Summary of Doctoral Thesis

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Title	Understanding forest ecosystems in steep mountains using Unmanned Aerial Vehicles, Yamagata, Japan

Mountain forests provide valuable support to watershed bio-activities, ecosystems with complex structure and composition . Most of watersheds are composed of natural forests and of forest. These forest ecosystems are of difficult accessibility and many of their characteristic such as growth healthy composition are unknown.

In recent years, Unmanned Aerial Vehicle (UAV) have become available for civilian use and in a short period of time has become one of the most essential tools in the study of natural ecosystems and especially on the investigation of forests where terrain constraints the access to close observations or measurements. UAV provide very high resolution of spatial and temporal data with high flexibility of maneuvering. Modeling of forests using overlapped UAV-acquired images and the photogrammetry technique, known as structure from motion (SfM) makes it possible to obtain highly detailed 3D information of forest ecosystems. Thus, UAV is a reliable alternative to the traditional energy time consuming field work or to the imprecise (because of poor resolution) satellite images. Different sensors can be attached to UAVs but Digital RGB cameras have shown to be cost efficient and the most versatile sensor to capture forest characteristics with a high level of detail.

Numerous methodologies and approaches are used to take full advantage of UAV images information, but the topography, specifically steep terrain, is an important factor to be taken into consideration for the interpretation of those images. Thus, the image quality or the correct representation of forests in steep slopes improves the overall understanding of the forest ecosystems, since the position of trees along the slope are considered in the image analysis. Terrain relief variability compromises the ground sampling distance (GSD) homogeneity and the image details along the slopes (mainly in the lower section of the slopes) since the flying height of UAVs is always higher than that at the top of the slope, when the UAV is flying at a fixed height.

Therefore, in the first chapter of this study, UAV-acquired images were collected taken into account the terrain and the performance of algorithms on the generated images after processing was conducted. The terrain awareness function (TAF) provided by the DroneDeploy software is based on publicly available digital surface model (DSM) with a coarse resolution which allows the UAV (Mavic 2 Pro) to follow the relief of the terrain. Thus, the UAV always keeps the flying height in relation to the ground, regardless of the position along the slope. The performance of TAF in the flying mission is compared with a flying mission where TAF was not used (NTAF) and the UAV is flown at a constant height, meaning that the forest at the upper part of the slope is closer to the UAV and the forest at the bottom of the slope is further from it.

The study area was dominated by fir (*Abies mariesi*) trees on a 20-degree slope. In order to test the improvement of image quality on the orthomosaics and the Canopy Height Model (CHM) an encode tree elevation value file produced by using TAF and NTAF, two algorithms were used to automatically find trees (treetop detection) in the forest. On the one hand, Algorithm 1, connected component, was a sliding window-based approach that screen the CHM altitudes of the pixels in decreasing order building trees canopy and then assigning a point to the maxima. On the other hand, Algorithm 2 point at the maxima height after applying several morphological operations. When using TAF, the dense point clouds (DPCs) were denser and more homogeneously distributed along the slope than when using NTAF. Algorithm 1 showed a 5% improvement in treetop detection accuracy when using TAF (86.55%), in comparison to NTAF (81.55%), at the minimum matching error of 1 m. In contrast, when using algorithm 2, treetop detection accuracy reached 76.23% when using TAF and 62.06% when

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using NTAF. Thus, for only treetop detection, NTAF can be sufficient when a sensitive algorithm such as Algorithm 1 is used. However, TAF showed more precision by less tree matched more than one to the ground truth point (3.2%) of detected treetops at 2m margin error. Repeated points, led to an overestimation of detected treetops.

In the second chapter we assessed TAF treetop detection improvement threshold in a steeper slope (28°) and complex terrain using algorithm 2. The hypothesis was that in a steeper slope a higher difference in the treetop detection algorithm would be found. The study site was a mature cedar forest. TAF was based on self-generated DSM (not publicly available as in the previous case), which is expected to improve the quality of flying path of the UAV. We assess the performance of treetop detection algorithm in comparison to NTAF during UAV data acquisition data. Our study site was a mountainous complex terrain. Most of the treetops were detected. The result shows 93.95% of treetops detected when using TAF and 91.42% when using NTAF with a 2.5m margin of error. Using TAF decreased matching repetition and even in highly sharp slope terrain the improvement was smaller than expected.

In the chapter 3, TAF (to assure homogenous orthomosaic quality) and a semi-automatic python tree species classifier was used for four tree species mapping in a mixed forests composed of beech (*Fagus crenata*), oak (*Quecus crispula*), larch (*Larix kaempferi*) and maple (*Acer spp*.). In this forest, the analysis of Nitrogen stable isotope (δ15N) and N concentration from foliar samples was performed. The results of individual trees were extrapolated from tree to mixed forest stand Nitrogen distribution using the automatic tree species classification and their model distribution within the forest. Thus, using high quality UAV acquired image orthomosaic in steep terrains, automatically detected tree distribution and biophysiological parameters were combined.