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Article

Adaptive fuzzy logic for gap filling in UAV orthomosaics: A methodology for accurate geospatial mapping

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Abstract: Unmanned Aerial Vehicles (UAVs) have gained spotlighted attention in the recent past and has experienced exponential advancements. This research focuses on UAV-based data acquisition and processing to generate highly accurate outputs pertaining to orthomosaic imagery, elevation, surface and terrain models. The study addresses the challenges inherent in the generation and analysis of orthomosaic images, particularly the critical need for correction and enhancement to ensure precise application in fields like detailed mapping and continuous monitoring. To achieve superior image quality and precision, the study applies advanced image processing techniques encompassing Fuzzy Logic and edge-detection techniques. The study emphasizes on the necessity of an approach for countering the loss of information while mapping the UAV deliverables. By offering insights into both the challenges and solutions related to orthomosaic image processing, this research lays the groundwork for future applications that promise to further increase the efficiency and effectiveness of UAV-based methods in geomatics, as well as in broader fields such as engineering and environmental management.

Keywords: UAV; orthomosaic; fuzzy logic; spatial mapping; image enhancement

1. Introduction

The increase in technological trend is glooming globally, allowing the innovations to enhance and advance at a rapid pace daily. Remote Sensing is a technique of gathering information about a phenomenon, or an object without being in physical contact with it [1]. Remote Sensing is such a field which demands constant advancements in the technological aspect to impart efficiency in its concept of accessing the inaccessible areas through non-contact means [2]. Space borne satellites are the prime backbone of remote sensing applications [3]. Despite having larger swaths and high-end sensor on-board, satellites make it harder for carrying out the research in short-area based planning and monitoring applications [4]. This is where the importance of Unmanned Aerial Vehicles (UAVs) become paramount [5]. UAVs are becoming popular day by day and provide extensiveness to almost all remote sensing fields where the field of study is concise and restricted like academic planners, construction sites, architectures, traffic management, transportation applications and urban planners [6,7]. UAVs unlike conventional remote sensing platforms, offers various advantages. Foremost being the temporal resolution as flying the UAV is custom and does not require global coverage followed by high-resolution ROI (Region-of-Interest) specific data acquisition unlike satellite data which acquires global information. Reason being that UAVs offer custom time-frame for dataset acquisition (rather than relying on temporal resolution of satellites) along with high resolution dataset with custom flights and region of interests (ROIs). Furthermore, with recent advances in UAV payload, application-specific sensors like NIR for vegetation, RADAR for urban and Hyperspectral sensors for high-resolution detailed information can be used.

Recent advancements in geospatial mapping have increasingly integrated UAV technologies to enhance accuracy and efficiency in data collection. However, challenges such as gaps, voids, and distortions in orthomosaic imagery remain significant hurdles. Various studies have proposed methods for improving orthomosaic quality through image processing techniques. For instance, Ye et al. [8] highlighted the importance of feature matching and multiple flight datasets in reducing distortion in UAV-generated orthomosaics. Meanwhile, Nguyen et al. [9] explored the use of fuzzy logic and edge-detection techniques for image enhancement, particularly in identifying and correcting faulty pixels in remote sensing imagery. Similarly, a study by Singh et al. [10] emphasized the potential of adaptive fuzzy logic approaches in automating pixel interpolation for gap filling, leading to sharper and more precise geospatial outputs. This was further escalated to water-based feature mosaicking which acts as a robust lay-work for pixel-based and image processing applications for orthomosaic imageries [11]. Furthermore, addition of multi-spectral sensor imparts effectiveness as an extra layer of information strengthens robustness into the entire platform of processing the UAV deliverables [12]. The theoretical advancements are necessary for providing georeferencing to the entire schema of accurate orthomosaic [13]. These studies collectively underline the importance of integrating adaptive image processing techniques with advanced pixel-based approach to address the common issues faced in UAV orthomosaic generation, paving the way for more accurate geospatial mapping applications. Furthermore, one of the paramount approaches of advanced image processing refers to Fuzzy logic technique which focuses on decision-making through rule-based heuristic approach, therefore, a pivotal pillar for such applications.

