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sUAS Remote Sensing for Closed-canopy Tree Inventory on Earthen Dams

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Abstract

More than half of the U.S. dams are privately owned and experienced the overgrowth of trees. There is a need to improve dam inspection and maintenance in a timely manner. Small Unmanned Aircraft Systems (sUAS) have been increasingly utilized for near-surface landscape mapping and reconnaissance. This study tests an sUAS protocol of closed-canopy tree survey on earthen dams. A DJI Matrice 100 flight was launched on September 22, 2020. The orthoimage and 3D point cloud are extracted, and the canopy height model is built. Treetops and crowns are delineated using an integrated watershed segmentation and image segmentation procedure. The results include a tree survey inventory that contains the locations, tree heights and crowns of 284 trees growing on the downslope of the dam. Given the flight flexibility and fine 3D details acquired from inexpensive drones, sUAS has a high potential for assessing tree overgrowth toward remediation solutions of earthen dams.

Keywords: sUAS remote sensing, watershed segmentation, 3D tree inventory, earth observation

1 Introduction

Dams provide beneficial functions such as flood control in our living environment. Of the 90,000 dams listed in the U.S. National Inventory of Dams, 65% are privately owned earthen dams, ageing and lacking maintenance (NID 2018), raising serious concerns about their hydraulic stability against extreme weather events. Trees growing on dams, for example, have been recognized as an attributor to dam erosion. Tree roots loosen the soil mass and create root cavities that may lead to seepage failure (FEMA 2005). Remediation varies depending on the size, health, and location of trees growing on the dam. Knowing the location and structural information of trees helps to understand the stability and potential remediation of a dam. However, earthen dams are generally small in size. Conventional remote sensing, even the high-resolution satellite imagery freely accessible via web platforms such as Google Earth, could not reach the resolution needed for a detailed tree survey on these dams.

Defined as *Personal Remote Sensing* (Jensen 2017), small Unmanned Aircraft Systems (sUAS), or drones, have been increasingly utilized for timely near-surface observations. Recent technological advancements have equipped drones with an improved capacity of payload, sensors and flight time to accomplish various field missions. With highly overlapped images taken from a drone flying above the canopy, the 3D landscape can be obtained (Dong et al. 2020). It makes the sUAS imaging superior to the 2D satellite/airborne remote sensing. The low-cost sUAS may also outcompete LiDAR on affordability, accessibility and operational efficiency in the vertical dimension.

This study aims to test the feasibility of sUAS for 3D canopy reconstruction and tree survey on earthen dams experiencing an overgrowth of trees. It indicates the potential of sUAS remote sensing in dam inspection. With the rapid development of sUAS technology, it may be operationally deployed for improved observations of land properties to assist societal decision making.

2 Materials and Methods

2.1 Study site and data sets

An earthen dam, the Sweet Bay Pond Dam in downtown Columbia, South Carolina, is selected as the study site. It is 180 meters long and is a state-regulated C1 dam, i.e., with high hazard potentials in loss of life or severe damage to infrastructure (FEMA 2005). As shown in the fall-season picture (Fig.1), dense trees grow into closed-canopy woodland on the downslope of the dam. Along with tree overgrowth, signs of seepage erosion on the downslope were spotted during our field survey. The most common tree is black gum (*Nyssa sylvatica*) that is leaf-off and shows a light grey tone in the figure. Another dominant tree is tulip poplar (*Liriodendron tulipifera*), which is still green but starts to show its fall colour. Loblolly pine (*Pinus taeda*) remains dark green.

Figure 1: An oblique view of Sweet Bay Pond Dam in Columbia, SC. Photo was taken with a DJI Mavic Pro on October 26, 2019.

The sUAS data was collected on September 22, 2020, using DJI Matrice 100 (M100) assembled with a 5-band MicaSense RedEdge-M sensor: blue, green, red, red edge, and near-infrared (NIR). The flight was made around noon on a sunny day at a flight height of 90m above ground. The images were taken at an 85% endlap and 80% sidelap. Ground control points (GCPs) was collected with a survey-grade GNSS Base+Rover unit. Forty-two trees were surveyed, and tree heights were measured. Also used in the study is the U.S. Geological Survey (USGS) LiDAR point cloud product collected in 2010 at 1.4m footprint and 18cm vertical accuracy.

