HIGH-RESOLUTION MAPPING OF FORESTED HILLS USING REAL-TIME UAV TERRAIN FOLLOWING

Chandra Has Singh[1*], Vishal Mishra[1], Kamal Jain[1,2]

[1] Department of Civil Engineering, Indian Institute of Technology, Roorkee, Uttarakhand, India- 247667
*chandrahas@ce.iitr.ac.in, vmishra1@ce.iitr.ac.in

[2] Centre of Excellence in Disaster Mitigation and Management (CoEDMM), Indian Institute of Technology Roorkee, Uttarakhand, India- 247667
kamal.jain@ce.iitr.ac.in

KEYWORDS: UAS, Mapping, Terrain Following, Photogrammetry, 3D mapping, Forestry, Landslide, Drone Surveying

ABSTRACT:

This study presents a novel method for high-altitude terrain following photogrammetric mapping using Unmanned Aerial Vehicles (UAVs) that adapt their height to the terrain's morphology. Traditional grid missions in UAV mapping surveys use nadir photographs to cover an area of interest which is taken from a fixed height from the datum. Many times this leads to difficulties in flight mission and processing when hilly/undulated terrain is under consideration. The proposed solution addresses this by adjusting the UAV's flying height based on real-time terrain information gathered by a range detection sensor. This paper tests the proposed method in a hilly area in the Himalayas, capturing high-resolution images and processing them using UAV-based photogrammetry software. The pre-acquired terrain information ensures safe separation from obstacles and enables trajectory generation at lower altitudes when planning initial flights. The experimental results validate the effectiveness of the proposed method and highlight its potential for generating high-resolution photogrammetric products applicable to various UAV mapping tasks and monitoring scenarios. Overall, this research contributes to advancing the field of UAV mapping by providing a practical and effective solution for UAV based surveys in hilly and undulated terrains. The findings of this study have significant implications for various applications, including land surveying, environmental monitoring, landslide mapping and other scenarios that require detailed and accurate data acquisition from UAVs.

1. INTRODUCTION

UAVs are finding their utilities in multiple sphere of research (Mishra et al., 2023; C. H. Singh et al., 2022; Tiwari et al., 2021). Primary among them is the field of surveying. In hilly areas, for surveying forests (Dainelli et al., 2021) or landslide inventory mapping (Ghorbanzadeh et al., 2019)(Kundal et al., 2023) single or swarm of UAVs (C. Singh et al., 2022) are being used for purpose of acquiring high resolution data.For capturing information in undulated terrain that may be hidden or inaccessible through high-altitude, straight-line UAV flights, the utilization of UAVs that can navigate and adapt to the its morphology becomes crucial. This is particularly significant in scenarios where steep or vertical features, such as cliffs, rock walls, or complex structures like transmission lines, characterize the terrain.

Terrain-following UAVs are essential for various applications due to their ability to maintain a consistent altitude above the terrain while navigating complex landscapes. These UAVs are needed primarily for accurate data collection and safe flight operations. They ensure that the captured data is representative of the actual topography and that the drone can navigate challenging environments effectively. By adjusting their flight paths based on the terrain's elevation, these UAVs guarantee uniform ground sample distance, enabling high-quality imagery or LiDAR data collection for tasks such as mapping, surveying, and environmental monitoring. Additionally, terrain-following UAVs integrate obstacle avoidance systems, enhancing safety by detecting and avoiding obstacles during flight. This capability is vital for preventing collisions, especially in areas with structures, vegetation, or other potential hazards. Overall, the need for terrain-following UAVs stems from their capacity to ensure accurate data acquisition, safe navigation, and efficient operation in diverse and demanding terrains.

This study introduces an innovative approach to high-altitude terrain following photogrammetric mapping, incorporating pre-informed data and a range detection sensor. The conventional method of conducting aerial surveys involves flying UAVs at high altitudes to cover large areas efficiently. However, this approach has limitations when capturing detailed information about rugged terrain or vertical structures. In such cases, a UAV that can closely follow the terrain's morphology is required to acquire accurate and comprehensive data.

