

Development of A Highly Automated System for the Remote Evaluation of Individual Tree Parameters

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Abstract.—A highly-automated procedure for remotely estimating individual tree location, crown diameter, species class, and height has been developed. This procedure will involve the use of a multimodal airborne sensing system that consists of a digital frame camera, a scanning laser rangefinder, and a position and orientation measurement system. Data from the multimodal sensing system will be processed by a model-based procedure for the recognition of individual tree crowns in aerial images. Both the multimodal sensing and tree crown recognition components have been separately tested, and data to test their integration have recently been acquired as part of an in-progress experiment. The tree crown recognition procedure has been extended to use data from the scanning laser rangefinder to increase the reliability of individual tree crown isolation and to estimate tree height. Depending on the results of the experiment, the integrated system may be useful in many forest inventory activities, delivering data at a low cost relative to its value.

The overall objective of this work is to develop a highly automated procedure for remotely estimating the location, vertically projected crown diameter, species class, and height of large numbers of individual trees from digital image and range data acquired from an aircraft. The procedure is being developed as the integration of a multimodal airborne sensing system that consists of a digital frame camera, a scanning laser rangefinder, and a position and orientation measurement system (POMS), with a model-based procedure for the recognition of individual tree crowns in aerial images. Both the multimodal sensing system and the tree crown recognition procedure have been separately tested. Data (including reference data) have recently been acquired for testing the integrated system.

MULTIMODAL SENSING SYSTEM

The multimodal sensing system is designed to simultaneously acquire vertical aerial images and dense spot elevation data in a manner that allows the spatial relationship between the spot elevations (or the cells in a regular-grid digital elevation model created from the spot elevations) and image locations to be readily determined. This facilitates the determination of the height of objects portrayed in the images, and the differential rectification (removal of scale variations due to scene elevation variation and camera tilt) of the images.

The currently implemented system incorporates an Optech Airborne Laser Terrain Mapper (ALTM) 1020 scanning laser rangefinder system, a Kodak DCS420

natural color digital frame camera¹, and a POMS consisting of a global positioning system (GPS) receiver and an inertial measurement unit (IMU). The camera and rangefinder sensing head are attached to a rigid mount (fig. 1) so that their central optical axes are parallel, and the scanning plane of the rangefinder is parallel to the rows of the camera detector array.

A Kodak DCS420 camera incorporating a 28-mm lens can acquire sharp aerial images with an approximately 20-cm ground projected pixel dimension and an approximately 310- by 207-m ground footprint at a 85- to 90-mph ground speed and at 620 m above ground level under most daylight illumination conditions. This camera configuration has a 28-degree long-axis field of view, which is close to the ALTM 1020 30-degree maximum field of view. The ALTM 1020 can be programmed to acquire spot elevations with an approximately 1-m horizontal ground spacing under these flying conditions (daylight illumination has no effect on ALTM 1020 performance). The Kodak DCS420 camera can be programmed to operate with a fixed shutter speed and automatic aperture adjustment (the settings used to capture an image are stored in the image file that is downloaded from the camera). This produces sets of images with close-to-uniform overall tone even when scene illumination varies during a flight.

Software controls and records images from the camera during the flight, and calculates from the POMS data the position and orientation of the camera at the instant of exposure of each image frame. This software was built at

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¹ The mention of a specific commercial product in this article is solely for the reader's information and is not intended to be an endorsement of the manufacturer's product.