2.2 Approaches

The sUAS images are calibrated in the Pix4DMapper package. Relying on the Structure from Motion (SfM) technique (Westoby et al. 2012), the 3D perception of the landscape is resolved, enabling the extraction of orthoimage and point cloud. The orthoimage is resampled to 5cm pixel size. With the 3D mass points from the point cloud, the Digital Surface Model (DSM) is created that represents the top elevation above ground. The Digital Terrain Model (DTM) is the elevation of the bare earth surface. Since sUAS point cloud is based on photogrammetry, it only contains a single z value at a given (x,y) location. Therefore, the DTM is not available in vegetated areas where the camera cannot view the ground.

Here we propose to integrate the airborne LiDAR with sUAS point clouds to create the DTM. LiDAR allows multiple returns at a single location owning to the strong penetration capacity of laser signals. Ground returns in LiDAR product are extracted, which fairly represent the terrain on the bare earth. For sUAS point cloud, point returns on open ground (no shrubs or forbs) such as dam crest are also extracted. Both sources of ground returns are merged to build the DTM product. Our previous study compared their ground returns on a bare dam, confirming that the sUAS-extracted elevation is comparable to LiDAR elevation (Morgan et al. 2020). Therefore, geo-matching of the two sources is not performed.

The DTM and DSM raster layers are resampled to 20cm cell size. The Canopy Height Model (CHM) is simply calculated as (DSM – DTM), which represents the height of all cells above ground (Mielcarek et al. 2018). Only pixels with CHM >10m are considered as tree canopy. The topmost point of an individual tree (treetop) in the CHM is identified using a Variable-sized Window Filter (Popescu and Wynne 2004). It identifies the local maxima with a height-dependent crown searching window. A circular searching window is used in this study, and the extracted local maxima represent treetops of individual trees.

Two approaches are adopted to extract tree crowns. A Marker-Controlled Watershed Segmentation approach (Meyer and Beucher 1990) is first applied. Assuming a tree crown follows the mathematical morphology of an inversed watershed, the approach divides the CHM into multiple segments or tree crowns. This procedure works fine in delineating standalone trees against the ground. However, poor performance has been commonly observed in closed-canopy when tree crowns overlap each other. The dam in this study has an overgrowth of trees, which often grow in closed canopy at a similar height. The CHM-based watershed segmentation could not effectively delineate these overlaid crowns. The orthoimage is then used to leverage the deficiency. The RedEdge-M image depicts the spectral variation of trees in the visible-NIR region. Adjacent pixels with similar spectral and textural features are grouped into segments using the Mean Shift approach, a nonparametric classifier to delineate clusters with complex shapes from multimodal feature space (Comaniciu and Meer 2002).

Tree crowns are thus extracted by intersecting the watershed segments and image segments. The colour information on the orthoimage allows breaking large watersheds while the height-based morphological feature breaks large image classes. Finally, the extracted tree height is compared with field measurements for accuracy assessment. Two commonly applied evaluation metrics are used: the root mean square error (RMSE) and the mean absolute error (MAE).

3 Results and Discussion

3.1 Orthoimage and point cloud

Fig.2 displays the sUAS orthoimage overlaid with the point cloud. The flight date is in early fall. As shown in the orthoimage, trees are still green but start to show signs of fall colour (e.g. the darker tone of black gum trees). The point cloud is visually continuous due to its highly dense points at cm-level spacing. An average density of 70 points/m^2 reveals more structural details of the tree canopy than the 0.5 points/m^2 USGS LiDAR product. The study site has an elevation range of 47.5-79.06m above sea level. Dam crest and open areas have lower elevation with a blueish tone. For trees in the woodland, taller ones stand out in a reddish tone. The large gaps in the top right of the figure represent data missing from calibration errors of sUAS images.

3.2 Digital terrains and canopy height

The sUAS point cloud on the dam crest and open areas are extracted after removing all points that have apparent vertical structures. The LiDAR ground returns have a much lower density, but there are enough ground points under the tree canopy. The integrated ground points from both sources are used to create the DTM. The grid size is set to 20cm to compensate for the two data sources. With densely distributed sUAS point cloud, canopy height is extracted in high details. Fig.3a demonstrates the 3D profile of a pine tree in which all points align to make up its crown's shape. The treetop is easily measured at the height of 27.66m. In the canopy height map (Fig.3b), trees grow into a closed canopy. Taller trees

