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Retrieval of Digital Elevation Models from optical sensors data in a Coastal Dune Systems: geomorphometric analysis for environmental monitoring

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Abstract - **Beaches and dune belts cover 20% of the world's coastline and represent one of the most vulnerable ecosystem due to their unique environmental, microclimatic, and spatial conditions. The Coastal Dunes System (CDS) is characterized by definite ecosystem and geomorphological features, often threatened by the anthropogenic pressure and specific challenges related to habitat fragmentation and environment vulnerability. The present work focuses on the integration of Unmanned Aerial Vehicle (UAV) RGB and LiDAR data for the environmental analysis of a CDS, located within a high-density vegetation area in the municipality of Lesina (Foggia, Italy). The primary objective is to assess the vegetation distribution, monitoring metrics of psammofile species referred to one Natura 2000 sites in southern Italy, specifically IT9110015 – "Duna e lago di Lesina - Foce del Fortore". In the study area, a major challenge for estimating vegetation volumes is the topographic analysis, as the dense vegetation matrix is too dense to let sensors signal go through. Hence, starting from the Digital Elevation Models (DEMs) and orthophoto obtained from the elaboration of the RGB/LiDAR data, it has been possible to distinguish the contribution of soil and vegetation by using the ExG spectral index. Consequently, by using the Natural Neighbor interpolation technique, it has been possible to reconstruct the Digital Terrain Model (DTM). Hence, the estimation of the total canopy volume was obtained from the Digital Difference Model (DDM), resulting approximately 42098.97 m^3. The following validation process occur comparing UAV-derived DDM with a reference object, analyzed by Terrestrial Laser Scanner (TLS). In summary, this study concerns the following activities: (i) acquisition and elaboration of TLS LiDAR and UAV RGB/LiDAR data; (ii) spectral indices calculation; (iii) spatial analysis and interpolation techniques; (iv) Digital Difference Model (DDM) retrieval; (v) volumes calculation; (vi) DDM-derived volume validation by comparing TLS data.**

I. INTRODUCTION

The study of Coastal Dune Systems (CDS) through remote sensing techniques assumes crucial importance in monitoring ecosystem integrity and resilience [1]. CDS is considered one of the most fragile ecosystems and is compromised, sometimes irreversibly, by both direct and indirect anthropogenic pressure [2]. These ecosystems host a highly specialized flora, constituting a focal point of biodiversity due to the loss of biological diversity and habitat fragmentation [2]. Nowadays, analyzing vegetation through remote sensing techniques has become crucial for the observation of eco-systems' integrity and resilience [3,4]. Accordingly, the data acquisition can involve in the use of sensors applied on Unmanned Aerial Vehicles (UAVs), a high-spatial resolution tool for the environmental monitoring [5,6]. This work features the integration of RGB and Light Detection and Ranging (LiDAR) data derived from UAV survey within a CDS. Furthermore, this work aims to extract and manage point clouds and mesh models, Digital Surface Model (DSM), Digital Terrain Model (DTM), and Digital Difference Model (DDM) for the study of a very dense vegetation environment. As seen in bibliography, the DDM can be an important requirement to compute canopy architecture, monitoring habitat reduction and fragmentation [7]. Currently, UAV technology results fundamental for the geomorphological and ecosystem analysis, representing accurate DEMs useful for land management, soil analysis, and watershed management [8]. Furthermore, several studies have demonstrated that DEM's resolution and scale can significantly influence the interpretation of geomorphic features and ecosystem metrics [9]. Accordingly, the validation of DEMs is essential for identifying uncertainties and ensuring the reliability of spatial data outputs [10]. Hence, in densely vegetated environments, it can be difficult for positioning and measuring Ground Control Points (GCPs) due to logistical constraints, inaccessibility, and consuming time procedures. Indeed, traditional ground-based vertical accuracy assessments may be insufficient of feasible in such contexts [10]. In this study is shown an alternative approach involving the use of a volume-based validation method, wherein known object geometries, comparing Terrestrial Laser Scanning (TLS) data, used as reference for the accuracy assessment. This strategy shifts the focus from vertical points comparisons to three-dimensional volumetric congruence, which can be particularly advantageous in ecosystems where vegetation structure is complex and spatially heterogeneous.

II. Material and methods

A. Geographical setting of the study area

The study area is sited in Lesina (Fig. 1), in the province of Foggia (Puglia region, Italy).

