COMPLEMENTING FOREST INVENTORY DATA WITH INFORMATION FROM UNMANNED AERIAL VEHICLE IMAGERY AND PHOTOGRAMMETRY

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Abstract—Although a prerequisite for an accurate assessment of tree competition, growth, and morphological plasticity, measurements conducive to three-dimensional (3D) representations of individual trees are seldom part of forest inventory operations. This is in part because until recently our ability to measure the dimensionality, spatial arrangement, and shape of trees and tree components precisely has been constrained by technological and logistical limitations and cost. Active remote sensing technologies such as airborne LiDAR provide only partial crown reconstructions, while the use of terrestrial LiDAR is laborious and has portability limitations and high cost. In this work we capitalized on recent improvements in the capabilities and availability of small unmanned aerial vehicles (UAVs) and light and inexpensive cameras, and developed an affordable method for obtaining precise and comprehensive 3D models of trees and small groups of trees. The method employs slow-moving UAVs that acquire images along predefined trajectories near and around targeted trees and computer vision-based approaches that process the images to obtain detailed tree reconstructions. We present a step-by-step workflow which utilizes open source programs and original software. We anticipate that further refinement and development of our method can render it a valuable source of tree dimensionality information, complementary to the data recorded in traditional forest inventory field operations.

INTRODUCTION

To date, precise tree crown dimensionality and location data supportive of a rigorous modeling of individual tree growth has been inhibited by feasibility, logistics, and cost. Measuring crown characteristics by using established inventory methods is very time consuming and hardly affordable outside special projects. Existing remote sensing methods of measuring tree crowns provide only partial crown reconstructions. Airborne LiDAR data acquisitions require prolonged planning and are costly. Recently, unmanned aerial vehicles (UAVs) equipped with inexpensive, off-the-shelf panchromatic cameras have emerged as a flexible, economic alternative data source that supports the retrieval of tree dimensionality and location information. Flying at low altitude above the trees and with the camera oriented at a nadir view, UAVs acquire high-resolution images with a high degree of spatial overlap. In such conditions, a point on the surface of a tree crown or a small object on exposed ground is visible from many positions along the UAV trajectory and is depicted in multiple images. Automated photogrammetric systems based on computer Vision Structure from Motion (VSfM) algorithms (Snavely et al., 2008) explore this redundancy to retrieve the camera location the moment an image was acquired, calculate an

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orthographic rendition of each original image, and ultimately produce a precise 3D point cloud that represents objects. These acquisitions with nadir-oriented cameras onboard UAVs, however, face the same issues as airborne imagery; the great majority of points in derived clouds are positioned near or at the very top of tree crowns. The representation of crown sides tends to be sparse and contains sizeable gaps, especially lower in the crown, a potentially serious limitation in efforts to quantify lateral crown competition for space and resources, as in the periphery of canopy openings.

In this study, we extend UAV-based image acquisition configurations to include oblique and horizontal camera views and UAV trajectories around trees or tree groups at variable above-ground heights to achieve comprehensive, gap-free representations of trees. To overcome the challenges imposed by these alternative UAV/camera configurations, we evaluated many UAV platforms and open-source VSfM software options, and developed original, supplementary programs.

METHODS

UAV Platform

After a preliminary evaluation of several commercially available UAV platforms, we focused on an APM:Copter, a hexacopter rotorcraft, because of its easily modifiable architecture and open source software for flight control. We also used a commercial IRIS quadcopter developed by 3DRobotics. The components of the customized hexacopter sum to a total cost of approximately 1,000$. Both systems feature gyroscopes and GPS receivers. Compared to systems available in the market, our hexacopter is an inexpensive but versatile configuration whose component acquisition cost is expected to drop substantially in the future as UAV technology evolves and its popularity continues to increase.

Both UAVs used in this study can be operated either autonomously along a predefined trajectory or manually. The manual flight control requires expertise and continuous line of sight between the system and the operator. Maintaining nearly constant planar and vertical speed and orientation of the onboard camera towards the target is challenging, even for operators with years of experience. Experimentation confirmed that imagery acquired with manual flight control exhibits variable rates of overlap between frames captured sequentially. Smaller components of the targets are sometimes depicted in too few frames or are missing completely, while others appear in an excessive number of frames. For these reasons, it was decided to rely on autonomous flights configured by prior mission planning, and reserve the manual mode only for intervention in the event of an emergency.