The primary objective of this research is to develop an adaptive fuzzy logic-based methodology for gap filling and enhancing UAV orthomosaics, addressing common issues such as distortions, voids, and mismatched features in traditional orthomosaic generation processes. This approach advances beyond conventional methods by incorporating fuzzy logic, gradient analysis, and interpolation techniques to dynamically adjust pixel values, providing more precise, high-resolution geospatial outputs. By achieving distortion-free and sharp orthomosaics, this method significantly improves accuracy in geospatial mapping, making it an attractive tool for researchers involved in environmental monitoring, resource management, and precision surveying. Its adaptability across different datasets and conditions further enhances its applicability, providing researchers with a robust, automated solution to produce reliable orthomosaics for a wide range of geospatial applications.

2. Material and method

2.1. Study area

The study area for the research is the Civil Engineering Department building, Indian Institute of Technology (IIT) Roorkee [29° 51' 46.998" N, 77° 53' 56.3928" E], [UTM Zone 43, Easting: 780,045.452 m, Northing: 3,307,140.529 m]. IIT Roorkee, formerly University of Roorkee and Thomason College of Civil Engineering, is a public technical and research university established in 1847 being considered as one of the oldest technical institutes located in Roorkee, district of Haridwar, Uttarakhand.

2.2. UAV and camera

The UAV utilized in this study is the Aibotix X6, a hexacopter classified as a rotary-wing UAV. The Aibotix X6, as part of the rotary-wing category, offers the advantage of vertical take-off and landing, making the acquisition process flexible. It can incorporate a payload up to 2.4 kg and comes with a Coming Home (CH) functionality. In the cases where pilot is unable to hover the UAV or the battery goes down to a cautious limit, this skill-set assists the pilot to bring the vehicle and land it safely to avoid any damage to the UAV, pilot or the environment where the flight is being held on. Sony Alpha 6000 E-mount RGB optical digital SLR camera is used with Advanced Photo System-type C (APS-C) sensor. It has 24.3 megapixel with capturing capability up to 24 fps. It also consists of inbuilt Wi-Fi and NFC control with JPEG and RAW data capturing provisions. The Aibotix UAV and the Camera sensor can be seen in **Figures 1a** and **1b**.

(a) **(b)**

Figure 1. UAV Components used **(a)** Aibotix hexacopter type UAV; **(b)** Sony optical camera.

2.3. Methodological schema

2.3.1. Acquisition of UAV data

UAV-based data acquisition is a common phenomenon these days due to the exponential surge in UAV-based remote sensing. However, as the process of acquisition like flight planning, payload deployment, area delineation and flight execution are quite common, the paramount part comes in the attributes of flight planning. With respect to Indian context, areas where UAVs can be flied are restricted and therefore, selection of site for data acquisition is a vitally important part. The attributes to be configured while planning a flight therefore acts as the backbone for efficiency of any UAV flight. The configuration used in this study comprised the following attributes as portrayed in **Table 1**.

Table 1. UAV Characteristics.

Attribute		Specification
Altitude	:	70 m
Front Overlap	:	75%
Side Overlap	:	65%
Flight Speed (Between waypoints)	:	3.5 m/s
GPS and Mode of Flying	:	RTK and Manual Fly

Figure 2 shows the acquisition of UAV data in schematic sketch followed by the schematics of UAV flight in **Figure 3**.