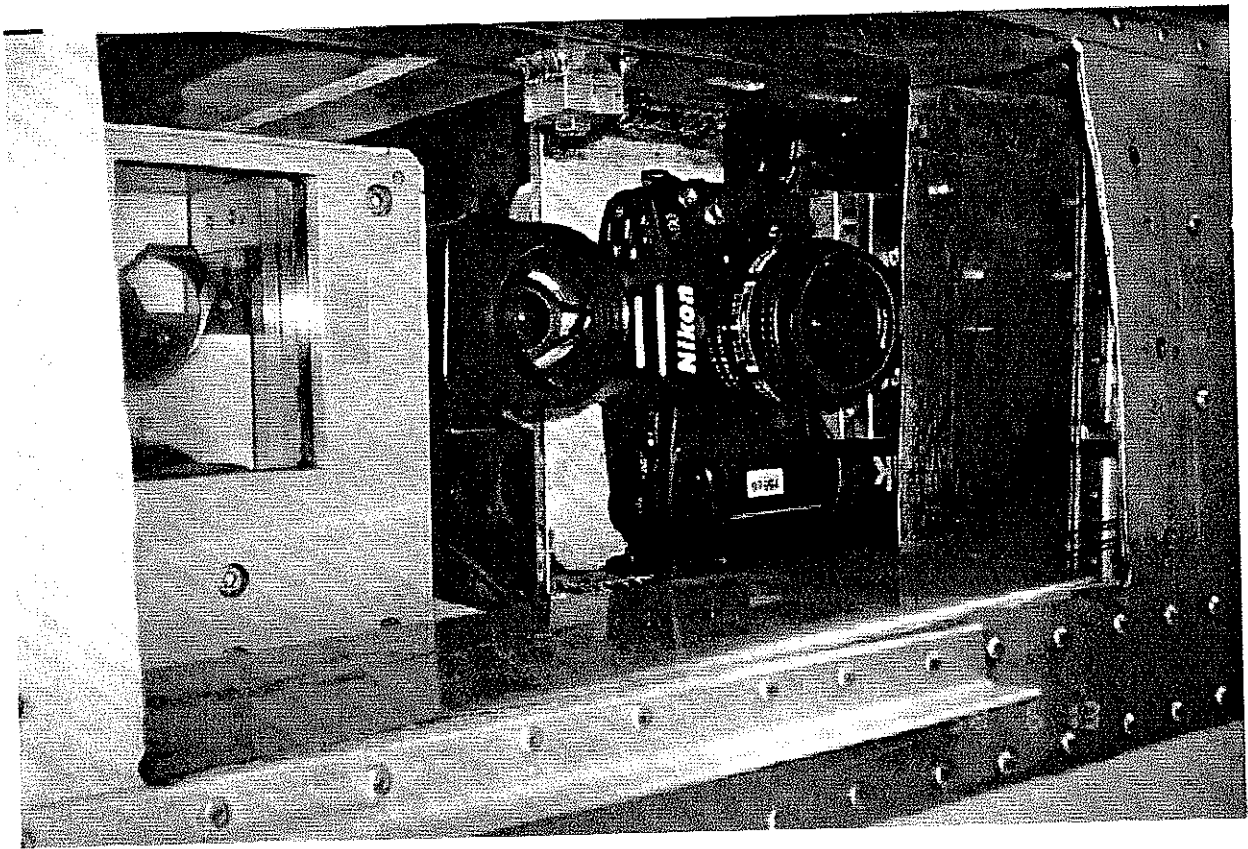


Figure 1.—View of the scanning laser rangefinder sensing port (left), a video camera for in-flight navigation (middle), and the digital frame camera (right) as seen through the observation opening in the floor of the aircraft.

the Alberta Research Council (ARC) under contract to New-Tech Remote Sensing of Calgary, Alberta. Further ARC software creates a regular-grid DEM from a set of spot elevations acquired with the rangefinder, differentially rectifies each image frame using the DEM and the frame-specific position and orientation data, and composes the rectified image frames that intersect a user-specified geographic region into a single mosaic image (fig. 2). The differential rectification procedure involves an initial manual step to check for significant misalignment of the camera and rangefinder optical systems using a sample of the image and elevation data, and to evaluate a global correction. Beyond this step, the rectification procedure is completely automatic. After the user specifies the mosaic region, all of the mosaic composition steps are automatic, including the placement of the joints between component images and the global tonal balancing.

Although care is taken in establishing the sensor alignment, it may not be perfect because it is done after the instruments are installed in the aircraft. Also, aircraft vibration and repetitive landing shock may cause significant misalignment. A new sensor mount with improved vibration and shock resistance, and a pre-installation

sensor alignment procedure are currently under development.