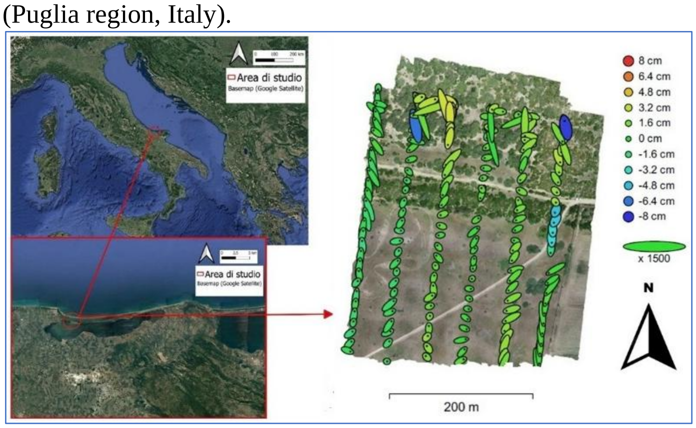

Figure 1. Geographical setting of the study area. Right, orthophoto (Area ~0.11 km^2, ~ 11 ha) where are represented error estimations. Z error is represented by ellipse color. X,Y errors are represented by ellipse shape.

This study focuses on one Natura 2000 sites in southern Italy, specifically IT9110015 – "Duna e lago di Lesina - Foce del Fortore". The area of interest is characterized by an extensive dune systems, presenting an heterogeneous vegetation path, as it encompasses multiple psammophile types of woody vegetation dominated by junipers and other Mediterranean sclerophylls.

B. Unmanned Aerial Vehicle (UAV) and Emesent's Backpack RTK

Surveys were conducted using a MATRICE 300 RTK drone, with an integrated RGB sensor and LIDAR. The mission was conducted with the following flight parameters: (a) flight altitudes (30 m asl); (b) 80% front/side image overlap ratio; (c) flying speed of 5 m/s. Moreover, Emesent's Backpack RTK was used for the validation procedure, ensuring high-precision volume assessment. Emesent's Backpack RTK enables automated georeferencing and drift correction for backpack-based LiDAR surveys, rationalizing the need for GCPs. Hence, by combining real-time RTK positioning with Simultaneous Localization and Mapping (SLAM), it ensures high-precision point cloud retrieval.

C. Data processing

The methodology used in this study means to estimate vegetation parameters (e.g., areas and volumes), starting initially from the generation of a point cloud layer, and, consequently, from the obtainment of orthophoto, DSM, DTM, and DDM, respectively having a spatial resolution of 20, 40, 40 and 40 centimetres. The data are processed through open-source tools, concerning the use of GIS (QGIS Desktop 3.34.13), photogrammetry (OpenDroneMap), 3D modelling (Cloud Compare v. 2.13.1), and data computation software (RStudio and Python). Initially, the workflow provides a dense points cloud integration starting from RGB and LiDAR data. Consequently, the generation of an orthophoto and a DSM occurred, needed for the extraction of a vegetation mask by applying spectral indices such as the Excess Green (ExG). Hence, it has been able to isolate the contribution of the vegetation from the original DSM by choosing pixel thresholds [11]. So, from the DSM has been eliminated the contribution of vegetation, leaving areas characterized by *NoData* values. Thus, to obtain a DTM, the Natural Neighbor interpolation technique is used to fill these areas with significant elevation values of their surroundings. Following, the DTM was subtracted from the DSM for obtaining the DDM. All the previous layers were manually cleaned from noise disturbance by operating directly on the point cloud by using CloudCompare tools. Thus, vegetation areas and volumes are designed from the DDM computation, where canopies' total volume calculation occurred by computing the sum of the product of each elevation value with its corresponding pixel area. In order to not overestimate the total canopy volume value, since it is not the entire volume of the voxel that is filled with canopy, a correction factor was applied to exclude the void gaps typically present within the vegetation structure. Based on a visual estimation conducted on a representative 2x2 meter area, it was observed that approximately 30% of each unit volume of vegetation was composed of air. Therefore, the total calculated canopy volume was adjusted by multiplying it by a coefficient of 0.70, reflecting an estimated 70% actual vegetative material within the total voxel volume. This empirical approximation allowed for a more realistic assessment of the effective canopy volume in the study area.