We conducted extended trials with several cameras, including the sport GOPRO 3+ Black Edition, Ilook Walkera and Canon PowerShot. The evaluations involved all operating modes offered by each camera, including normal, wide, and wide zoom settings, as well as acquiring video and then extracting individual frames with post-processing.

3D reconstruction procedure

The procedure that uses a set of images exhibiting substantial spatial overlap to obtain a point cloud representing the objects present in the images contains three main steps: feature detection, bundle adjustment, and dense reconstruction. To implement this procedure, we have carefully examined a variety of software available for image processing. The workflow presented below was found by experimentation to be the most efficient for our project. We employed a sequence of computer programs, most of which are available as freeware or provide free licenses to academic institutions. The software used includes OpenCV libraries, VisualSFM, CMVS, SURE, OpenGL, and Mission Planner.

The sparse and dense reconstructions obtained from a set of overlapping images are configured in the same internal coordinate system and scale. Conversion to real-world orientation and coordinate system is a prerequisite for meaningful measurements of reconstructed objects or for comparisons with ancillary spatial data. Such conversions can be performed manually on the reconstructed scene, assuming reference *in-situ* measurements of object dimensionality are available. In this study, we used an alternative, automated approach. The latitude, longitude, and elevation of camera locations recorded by a recreational-grade GPS device onboard the UAV were converted to orthographic Universal Transverse Mercator (UTM) coordinates using a GDAL reprojection function. The rotation/ translation matrix linking the UTM and sparse model coordinates of the camera positions was then calculated via maximum likelihood, and applied to convert the sparse model coordinates system to UTM. All subsequent processing by CMVS and SURE were performed on the UTM version of the sparse model.

RESULTS

We used simulation and synthetic images to evaluate the robustness of our standard workflow to the idiosyncrasies of lateral tree imagery described above. We relied on terrestrial LiDAR data representing a collection of free-standing trees, each scanned from multiple near-ground locations. The scanning was performed in high-density mode with the laser beams distributed in fine horizontal and vertical angular increments (0.4 mrad). Details on the data acquisition are available in Gatziolis et al. (2010). The original Terrestrial LiDAR and dense reconstruction point clouds for each tree were compared in voxel space (Popescu & Zhao, 2008; Gatziolis, 2012). With sufficient field-of-view overlap between two consecutive synthetic images, the 3D model obtained using our photogrammetry workflow showed excellent agreement with the reference LiDAR model (more than 95% voxel co-localization between the two models).

Our typical setup uses a location positioned in the middle of an open area for both the start and end of the flight. The UAV would initially ascend vertically above its starting location to a pre-specified height, then move horizontally to the beginning of the trajectory, complete it, and finally return to the starting location (Figure 1). In the present development state of our system, it is the user's responsibility to ensure that the designed flight path is free of other objects, an easy to achieve requirement considering the wealth of georeferenced, high resolution, publicly available aerial photographs.

Most UAV flights produced complete tree reconstructions (Figure 2). In the absence of detailed crown dimensionality measurements, we relied on ocular assessment of reconstruction accuracy and precision. The typical examples shown on Figure 2, obtained with the spiral UAV trajectory (Figure 1c), among our most reliable for complete target reconstruction, shows that even the shaded components of the tree crown interior are represented.

DISCUSSION

Rapid developments in UAV technology and enhancements in structure from motion software have enabled detailed representation of manmade objects. In this work and in Gatziolis et al. (2015), we describe how this technology can inexpensively be extended to representations of natural objects, such as trees or groups of trees. After extensive experimentation that involved several UAV platforms, cameras, mission planning alternatives, processing software, and numerous procedural modifications and adjustments, our workflow has been proven capable of handling most conditions encountered in practice to deliver detailed reconstruction of trees. In addition to robust performance, our imaging system can be employed rapidly in support of time-sensitive monitoring operations as, for instance, the assessment of forest fire damage or progress of forest recovery from disturbance. It is also well suited to providing tree dimensionality data through time, a prerequisite for improved models of tree growth and for an accurate assessment of tree competition and morphological plasticity.