TREE CROWN RECOGNITION PROCEDURE

The original tree crown recognition procedure is designed to recognize tree crowns in monocular high spatial-resolution aerial images of scenes containing boreal or cool temperate forests in a leafed state, and is based on a model of the image formation process at the scale of an individual tree. This model provides a means of applying specific scene and image formation knowledge to the recognition task. Natural variation of tree crown size, shape, and composition is considered, as well as the tree-image variation (including the effect of height displacement) that is a function of image geometry. The procedure also involves user-generated training data and exploits a basic constraint on the spatial relationship of neighboring trees.

The procedure associates instances of a three-dimensional shape description with locations in a scene image so that the descriptions estimate the visible scene extent of tree crowns that existed at the corresponding scene locations when the image was acquired (fig. 3). This provides an



Figure 2.—A portion of a differentially rectified image mosaic that was automatically generated from data acquired with the multimodal sensing system. This portion includes all or part of eight separate image frames. The original image is natural color and has 20-cm pixels. The image has been highly subsampled for printing and display here.

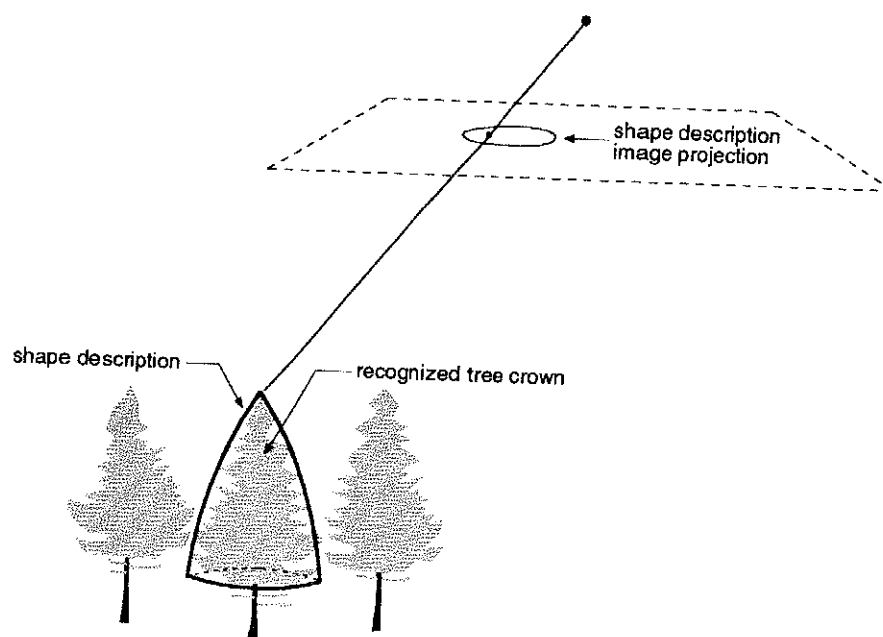


Figure 3.—The tree crown recognition scenario.

estimate of the tree location and the average horizontal diameter of the vertical tree crown projection. The projection of a shape description onto the image is an estimate of the image extent of a single tree crown. Species classification is based on the multispectral image values within these image extents (i.e., classification is done on a whole crown-image basis rather than on a pixel-by-pixel basis). Further details on the original procedure may be found in Pollock (1996).

Two tests of the original procedure have been conducted. The first test was conducted on images of scenes within the research forest of the former Petawawa National Forestry Institute (PNFI) near Chalk River, Ontario, Canada. The second test was conducted on images of scenes within the Athabasca 24 compartment of the Weldwood of Canada, Ltd., forest management area near Hinton, Alberta, Canada.

PNFI Test

The PNFI images were acquired during the morning of August 16, 1988. The scenes contain mixed forest and represent many stand types, including mixed hardwood and softwood stands, and a wide range of individual tree sizes. The images were acquired in multiple wavelength regions with the second generation of the Multi-detector Electro-optical Imaging Scanner (MEIS II), an airborne pushbroom scanner (McColl *et al.* 1983). The images have a 36-cm ground-projected pixel dimension. Some of the scene variation and samples of the results that were produced by the recognition procedure are shown in figure 4.