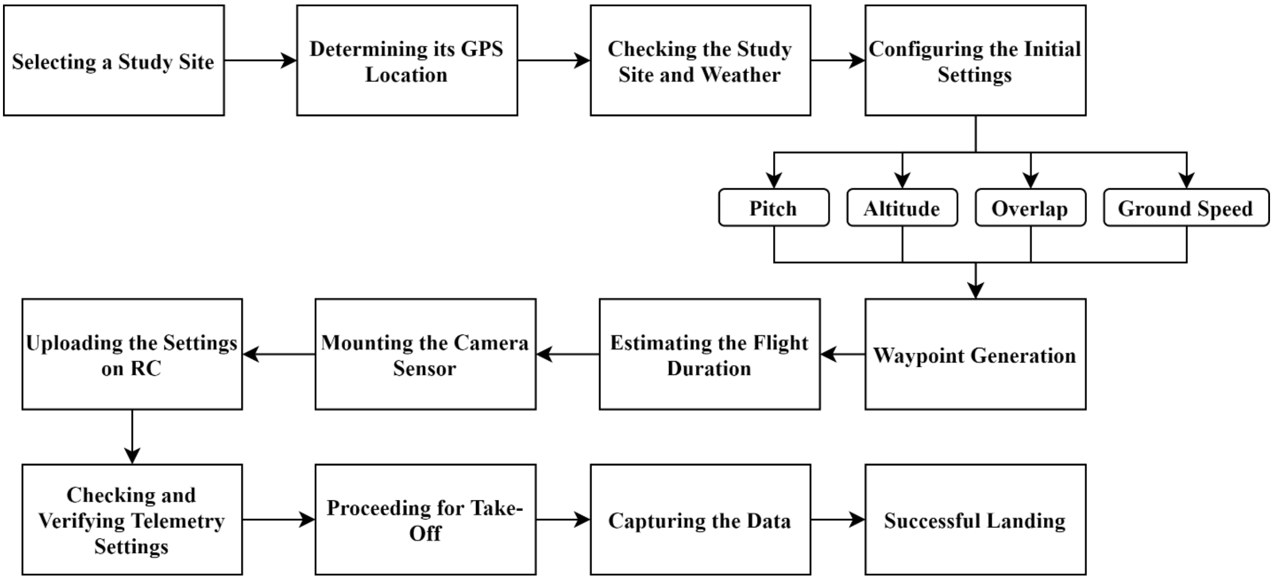


Figure 2. Acquisition of UAV data.

Figure 3. Flight of UAV in the study area for data acquisition.

2.3.2. Generation of Orthomosaic from the point cloud data

The paramount deliverable of the majority of UAV applications is the Orthomosaic image. The mosaicked image refers to the cumulative stitching of the aligned photographs captured in the most initial stage [14]. This image may contain error, and in fact, it has been witnessed by many types of research that geometric distortion is quite prominent in the mosaicked image [15]. Orthomosaic image is the final product of mosaicked image after the successful completion of geometric correction to eliminate the distortions and errors [16]. It is shown in **Figure 4**.

Figure 4. Process for generating the orthomosaic image.

2.3.3. Enhancement of orthomosaic image through fuzzy logic techniques

Fuzzy logic works through the definition of input variables as well as the membership functions and in this case, the input variables pertain to the attributes of pixels surrounding the void/gap areas in the orthomosaic image. There exist a plethora of platforms ranging from python to MATLAB for the processing domain and in this research, MATLAB was chosen as the software platform. Reason being the flexibility of MATLAB functions to tweak the pixels of the orthomosaic image and seamless integration between image and pixel-information. The initial generation of orthomosaic, textured mesh, tie-points and point clouds originate from Pix4D and then the orthomosaic generated is integrated with MATLAB environment. The initial step is the measuring of pixel intensity gradient. This assesses the change in values of the pixel's intensity around the void/gap. In simpler words, this identifies whether the neighboring pixels contain smooth or sharp transitions.

$$Grad.(x,y) = \sqrt{\left(\frac{\delta I}{\delta x}\right)^2 + \left(\frac{\delta I}{\delta y}\right)^2} \quad (1)$$

where $Grad.(x,y)$ signifies the gradient at pixel locations (x,y).

The next step involves the estimation of spatial distance from the known pixels D_s. This assists in measuring the distance of the void/gap pixels from the neighboring valid pixels (correct and accurate pixels). To portray the execution process, the pixels closer to the valid areas are more likely to be interpolated based on their nearby values.

$$D_s(x,y) = \sqrt{(x - x_p)^2 + (y - y_p)^2} \quad (2)$$

where x_p and y_p are the pixel location coordinates of the valid pixels nearest to the void/gap pixels.

Intensity Variance ($I.V.$) is the variance in intensity between the valid neighboring pixels indicating whether the void is within a homogeneous area (corresponding to Low variance) or near an edge *viz.* complex feature (corresponding to High variance).

$$I.V. = \frac{1}{N}\sum_{i=1}^{N}(I_i - \bar{I})^2 \quad (3)$$

where $\bar{I}$ denotes the mean intensity of the neighboring pixels and I_i corresponds to the individual intensities. Once the gradient, spatial distance and the intensity variance of the pixels are available, fuzzy membership functions are the primitive corresponding steps for each of the input variables. These functions categorize the input variables into different fuzzy sets, like High, Medium and Low.