The proposed method integrates pre-informed information with a range detection sensor to enable precise navigation and mapping of challenging terrain. Pre-informed data includes prior knowledge about the specific terrain attributes, such as the presence of cliffs, rock formations, transmission lines, etc. This information aids the UAV plan its flight path, ensuring its secure navigation while maintaining uniform proximity to the terrain surface.
The range detection sensor assumes a crucial role in this mapping technique. By accurately gauging the distance between the UAV and the terrain features, the sensor assists in maintaining an optimal distance for capturing high-resolution images. It imparts UAV versatility to dynamically adjust its altitude, pitch, and roll in real-time to follow the surface of the terrain. This adaptive approach facilitates the meticulous collection of data, including fine textures and intricate structures that might get overlooked in high-altitude, straight-line flights. Integrating pre-informed information and the range detection sensor in this novel method offers an effective solution for terrain-following based photogrammetric mapping. It enhances the capabilities of UAVs to capture valuable data from

https://doi.org/10.5194/isprs-annals-X-1-W1-2023-665-2023

challenging landscapes, contributing to improved accuracy and completeness of survey results. This advancement opens up new possibilities for applications such as geological surveys, infrastructure inspections, and environmental monitoring, where detailed information about steep and complex terrains is essential for decision-making and analysis.

In this study a range sensor is integrated with the flight controller to achieve this adaptive altitude control, allowing real-time gathering of terrain information. The sensor provides crucial data that enables the UAV to adjust its flying height autonomously while in autopilot mode.

The solution significantly improves traditional grid missions in UAV mapping surveys by combining adaptive altitude control, real-time terrain information, and advanced photogrammetry software. Integrating a range sensor with the flight controller allows for accurate and autonomous adjustments in flying height, ensuring consistent GSD throughout the survey. The successful test conducted in a challenging hilly terrain demonstrates this approach's practical application and effectiveness, paving the way for enhanced data collection and analysis in various fields such as land surveying, environmental monitoring, and infrastructure inspections.

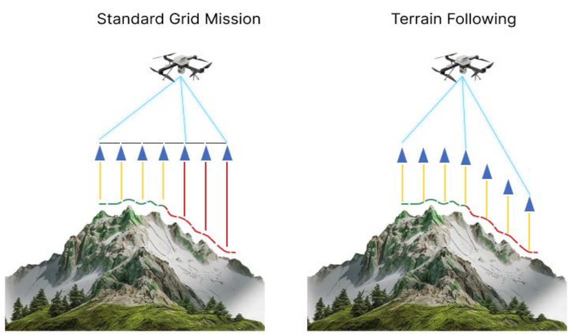

Figure 1. Terrain following mapping.

This paper introduces an innovative method for generating trajectories for UAVs that consider the morphology of the area of interest, represented by a georeferenced Digital Surface Model (DSM), while ensuring safe separation from obstacles. To create the surface model of the area, Agisoft Metashape is utilized, processing the images captured during a primary mission conducted at a high altitude. The proposed solution has been developed, tested, and verified through simulations and real-life scenarios using a multirotor UAV equipped with a low-cost range sensor integrated with a flight controller. The experimental results obtained from these tests serve to demonstrate the effectiveness and reliability of the trajectory generation technique, particularly at lower altitudes compared to existing methods. By considering the morphology of the area of interest, the generated trajectories enable the UAV to navigate more closely to the terrain, capturing high-resolution data and optimizing mapping accuracy.

The images acquired during the high-altitude mission are further processed to obtain a comprehensive and detailed reconstruction of the surveyed area. This process involves leveraging photogrammetric techniques to generate high-resolution photogrammetric products, which can be applied to various UAV mapping tasks and monitoring scenarios. The proposed solution presented in this study offers a best-practice approach for generating high-resolution photogrammetric products through UAV trajectories that consider the morphology of the area of interest. Integrating a georeferenced DSM, a low-cost range sensor, and a flight controller ensures safe and accurate UAV operations, even in complex environments with obstacles. The ability to generate trajectories at lower altitudes expands the possibilities for capturing detailed information, enhancing the quality of photogrammetric outputs.