D. Accuracy metrics

To validate the model, a volume assessment is provided by comparing a known object detected from UAV and TLS investigations. Accuracy of the DDM-derived volume is calculated by comparing reference volumes derived from TLS survey. Data are processed in CloudCompare, using both point cloud (.las) and mesh (.obj) formats. Hence, V_{LAS} (derived from the TLS point cloud) and V_{OBJ} (derived from the TLS mesh model) volume references are obtained. As follows, the validation occur by estimating DDM-derived volume against the reference volumes (P_{LAS} and P_{OBJ} as volume ratios):

$$P_{LAS} = \frac{V_{DDM}}{V_{LAS}}, P_{OBJ} = \frac{V_{DDM}}{V_{OBJ}}$$

Moreover, the relative errors for point cloud ($E_{REL,LAS}$) and mesh model ($E_{REL,OBJ}$) were calculated, determining the estimation as percentage of the reference.

$$E_{rel,LAS} = \left|\frac{V_{DDM} - V_{LAS}}{V_{LAS}}\right| * 100, E_{rel,OBJ} = \left|\frac{V_{DDM} - V_{TLS}}{V_{TLS}}\right| * 100$$

III. Results

The work starts with the acquisition of UAV RGB and LiDAR data, from which a dense cloud points has been obtained, resulting from the integration of the previous. Firstly, from the orthophoto, the ExG index is obtained, classifying vegetation and soil classes. Hence, the vegetation pixels were deleted, obtaining a raster with only topographical information. Consequently, to fill these areas with significant elevation values of their surroundings, the Natural Neighbor interpolation technique was used (Fig. 2).

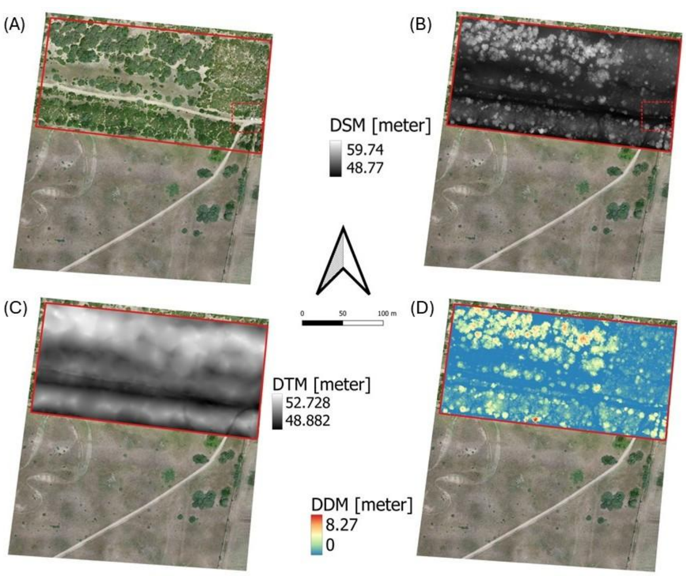

Figure 2. Representation of the main layers used in this study. A) Orthophoto with spatial resolution of 2 cm. B and C) Respectively, DSM and DTM of the study area with spatial resolution of 40 cm. D) DDM representing trees' heights in the study area (spatial resolution: 40 cm). In A and B is shown the AOI used for the validation of the volumes model. All the images are imported into QGIS software (v. 3.28).

Thus, by using the QGIS Raster Calculator, the DTM is subtracted from the DSM to obtain a DDM, concerning trees' heights in the area of interest. The canopy volume values are estimated by measuring the area of each pixel (0.40x0.40m) occupied by vegetation and multiplying the obtained data by the height values relative to the altitude of each selected pixel. Thus, to approximate the volume using the following equation, the canopies are considered as 2.5D geometries.

$$\text{Total canopy volume} = \sum_{i=1}^{n} (area_j * height_j)$$

where *j* is the pixel of interest. The spatial resolution of each pixel is 0.40 m, resulting in an individual pixel area of 0.16m^2.

Hence, from the DDM raster, a topographic dataset is derived to assess spatial distribution of elevation/volume values and their statistical characteristics. Elevation statistics indicate a right-skewed distribution with a long tail toward higher elevation values. The subset of elevation values between 0.5 m and 8 m was analysed separately (Fig. 3).

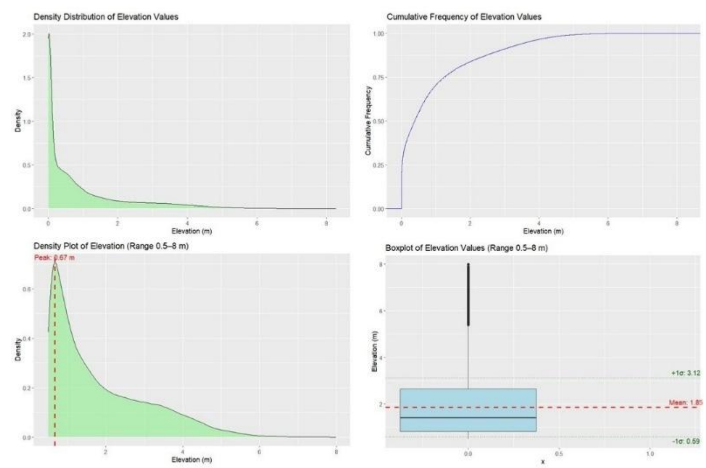

Figure 3. Descriptive statistics, boxplot of elevation values, and density analysis in the range of 0.5-8 m.