For Gradient (*G*):

Low: Indicates smooth transitions, often in homogeneous regions.

Medium: Moderate changes in intensity, possibly near objects or boundaries.

High: Sharp changes in intensity, indicating edges or complex textures.

For Distance (*D*):

Close: Pixels are close to known valid pixels.

Medium: Moderate distance from valid pixels.

Far: Pixels are far from valid pixels, making interpolation harder.

For Variance (*V*):

Low: Indicates homogeneous regions where interpolation will be smoother.

Medium: Moderate variation between neighboring pixels.

High: Large differences between pixels, indicating edges or object boundaries.

The membership functions can be represented using a triangular function shown in Equation (4) below where a and b are the parameters that defines the range of the low set and in the similar manner, they can be defined for medium and high sets.

$$\mu_{Low}(x) = \begin{cases} 0, x < a \\ \frac{x-a}{b-a}, a \leq x \leq b \\ 1, x > b \end{cases} \quad (4)$$

3. Results and discussion

The tie points are generated once the images are aligned correctly. Tie-points depend upon the overlap in general and in this research, the forward and side overlap are set to 75% and 65% respectively. These points signify the density of the information and features available. The denser the tie-points would be, denser would be the point cloud which promises high efficiency in the resultant orthomosaic. Additionally, the utilization of the point clouds can be visualized in the analysis of evapotranspiration models which opens up new emerging fields of research using UAVs [17]. The orthomosaic image, shown in **Figure 5** even though contains voids and gaps but, unlike the dense point clouds and 3D mesh, it does not show redundant information which is not the point or object of interest. The utilization of orthomosaic imagery is of utmost essentiality but it is equally essential to maintain its homogeneity and uniformity throughout generation [18–20].

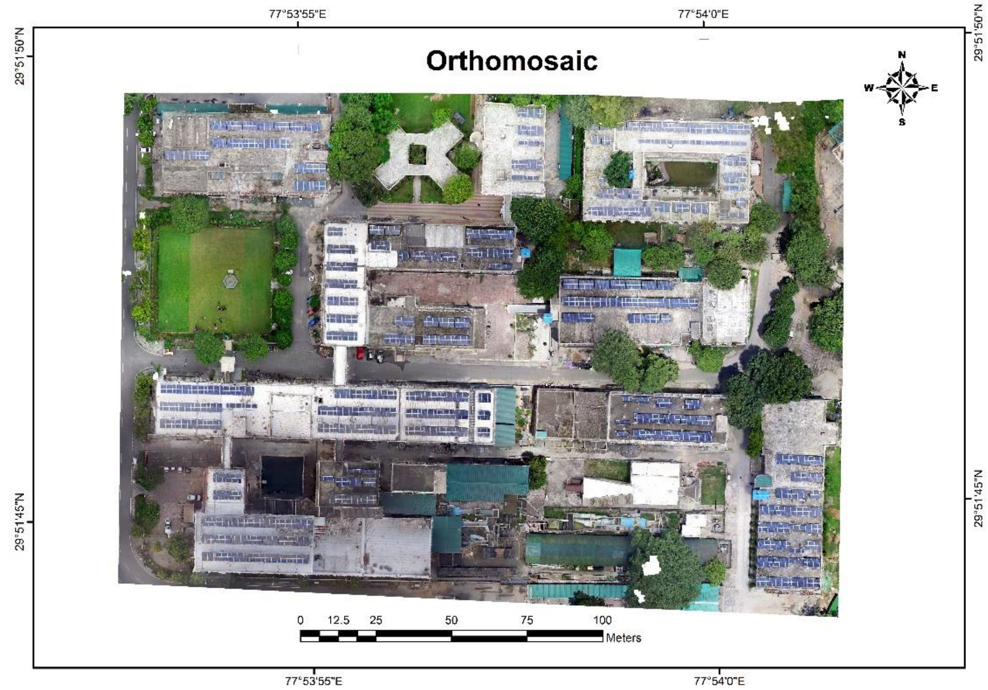


Figure 5. Orthomosaic generated initially consisting of errors and dead pixels.