PNFI personnel evaluated various attributes (including crown diameter) of a sample of 587 overstory trees that were distributed among twenty-four 20- by 20-m square sample plots in the scene, and manually estimated the crown apex location for 548 of the sample trees. These reference data were used to assess the accuracy of the recognition procedure.

The errors in the automatic recognition results for the PNFI test were mostly omission errors. These errors were evidently caused by non-ideal crown irradiation, irregular crown form (especially for some hardwood trees), partial occlusion of tree crowns due to height displacement, and faulty interpretations of tight clusters of tree crowns as relatively large tree crowns. The errors in automatic and manual image-based crown diameter estimates were comparable. Both sets of estimates tended to be low relative to the ground measurements, probably because of tree crown intersection and the failure to resolve branches at the outer crown extent that are visible from the ground. Detailed descriptions of the test results are given in Pollock (1996).

Athabasca 24 Test

The Athabasca 24 images were acquired during the early-to-mid-afternoon on July 24, 1996. The scenes contain mostly coniferous forest and some aspen stands, and have a less varied species composition than the PNFI scenes; nevertheless, the Athabasca 24 scenes represent a wide range of tree sizes and crown shapes. The images were acquired in multiple wavelength regions with the Compact Airborne Spectrographic Imager (CASI) (Babey and