2. LITERATURE REVIEW

(Li et al., 2012) focused on 3D texture mapping within UAV Visual Simultaneous Localization And Mapping (VSLAM), employing feature detection methods such as SIFT and SURF for landmark selection, with subsequent refinement via RANSAC to enhance navigation visuals, as evidenced by experimental results. Additionally, the study demonstrated the potential of this approach for complex structures like riverbeds. UAVs played a crucial role in defining topography in geologically hazardous areas, offering rapid and precise qualitative and quantitative data essential for geological stability analyses and photo documentation (Manousakis et al., 2016). These UAV-captured images facilitated the extraction of highly accurate photogrammetric topographical measurements (Taha et al., 2022). Absolute localization was successfully achieved by integrating 3D local ground Lidar data with global 3D aerial data (Vandapel et al., 2006). UAVs were found to be invaluable for slope mapping and hazard assessment based on slope angles within geotechnical engineering (Zolkepli et al., 2022)(Layek et al., 2022). Furthermore, they were recognized for their efficiency in generating Digital Terrain Models to serve various purposes (Giordan et al., 2020). Another study introduced a real-time exploration and reconstruction algorithm for UAVs, particularly in undulating terrain, without the need for prior area maps (Singh et al., 2023). Moreover, a method was proposed to optimize UAV flight networks based on digital elevation models (DEMs), effectively addressing issues related to scale uniformity and photogrammetric accuracy, with empirical testing validating its effectiveness in reducing large-scale differences among images and maintaining a constant ground sample distance (GSD), ultimately enhancing photogrammetric product accuracy (Gargari et al., 2023).

3. STUDY AREA

The study conducted an experiment using a customized Unmanned Aerial Vehicle (UAV) in a hilly region surrounded by forested mountains as shown in Figure 2. The study site was located on a flat plateau beneath the Himalayan Shivalik Hills, situated on the border of Uttar Pradesh and Uttarakhand state in India, These foothills made it an ideal site for testing the proposed methodology. Geographically, the area lies between the Ganga and Yamuna rivers, while the altitudes in the study area ranged from 437 to 507 meters.

The UAV mission covered a total area of 0.28 square kilometres, including the riverbank and mountainous regions affected by seasonal rainfall. The study contains multiple landcover features such as forest, bare soil, river and boulders.

This contribution has been peer-reviewed. The double-blind peer-review was conducted on the basis of the full paper.
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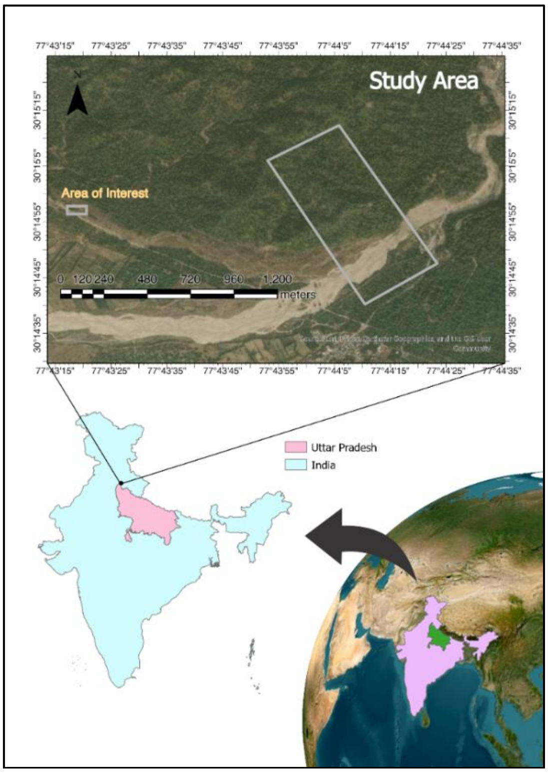

Figure 2. Study area map.

4. METHODOLOGY

Figure 3. Designed and assembled UAV for data collection.

In UAV mapping surveys, traditional grid missions are commonly employed to cover a specific area of interest by capturing nadir photographs. However, an innovative solution has been developed to enhance this approach. This solution involves adapting the UAV's altitude based on the local terrain profile during the flight, ensuring a consistent ground sampling distance (GSD). The drone used for our experiment is shown in Figure 3.