It can be clearly seen from **Figure 5**, the initially generated orthomosaic image contains gaps and voids in the form of null pixels. These faulty pixels contain features and the necessary information about the area mapped by the UAV. The necessity of eradicating these faulty pixels is of highest priority and obtaining the enhanced fault-free image is utmost desirable. The faulty pixels (voids) arise due to multiple reasons. The primary reason pertains to irregular feature resolving process during the data processing comprising either water-based or tree-based features (prevalence of greenery characteristics) [21]. Secondary reasons could include faulty instruments or poor resolution of data acquisition. Once the ortho is itself not precise, the output extractions of elevation and other topographic models wouldn't be precise as well and in turn, imparting inefficiencies in the entire workflow of the spatial mapping [22].

The fuzzy logic approach employed in this study leverages gradient analysis, membership functions, and fuzzy rules to enhance the quality of the orthomosaic image. The gradient function helped identify areas with abrupt changes in pixel intensity, which often signify edges or faulty regions [23]. These gradients were then categorized using membership functions, which classify pixel characteristics into fuzzy sets such as "low quality," "medium quality," and "high quality." By utilizing these classifications, fuzzy rules were applied to determine the necessary corrections. For instance, if a pixel was identified as having a high gradient but low intensity, the fuzzy rule might dictate an enhancement by interpolating values from surrounding pixels [24]. This rule-based system enabled the dynamic correction of faulty or distorted pixels, filling in gaps and ensuring smoother transitions between image features. The combination of gradient detection, fuzzy logic, and membership-driven pixel adjustments provided a robust framework for rectifying and refining the orthomosaic, ultimately resulting in an enhanced, more accurate image for precise mapping and monitoring applications [25].

The process involves execution of gradient and evaluation of the spatial distance of valid and invalid pixels using Equations (1) and (2) shown in the methodological section. Once done, these primitively baselines a robust foundation for membership function estimation and correspondingly, the respective fuzzification functions. **Figure 6** shows the sample detection of voids/gaps in the orthomosaic image. Furthermore, through the estimation of membership function and corresponding fuzzification, the interpolation and/or rectification is done accordingly. The aforementioned process generates a voidless image *viz.* the rectified orthomosaic image as shown in **Figure 7**.

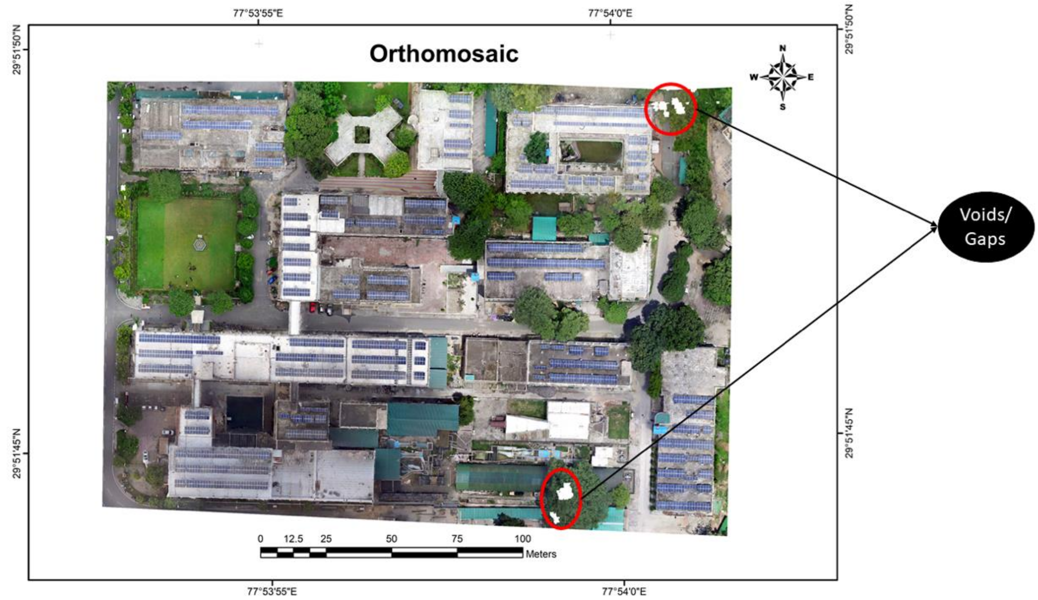


Figure 6. The null pixels or voids detected.