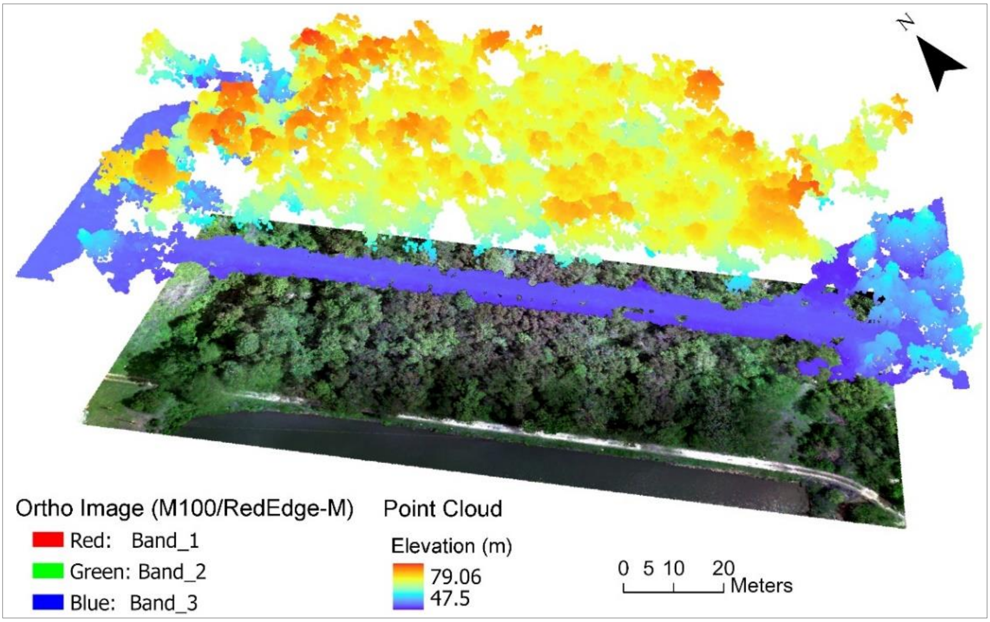

Figure 2: The sUAS-extracted orthoimage and point cloud.

stand out as individual clumps in a dark green tone. Similarly, the TIN noises in the southwest end of the mission area reflect image calibration errors.

3.3 Treetop and crown delineation

The CHM allows the delineation of treetops and crowns from the continuous canopy cover. A treetop is a point with the local maximum of CHM that represents the topmost point of a tree. One tree is assumed to have one treetop point. A total of 286 crowns are extracted (Fig.4). A treetop point is associated with a watershed segment but not necessarily the image segment.

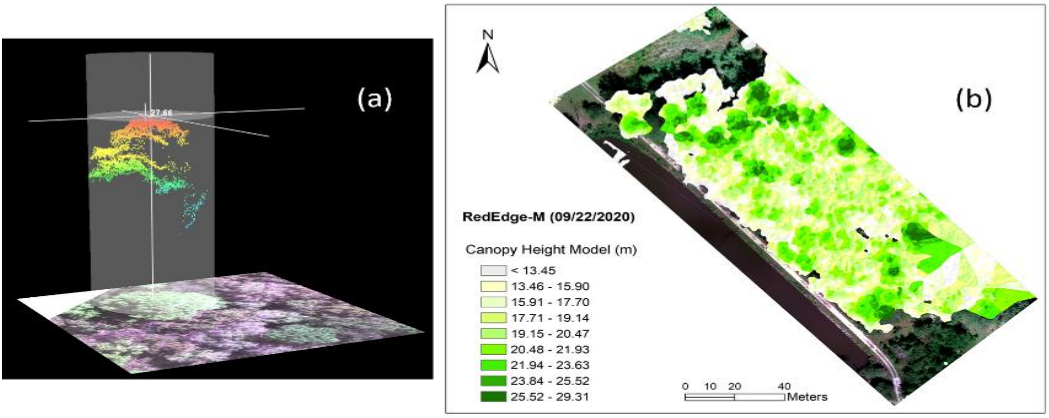

Figure 3 Example 3D profile of a pine tree (a) and the CHM map (b).

Therefore, some tree crowns do not have their treetops marked. For trees with relatively standalone crowns, for example, those at the northwest entrance, circular-shaped tree crowns are identified. Inside the woodland, trees turn to grow together in a close canopy; therefore, tree crowns become irregularly shaped and inter-connected.