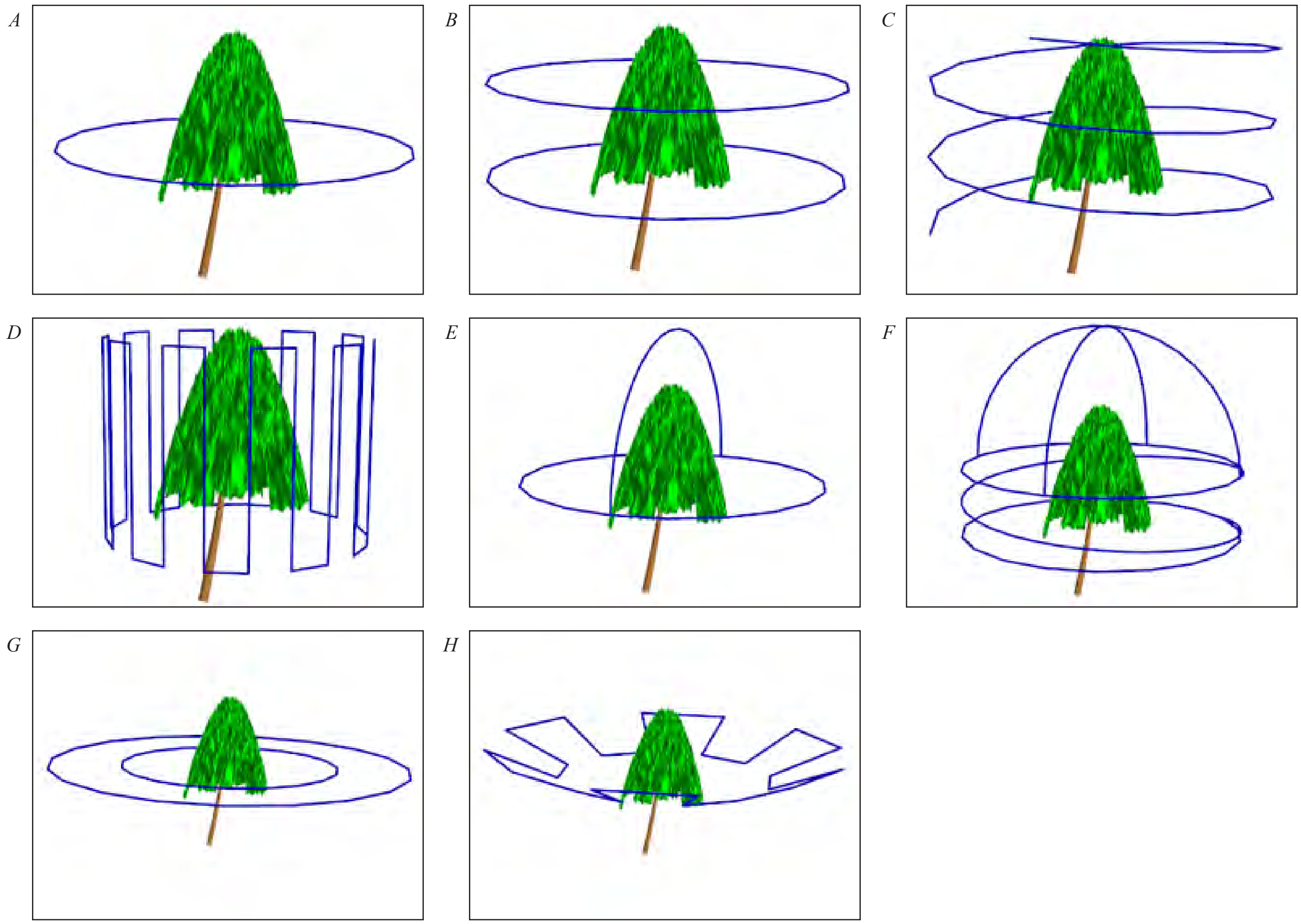

Figure 1—Different UAV trajectories tested for image acquisition. a. circular, at constant height; b. 'stacked circles', each at different above-ground height, for tall trees (height more than 20 m); c. spiral, for trees with complex geometry; d. vertical meandering, targeting tree sectors; e. clover, for trees with wide, ellipsoidal tree crowns; f. 'spring-hemisphere', designed for trees with flat-top, asymmetrical crowns; g. 'nested circles', centered on the tree; and h. 'jagged saucer', designed for trees with dense foliage but low crown compaction ratio.