This architecture necessitates several essential components, including a localization module for determining the UAV's position in the world geodetic system, a mission planner for task assignment and monitoring, a projected path planner for route assignment with obstacle avoidance, a trajectory control system for guiding the UAV along the designated routes provided by the trajectory planner, and various modules for error checking, environment parameter monitoring, communication, and supervision. A solution emerged in the form of an exquisite 460 mm dimension quadcopter, meticulously designed and validated with the aid of carbon fiber materials. This UAV was equipped with an exceptionally reliable autopilot flight controller seamlessly integrated with the cutting-edge computing prowess of the remarkable Raspberrypi device. The fusion of stability, precision, and computational power endowed this quadcopter with the capability to do difficult terrain following mapping. Flight apps commonly utilize a flight pattern where a drone performs a back-and-forth sweep over the landscape at a fixed altitude. This pattern achieves comprehensive horizontal coverage while maintaining a relatively constant drone elevation. Before the mission, a predetermined altitude is set, and the drone ascends to and maintains this height throughout the mission. However, challenges arise when mapping hilly and forested terrains. The dynamic topography causes the drone's actual height above the ground to fluctuate, leading to potential collisions with the terrain or breaching altitude limits.

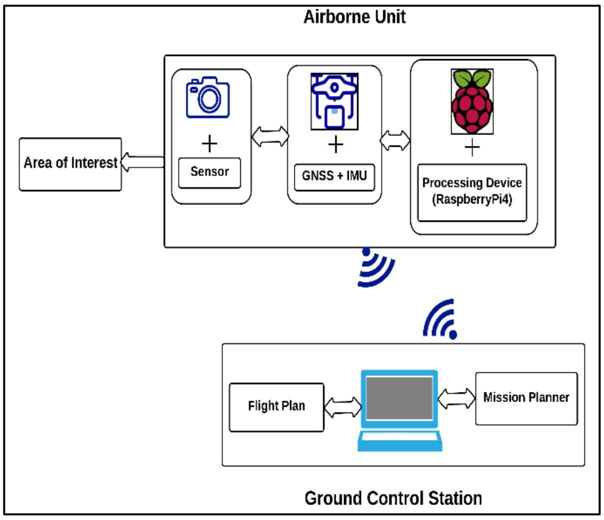

Figure 4. UAS schema for terrain following data collection.

Additionally, these elevation changes introduce subtle variations in the captured image set, compromising the quality of the resulting 3D model. To address these challenges, alternative flight strategies like terrain-following techniques should ensure accurate and high-quality data capture across diverse terrains.
To execute a UAV mission with terrain-following capabilities, the following technical steps are undertaken:

- **Selection of Points of Interest:** Identify and select the desired points on the map where data acquisition is required.
- **Configuration of Flight Parameters:** Set the desired height, speed, and overlapping parameters necessary for generating the map. These parameters define flight characteristics and data acquisition specifications.
- **Terrain Configuration:** Enable the Terrain feature with a value of 1 to ensure smooth terrain-following functionality. Set the minimum and maximum limits of the LiDAR sensor to suitable values, allowing the autopilot system to operate effectively.
- **Altitude Type Setting:** In the mission planning software all altitude-related mission commands are

interpreted as heights above the terrain, accounting for the varying landscape.

- **Uploading Waypoint File:** Upload the configured waypoint file to the onboard autopilot system. This prepares the UAV flight controller to autonomously execute the mission in auto mode, following the predefined trajectory and altitude instructions.

Table 1. Photogrammetric Parameters

Parameter	Dataset
Flying Height	100 meter
Side Overlap	70 %
Front Overlap	75 %
Camera Model	Map-02
Focal Length	25 mm
Dimensions	4000x3000

By following these technical steps (Figure 5), the UAV equipped with terrain-following capabilities is ready to perform its mission, capturing data while dynamically adjusting its altitude to adhere to the terrain variations.

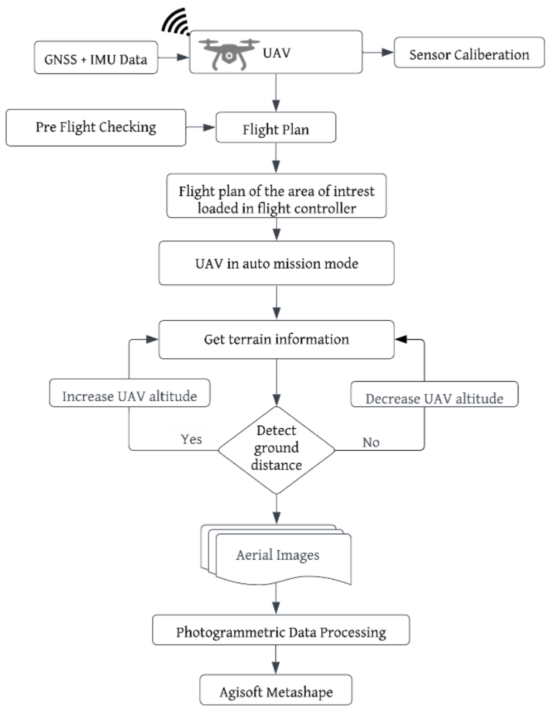

Figure 5. Flowchart depicting the UAV Terrain Following mechanism.