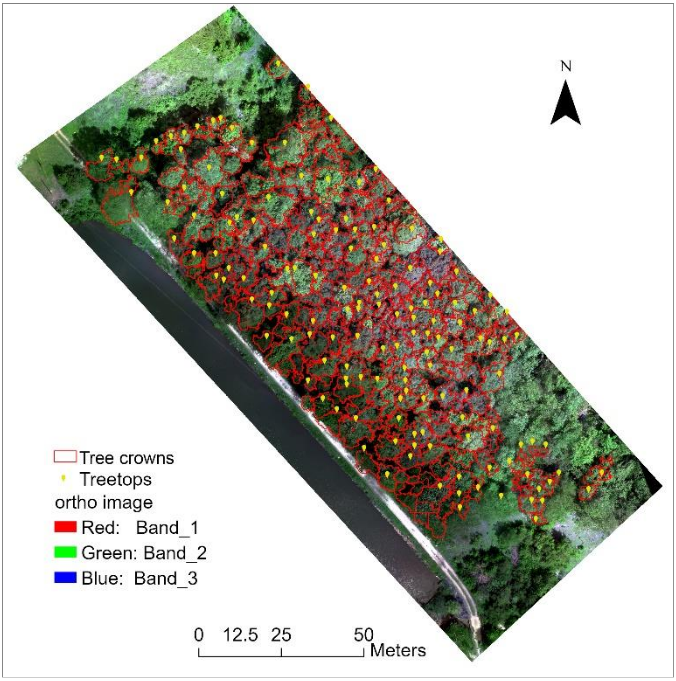

Figure 4 The extracted tree crowns and treetops.

With 27 randomly selected points on the flat dam crest, the average sUAS-extracted elevation is 3.59cm higher than the LiDAR-recorded elevation, indicating that the sUAS point cloud has decent vertical accuracies. Of the 42 field-measured trees, the sUAS-extracted tree height has a linear agreement with field records ($r = 0.517$, $p<0.001$). However, the sUAS results have an omnidirectional overestimation, with the MAE and RMSE values 6.59m and 7.37m, respectively.

The overestimation of tree height may partially come from the imperfect field measurements using Nikon Forestry Pro. In the ideal circumstance of flat terrain and open areas, the laser rangefinder can reach a 1.0m accuracy. At our study site, trees grow in a dam downslope that is lower than the crest. Due to dense tree covers, tree height can only be measured by the surveyor standing at the crest. Its readings are inevitably lower when assuming a flat ground of the woodland. The tree base is also easily biased by a dense understory canopy. A more rigid field experiment will be conducted in the future for an improved validation process.

Integrating orthoimage and point cloud enables the 3D imaging that considers both colour and height information in canopy reconstruction. It is superior to conventional remote sensing due to the much finer spatial details. We can launch flexible sUAS missions to collect data over the interested area at desired dates. In this sense, sUAS serves as user-controlled remote sensing or "*personal remote sensing*" as defined in current literature. Despite these technical and operational advances, image calibration errors are a common drawback for sUAS missions over dense forests. Our M100/RedEdge-M has a net weight of 2,663g, and the mission has a calibration rate of 92% at a 90m flight altitude. Uncalibrated images result in data missing. Another challenge of the low-cost sUAS for 3D tree survey in closed-canopy is the need for bare earth surface because sUAS point cloud only records the elevation of the top canopy. Nowadays, the LiDAR data products have been popularly available, which provide a reliable source of ground elevation for sUAS deployment.

Overall, this study demonstrates the high potential of sUAS in quantitative tree survey in dense forests. Owing to its fine spatial details, time efficiency and flexibility in data acquisition, sUAS remote sensing could bridge traditional remote sensing and intensive *in-situ* field experiments in monitoring our ever-changing environment. Earth observation for social well-being is an essential aspect of the Digital Earth information system. As the 3D imaging for dam inspection showcased in this study, sUAS may provide improved Earth observations for our society.

4 Conclusion

This study tests the feasibility of sUAS for 3D tree survey of closed-canopy woodland. With the reconstructed 3D canopy from sUAS orthoimage and point cloud, treetops are extracted using a local maxima approach. Tree crowns are delineated by an integrated approach of watershed segmentation and image segmentation. A tree survey inventory is established that includes a total of 284 trees with records of the location, height, and crown size. A comparison of elevation on the dam crest shows that the M100 point cloud has decent vertical accuracy against LiDAR (<5cm). The sUAS-extracted tree height indicates an overestimation of 6-7 meters, although it may partially attribute to imperfect field measurements. Image calibration error in dense woodland remains an issue for drone deployment, which needs further investigation of flight configuration for more stable sUAS missions. Nevertheless, the study indicates that sUAS could become an efficient tool of 3D tree surveys for engineers to assess the impact of tree overgrowth on dam performance. With high-resolution satellite imagery readily available, 3D imaging from sUAS offers consumer-oriented updating of our living environment to assist societal decision making.

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