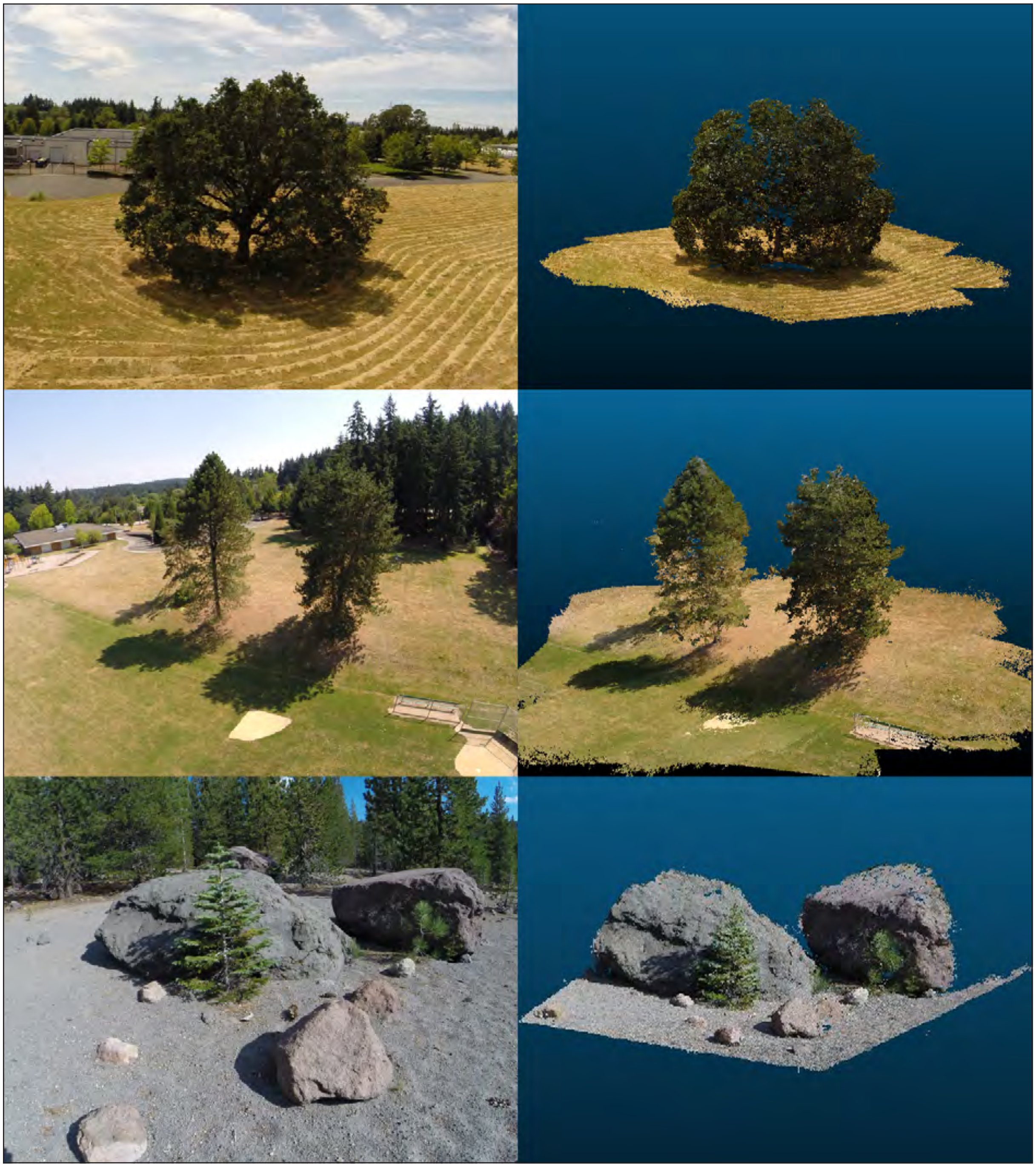

Figure 2—Illustration of comprehensive tree reconstructions (right column) and reference UAV-based images (left column).

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