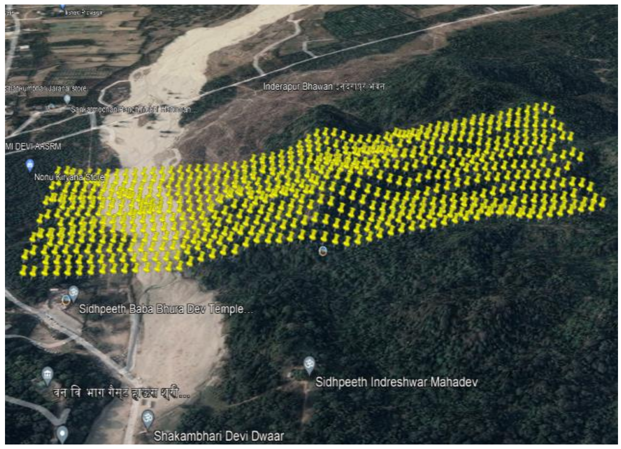

Figure 6. Executed UAV Flight Path (Terrain Following Mapping).

By constantly monitoring the terrain, the UAV can dynamically modify its altitude to maintain a fixed GSD, resulting in accurate and consistent image resolution.

To evaluate the effectiveness of the proposed solution, a test was conducted in a hilly region located within the Himalayas range. During the flight, a total of 673 high-resolution images were captured, with the UAV reaching a maximum altitude of 573.43 meters and a minimum altitude of 521.23 meters. These images were subsequently processed using photogrammetry software specifically designed for UAV-based applications. The processing of the images aimed to reconstruct the surveyed areain high resolution, enabling detailed analysis and interpretation of the captured data.

UAV photogrammetric data processing in Agisoft Metashape involves scientifically grounded steps. Firstly, the aerial images captured by the UAV are imported into the software, ensuring sufficient overlap and coverage for accurate 3D reconstruction. The images are aligned using automatic feature matching techniques, estimating the precise camera positions and orientations in 3D space. A dense point cloud is generated by leveraging the matched image data. This process involves pixel correspondence calculations across multiple images, enabling the derivation of 3D coordinates for each point in the scene. This point cloud serves as a foundation for subsequent analysis and visualization. Figure 6 depicts the overall workflow of UAV based photogrammetric processing.

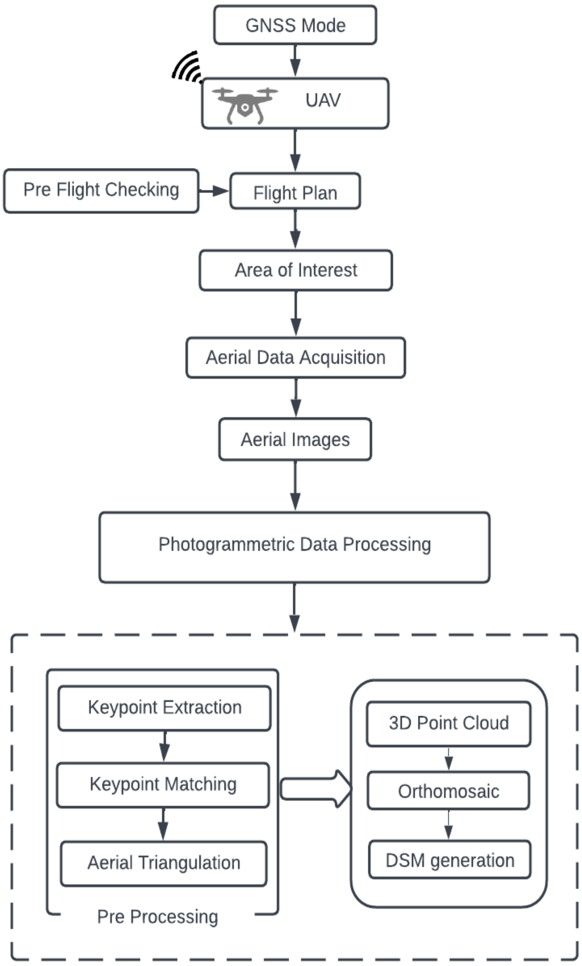

Figure 7. UAV Photogrammetric data processing.