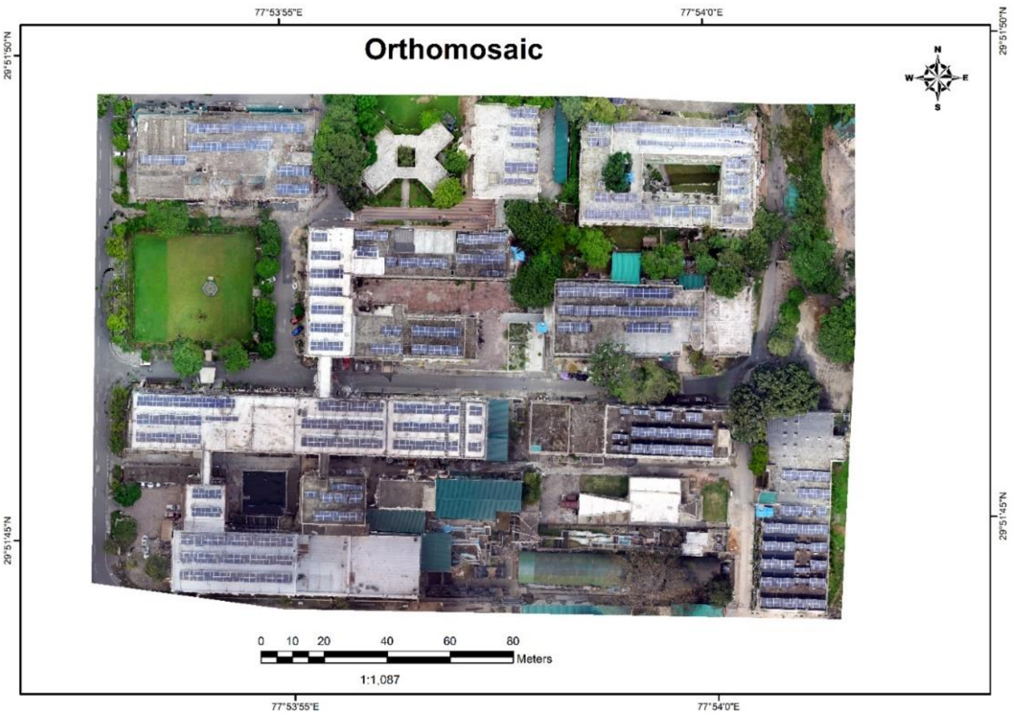
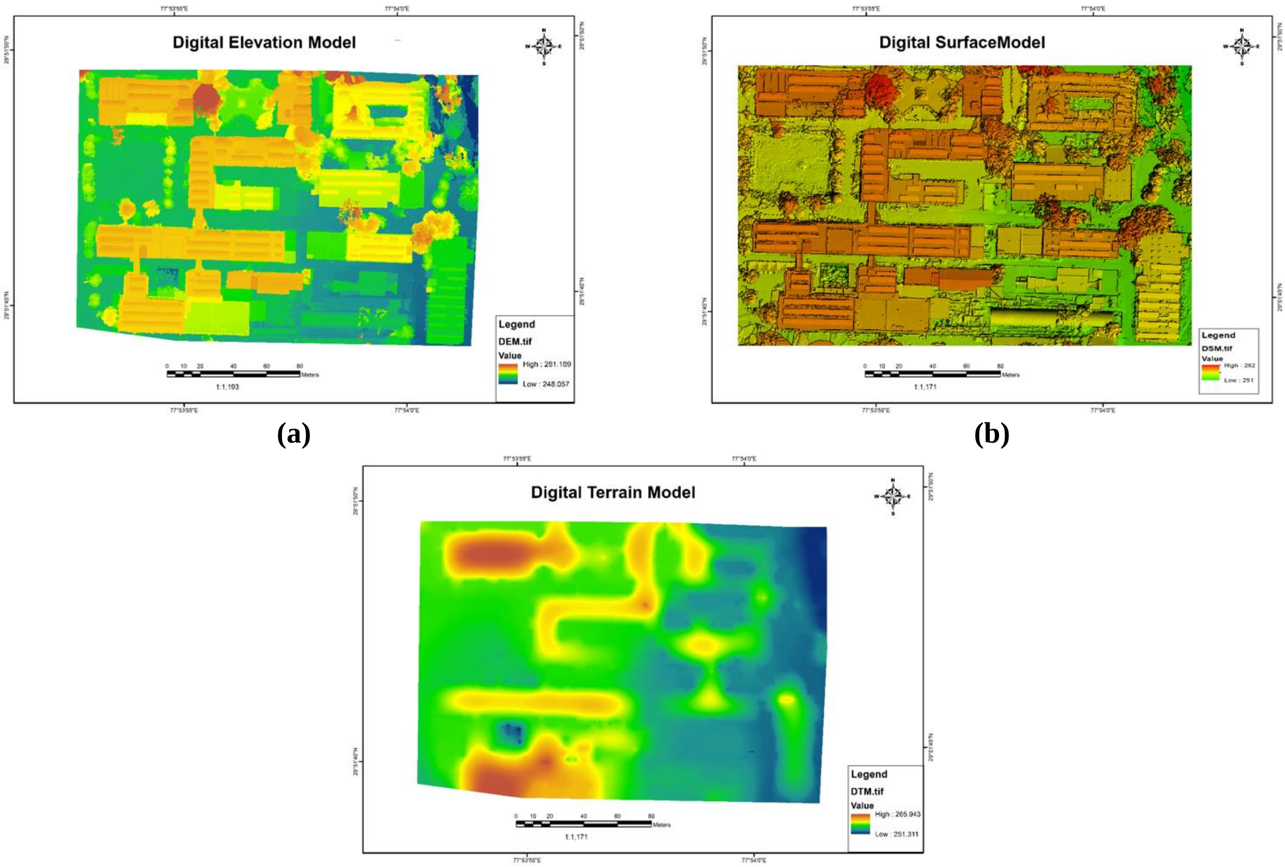


