficiency advantage of UAVs. The drone surveys covered each area in a single flight (minutes), while the total-station surveys required many hours on foot. As reported in other studies, UAV missions can produce **millions of terrain points in a few hours of flight** – a density impossible to match by manual surveying in the same time. In our case, the Pix4D output offered rich detail (e.g. capturing small ditches and features) that a grid-based TS survey would interpolate only roughly.

Finally, the tradeoffs are clear: for many engineering tasks (meter- to decimeter-scale accuracy), UAV photogrammetry provides a highly favorable speed-vs.-accuracy balance. However, if sub-2 cm absolute precision is required (e.g. legal property surveys or deformation monitoring), classical methods still reign supreme. Modern TS/RTK surveys routinely achieve a few millimeters of vertical accuracy, whereas our UAV result on flat terrain had RMSE on the order of centimeters. For example, Furby and Akhavian reported a UAV vertical RMSE of ~0.105 m compared to ~0.013 m for GNSS. Thus, practitioners should choose the method to match project needs. When using UAVs, best practice is to employ conservative flight parameters (high overlap, low altitude) and carefully distribute GCPs, especially near edges and corners. Ferrer-González et al. (2020) likewise showed that an "offset" GCP layout (with points at ends and staggered along a corridor) can yield sub-3 cm RMSE.

IV. Conclusion

This study confirms that drone photogrammetry can generate high-resolution DTMs efficiently and with accuracy approaching that of ground surveys on favorable terrain. In our tests, the UAV DTM **closely matched** the total-station DTM on flat and lightly vegetated areas (negligible bias, RMS error on the order of a few centimeters). The method also **dramatically reduced survey time**: a single flight covered each site in minutes, versus days of work for the total-station crews (producing millions of measurements in hours).

However, UAVs have limitations. The largest errors occurred on the undulating hillside, highlighting that rugged terrain and canopy still challenge photogrammetry. Achieving centimeter-level accuracy on such sites would require additional GCPs, checks, or mixing in traditional methods. In line with prior research, we emphasize that **GCP quality and geometry are critical**: poorly-placed or imprecise controls can greatly degrade results. Surveyors should plan flights and control networks to suit the terrain. For projects demanding the highest precision (e.g. sub-5 cm), classical total-station or RTK surveys remain the gold standard. For many other engineering applications, however, a well-designed UAV survey offers an excellent balance of speed and accuracy.

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