Agisoft Metashape further facilitates the creation of a Digital Surface Model (DSM) and orthomosaic. The DSM provides elevation values for the terrain, while the orthomosaic is a high-resolution, georeferenced aerial image. These outputs are invaluable for precision agriculture applications, enabling precise elevation analysis and detailed visualizations of the surveyed area.

This step validates the quality and reliability of the photogrammetric outputs, ensuring the fidelity of the reconstructed 3D models and derived geospatial information.Agisoft Metashape offers a scientifically rigorous workflow for processing UAV-based photogrammetric data. By leveraging advanced algorithms for image alignment, point cloud generation, DSM and orthomosaic creation, and accuracy assessment.

5. RESULTS

Following the completion of preliminary testing, subsequent on-field experimentation was conducted within the designated area of interest. The collected data, as depicted in Figure 7, illustrates the UAV's ability to faithfully track the predefined reference path. However, slight elevation variations can be observed between the two trends, attributed to the time required for the UAV to reach each specified waypoint along the route. During the tests, the UAV maintained a consistent altitude of 100 meters above ground level, as indicated by the depicted altitude trends.

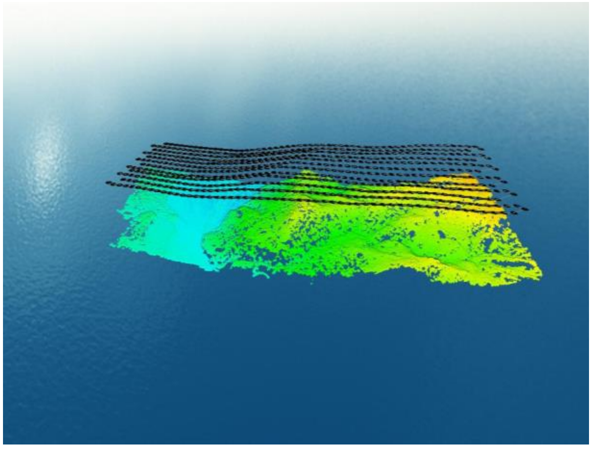

Figure 8. Sparse Point Cloud generated after photogrammetric process.

To showcase the terrain-following capability, the executed trajectory, and proposed flight waypoints were overlaid onto the longitude-latitude plane, offering a visual representation of this distinctive feature.

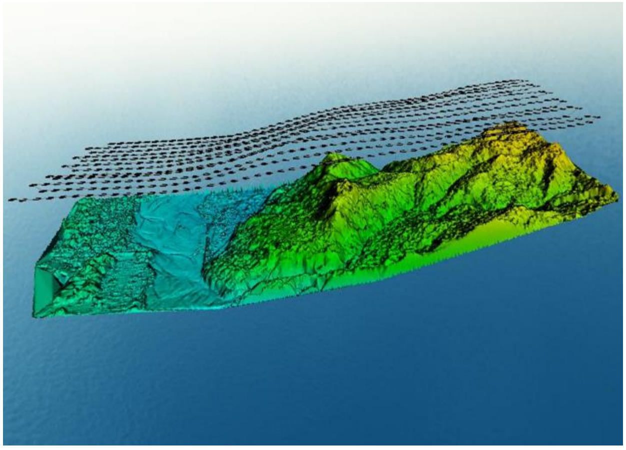

Figure 9. Generated Dense Pointcloud.

To achieve accurate Digital Surface Model (DSM) generation, it is crucial to have reliable feature points extracted from the image, along with precise exterior orientation parameters. In this context, drone-based Inertial Measurement Unit (IMU) and GPS data are utilized, and this information is stored in EXIF tags for each captured image. The initialization of the photogrammetric process involves using this information for calibration and subsequent re-optimization of the solution. The triangulation algorithm employed is based on Delaunay triangulation.