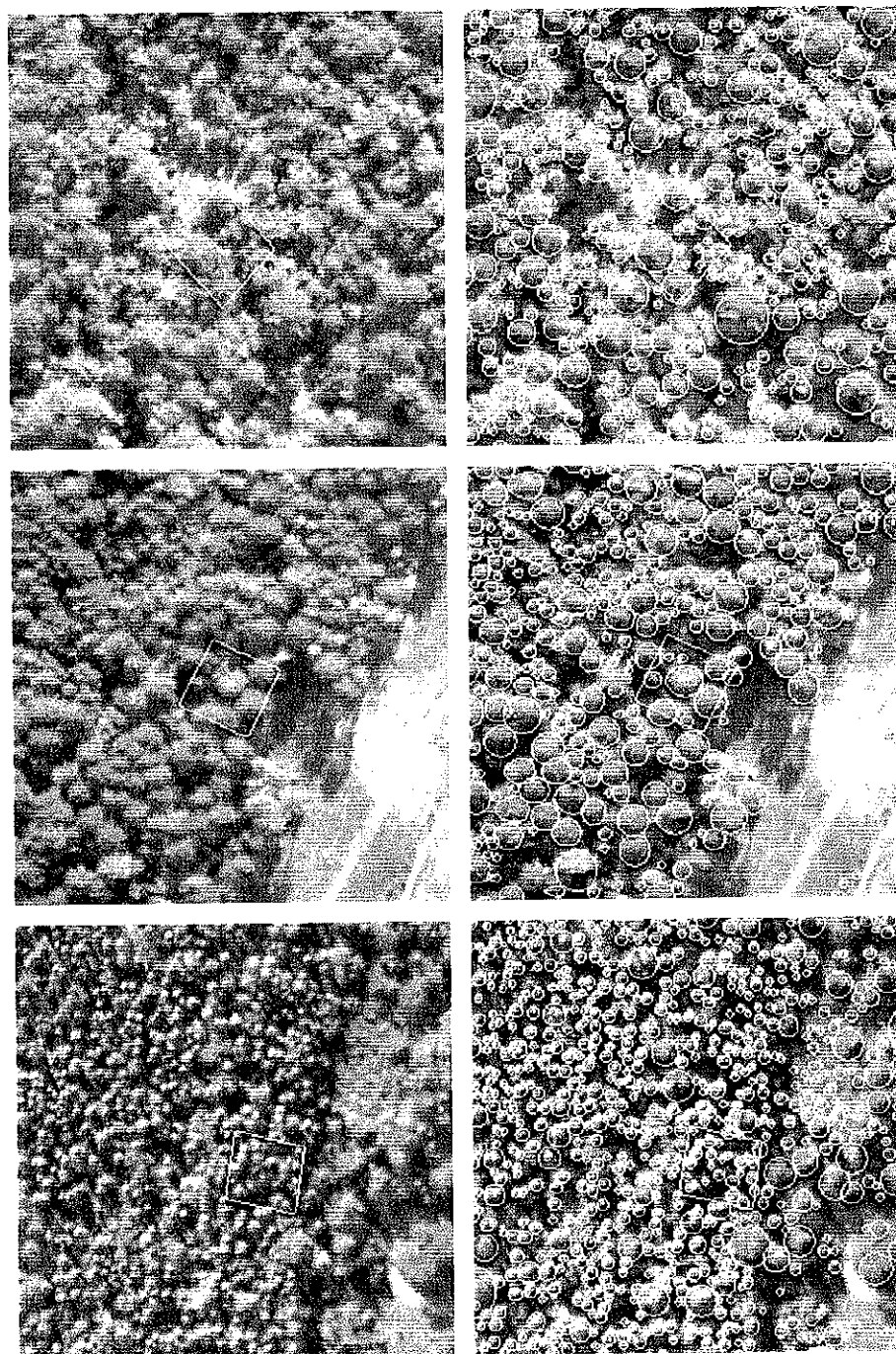


Figure 4.—Subimages from the image data and automatic individual tree crown recognition results for 1-ha PNFI subscenes. The subimages were extracted from the visible green wavelength channel of the test image data. The image projection of the shape description boundary for each of the recognized crowns is superimposed in white on the subimages in the right column. The boundary of a 20- by 20-m ground sample plot is superimposed in white on all subimages.

Anger 1989). The images were acquired with a 60-cm ground-projected instantaneous field of view, and resampled to a 50-cm pixel dimension during rectification. Some of the scene variation and samples of the results that were produced by the recognition procedure are shown in figure 5. The results show that the recognition procedure is largely able to accommodate the variation represented by the scene.

Early in the examination of the Athabasca 24 image data and the recognition results, we concluded that the spatial

resolution of the image data and the amount of aliasing present were very likely significant obstacles to both manual and automatic tree crown recognition. Field visits confirmed that many relatively small trees of merchantable size could not be manually resolved in the image data. Because of this, only a superficial assessment of the results (relative to the PNFI test) was conducted. Funds that were to be spent on more intensive fieldwork in Athabasca 24 have been diverted to the assessment of the results from the test of the current integrated system.