From the previous data, the total canopy volume estimation is provided. Statistics indicate a range spanning from 0 to 1,32 m^3, a mean of 0.15 m^3, and a standard deviation of 0.20 m^3. Finally, the estimation of the total canopy volume value results approximately 42098.97 m^3.

The validation process relates the volume error assessment between the UAV RGB/LiDAR and TLS 3D LiDAR RTK-SLAM data. So, topographical analysis, 2.5D and 3D modelling of a known object were gained from the previous data, considering object volume assessment in an AOI within the study area. Below is a summary table (Table 1) and a spatial overview (Fig. 4) for the sample object.

Source	V_{LAS} (m^3)	V_{OBJ} (m^3)	P_{LAS}	P_{OBJ}	$E_{rel,LAS}$ (%)	$E_{rel,OBJ}$ (%)
UAV RGB/LiDAR	18.90	19.10	1.12	1.03	12.10	2.85
TLS	16.86	18.57				

Table 1. Results of the DDM (UAV-derived) validation procedure by using TLS reference volumes. The accuracy metrics P and E_{rel} are based

on the volume ratio and the relative error, expressed as non-dimensional and percentage values, respectively.

The comparison between DSM-derived volume and TLS reference volume is obtained both from point cloud and mesh model. The volume ratio P_{LAS} and P_{OBJ} result 1.12 and 1.03, respectively. The point cloud-based reference $E_{rel,LAS}$ exhibits a relative error of 13.26%, suggesting a moderate overestimation. Instead, the mesh-based reference $E_{rel,OBJ}$ presents a relative error of 3.20%, indicating a closer correspondence.

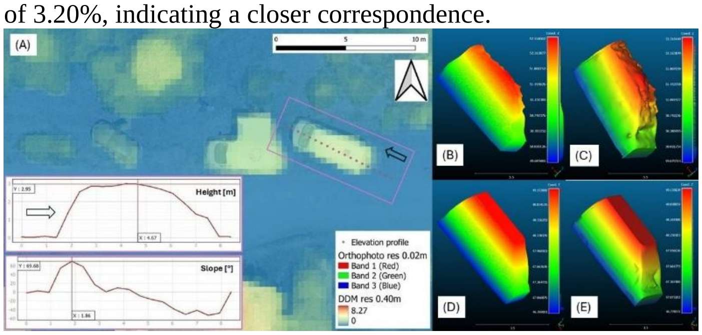

Figure 4. Known object considered for the canopy volume validation. A) DDM, elevation and slope information; B) DDM based point cloud; C) DDM based mesh model; D) TLS-based point cloud; E) TLS-based mesh model.

IV. Discussion and Conclusion

Canopies' areas and volumes estimation set the stage for a biodiversity analysis about habitat reduction and fragmentation within CDSs. Previous findings related to DTMs acquisition from aerial photogrammetric and LiDAR data showed difficulties for the vegetation contribute monitoring [12]. In this study, data extraction has been provided elaborating UAV RGB and LiDAR data. The workflow include the calculation of a DTM, based on a DSM characterized by a high dense vegetation pattern. Geospatial data analysis has permitted the elaboration of data, reducing signal noise in Cloud Compare and determining, through spatial interpolation techniques, topographic values on unknown unsampled points (Natural Neighbor). Consequently, the difference between the DSM and DTM allow to obtain the DDM, representing the height canopy value on each pixel along the area of interest. Accordingly, the total canopy volume estimation is provided, resulting in approximately 42090.97 m^3. Instead, the innovative approach in this study concern the validation process, comprising a known object within the study area for assessing the vertical and volume accurateness. Results have suggested that the DDM-based volume slightly overestimates the measurement, with higher accuracy when validated against mesh-derived volume references. Accordingly, future prospectives will provide information and elaboration of data through an inferential statistical approach, considering the uncertainty of the DTM obtained, fundamental for the DDM extraction. Moreover, future works will plan the measurement of more known object for the vertical accuracy and an optimal volume error estimation. The comparison of these findings underscores the importance of considering the advance on vertical accuracy assessment. In conclusion, this study offers a comprehensive understanding of the spatial distribution of volume's values through raster, point cloud, and mesh model. These insights can be crucial for informed decision-making, particularly in biodiversity, where understanding spatial variability and habitat fragmentation is fundamental.

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