The resolution of the orthophoto is closely tied to the resolution of the DSM. Typically, the DSM is generated using a set of images with a resolution that is at least four times greater than that of the input image. The accuracy of the point cloud, DSM, and resulting orthophoto is affected by both the quality and visual content of the initial images. In the present scenario, the generated orthophoto provides an orthographic depiction of the study area, encompassing a riverbed, forested mountains, etc.

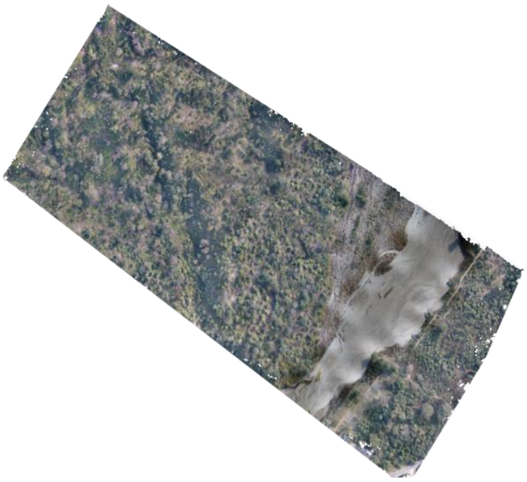

Figure 10. Orthomosaic.

6. CONCLUSION AND FUTURE WORK

This paper introduces a method for UAV flights that enables following the terrain profile from high altitude to the ground while considering uncertainties in the flight controller and onboard computing device. Such missions have significant applications in close-to-ground image collection, contributing to various fields of human life. The proposed solution is versatile, encompassing mission assignments and survey tasks. It is compatible with commercial and open-source ground control stations and can be integrated with different autopilots and multirotor platforms. Experimental missions successfully validated the initial results, demonstrating the vehicle's ability to maintain a safe distance from challenging terrain and obstacles, utilizing standard GPS dimensions. The comprehensive approach outlined in this study ensures reliable outcomes and broad applicability.

An existing limitation pertains to the reliance on GPS, which may not be robust in the face of potential LiDAR failures or dynamic terrain changes. However, this limitation can be overcome by equipping the vehicle with range sensors and 3D LiDAR, along with reactive-based local barrier control. To ensure timely data processing and generate alert messages, a fast calculating device needs to be deployed on the UAV. It should be noted that the current solution is specifically designed and tested for multirotor vehicles due to their ability to efficiently survey and hover for extended periods. Further investigation is needed to determine compatibility with other aerial vehicles such as fixed-wing or VTOL (vertical takeoff and landing). Moreover, exploring low-altitude flight solutions and integrating additional sensors or LiDAR can further enhance the terrain-following mapping feature, requiring appropriate control strategies.

Terrain-following UAV surveys offer advantages in capturing detailed data from challenging landscapes, but they are accompanied by certain drawbacks. Operating at lower altitudes to closely track terrain limits coverage efficiency compared to higher-altitude surveys. Close proximity to obstacles raises collision risks, necessitating advanced navigation systems that can increase maintenance costs. Weather sensitivity can impact flight stability and data quality. Inaccurate data collection can occur in steep or densely vegetated areas. Reduced speed for safe navigation affects overall survey efficiency. Complex terrains may limit accessibility. Energy-intensive flight lowers battery life. Regulatory concerns and specialized skills are necessary. Considering these cons is essential when choosing terrain-following UAV surveys, weighing their benefits against potential limitations for specific applications.

One of the limitations of the proposed solution is the challenging nature of the high surface terrain, making it difficult to obtain LiDAR data. This limits the ability to improve the solution's positioning on time and hinders navigation through obstacles. Consequently, our approach is not suitable when accountability is crucial.For low-altitude flight solutions, integrating additional sensors or LiDAR can enhance the terrain following mapping feature, enabling more precise control strategies.

ACKNOWLEDGEMENTS

Authors would also like to acknowledge the Indian Institute of Technology Roorkee for providing us with the necessary resources, infrastructure, and academic environment to conduct this research.. Authors are thankful to IEEE-GRSS for awarding IEEE GRSS Inspire, Develop, Empower, and Advance (IDEA) Micrograntt to Chandra Has Singh which facilitated the presentation of this paper. Authors also acknowledge the department of Civil Engineering, IIT Roorkee for partial funding the travel for presenting this paper.

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