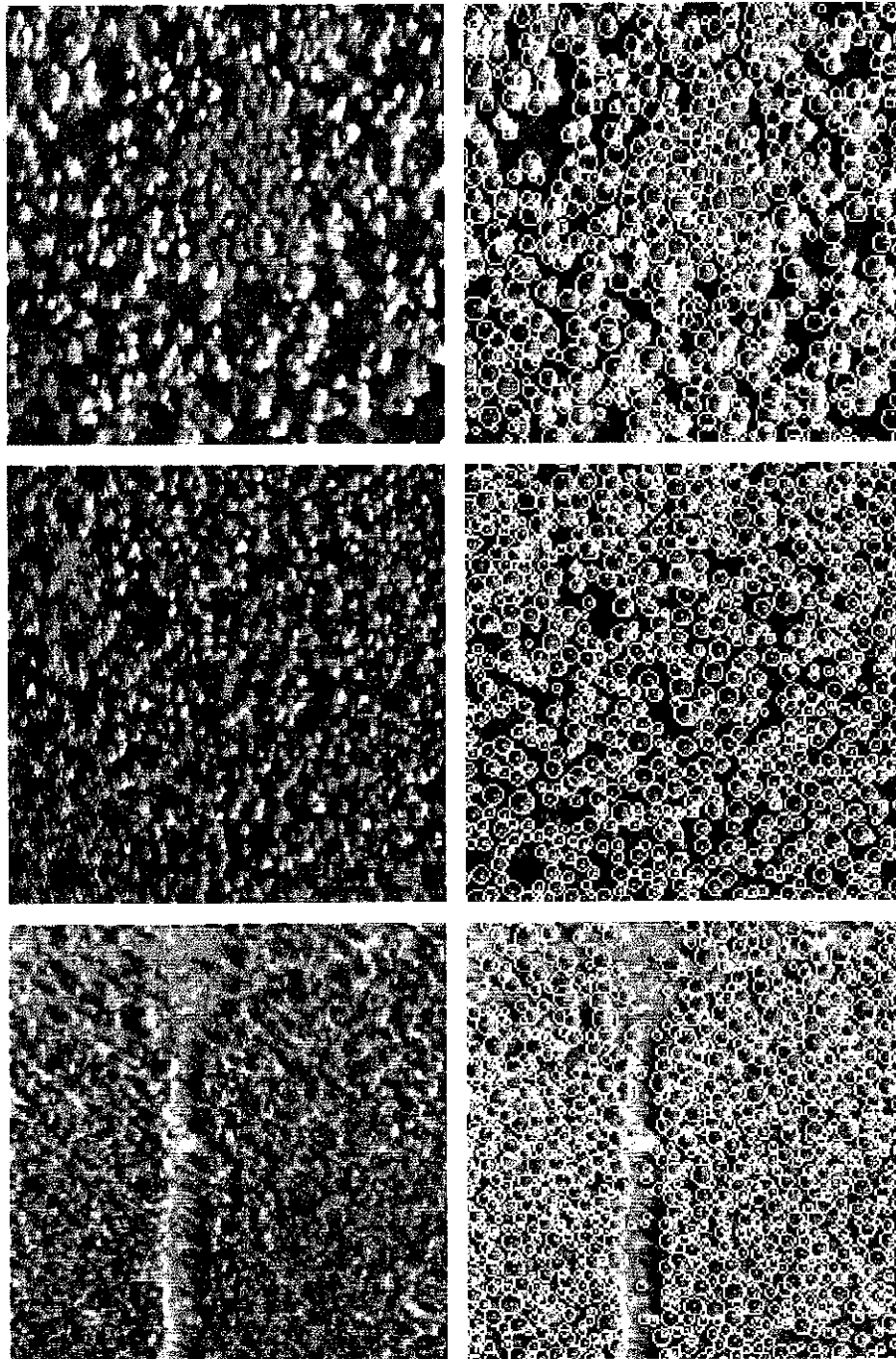


Figure 5.—Subimages from the image data and automatic tree crown recognition results for 1-ha Athabasca 24 subscenes. The subimages were extracted from the visible green wavelength channel of the image data. The image projection of the shape description boundary for each of the recognized crowns is superimposed in white on the subimages in the right column.

A comparison of the recognition results within six 1-ha scene regions with on-foot field observations revealed the following common errors: (1) trees with a crown diameter of less than 1 m were often missed, even when they grew in uncrowded conditions; (2) tight groups of small trees were often automatically recognized as a single tree; (3) where crowns were relatively close together, shorter and smaller crowns were often missed; (4) forked trees were usually recognized as single crowns; and (5) members of tight groups of aspen have highly irregular

crowns and were often either missed altogether (i.e., interpreted as ground vegetation) or were interpreted as a group of relatively few trees. These errors usually could not be recognized through manual interpretation of the image data alone.

The field observations revealed that near-infrared/red/green false-color composites of the Athabasca 24 data contain color-distinctions between different coniferous species (lodgepole pine, white spruce, tamarack) and very

obvious color distinctions between coniferous species and aspen, at least where individual tree crowns are easily recognized. An automatic supervised classification of tree crown image regions based on multispectral image values within the direct irradiation portions of these regions yielded results that were consistent with manual interpretation results.

Summary

The PNFI and Athabasca 24 tests of the original recognition procedure strongly suggest that improved spatial resolution is required for the procedure to produce tree recognition results that would be generally accepted for use in forestry. The tests also indicate that greater accommodation of the effects of crowding on tree crown images (irregular crown form and lighting) is required. Color-infrared image data provide a basis for a useful species classification. The procedure does not address the estimation of tree height, which is a significant omission because tree height is highly valuable for the estimation of timber volume.