Figure 7. Enhanced orthomosaic image.

Correspondingly, the enhanced orthomosaic free of voids/gaps acts as a strong baseline for computing digital elevation models, digital surface models and digital terrain models [26–28]. They are presented in **Figure 8**.



(a) **(b)** **(c)**

Figure 8. Advanced models based on enhanced orthomosaic. **(a)** DEM; **(b)** DSM; **(c)** DTM.

4. Conclusion and future scope

In recent times, UAV-based data acquisition has become the preferred method due to its ability to capture high-resolution images with precise points of interest. Key deliverables in geomatics, such as point clouds, 3D meshes, and orthomosaics, serve as the foundation for generating Digital Elevation Models (DEM), Digital Surface Models (DSM), and Digital Terrain Models (DTM). However, challenges arise during the generation of point clouds and orthomosaics due to voids and gaps caused by incorrect feature matching, leading to distortions that compromise the accuracy of the outputs. This issue can be mitigated, though not entirely eliminated, by incorporating multiple flight datasets to improve feature matching and produce distortion-free outputs.

Orthomosaic generation is crucial for a wide range of applications, including environmental assessment, resource management, and sustainable utilization. This research focuses on generating orthomosaic imagery and enhancing it using fuzzy logic and morphological image processing techniques. The application of fuzzy logic is pivotal in modern research, and the integration of morphological techniques enhances the overall system's efficiency. The study involves creating the orthomosaic image, followed by its enhancement using fuzzy logic rules. Histogram equalization and edge-detection-based dilation methods are applied to identify and correct faulty or missing pixels within the orthomosaic. Additionally, interpolation techniques are used for further image enhancement, resulting in a sharp, clear orthomosaic free from pixel errors. In conclusion, the combined use of fuzzy logic, morphological techniques, and interpolation not only improves the quality of orthomosaic images but also offers a robust framework for addressing image distortions, contributing to more accurate and reliable outputs in geomatics applications.

The field of mapping and related applications require such enhanced form of orthomosaic images to carry out urban-planning, strategy making, rural studies, cropland monitoring and also the advanced application like post-disaster assessment. The edge-detected images can be utilized for fragmenting the numerous entities present in the orthomosaic like roads, structures, vegetation, water bodies, parking areas, residential areas, etc. The future of UAV-based technology is very bright and it serves as the most efficient tool for sensing any entity remotely. Traffic analysis and precision agriculture are the two most prominent applications and constant researches are spotlighted in these domains with emphasized and amplified magnitude involving AI and IoT approaches.

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