INTEGRATION

Kodak DCS420 three-color aerial images with a 20-cm ground-projected pixel dimension allow better manual resolution of small trees than do the MEIS II and CASI images involved in experiments described earlier (both of these data sets were acquired at the finest spatial-resolution possible at the time with a standard twin-engine aircraft platform). This is significant with respect to the findings of the Athabasca 24 experiment described above. Also, the Kodak DCS cameras are available in green-red-nir (color infrared) versions, which is significant with respect to tree species classification.

The ALTM 1020 can be programmed to determine range according to either the first or the last pulse in the return pulse-train associated with an outgoing laser pulse (commonly referred to as operating in, respectively, "first pulse" or "last pulse" mode). In principle, the ALTM 1020 produces spot elevations for the top surface of a forest canopy when operating in first-pulse mode, and produces spot elevations for beneath-canopy terrain when operating in last pulse mode. In fact, a significant return pulse may only be returned once the outgoing pulse has penetrated some distance into a forest canopy, and a trailing pulse may be returned by a tree trunk or dense undergrowth rather than what may be considered to be the ground). Data from the ALTM 1020 have a clear-terrain elevation precision of 15 cm, so it is reasonable to expect that such data could be used to estimate tree height to a precision within 1 m.

Although the ALTM 1020 cannot collect first- and last-pulse data simultaneously, which necessitates dual flight

passes for estimating tree height, newer models of the ALTM have this capability.

We have shown that the spatial registration of spot elevations and image data from the multimodal sensing system is at a submeter accuracy. Therefore, we expect that tree crown recognition results could be used to automatically select first-pulse spot elevations that coincide most closely with the tops of tree crowns (as opposed to the margin of the crowns or to between-crown gaps), and last-pulse spot elevations from pulses that have traveled between tree crowns on their way to the ground. Software that performs this type of spot-elevation selection has been built at ARC. In addition, the tree crown recognition software has been extended so that it will use local elevation minima in a top-of-canopy elevation model as an additional cue for separating crowded tree crowns that may have irregular form and lighting.

IN-PROGRESS EXPERIMENT

The in-progress experiment is designed to answer the following questions:

1. How accurate is the georeferencing of the data from the multimodal sensing system?
2. How well does the ALTM 1020 determine ground elevation through different types of forest canopy?
3. How accurately can tree height be estimated with the integrated system?
4. Can top-of-canopy elevations be used to improve the separation of crowded tree crowns?

Data were acquired with the multimodal sensing system on July 25, 1998 for a 5- by 10-km site near Manning, AB, Canada. This site contains a variety of boreal forest stands. Markers that are visible in the aerial images have been placed over 26 points distributed throughout the site whose locations have been determined to 3 cm accuracy with GPS; these data will be used to answer the first question. Dense networks of ground elevations have been measured within a variety of tree stands (e.g., black spruce, white spruce, aspen) using a total station instrument; these data will be used to answer the second question. Large-scale (1:800) 70 mm format photographs have been obtained for 50 plots within the site (tree height can be manually estimated with a 10 cm accuracy on the basis of these photographs); these data in combination with ground visits will be used to answer the third and fourth questions.

CONCLUSION

A highly automated system for the remote evaluation of large numbers of individual tree crowns has been built by integrating a multimodal sensing system with a tree crown

recognition procedure, both of which have already been tested. Data have recently been acquired with the multimodal sensing system for a site in northern Alberta. These data, together with large-scale airphotos and ground reference data that have also been collected, will be used to assess the performance of the integrated system. Depending on the results of the in-progress experiment, the integrated system may be useful in many forest inventory activities, delivering data at a low cost relative to its value. This work has also set the stage for exploiting improvements in scanning laser rangefinder, digital camera, and POMS technology. In fact, the equipment that the existing multimodal sensing system is built from is no longer state of the art; now commercially available are digital frame cameras with larger detector arrays and faster data downloading components and scanning laser rangefinders with a greater sampling rate and simultaneous first- and last-pulse recording capability.

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