AUTOMATED 3-D FEATURE EXTRACTION FROM TERRESTRIAL AND AIRBORNE LIDAR

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ABSTRACT:

The U.S. Army and other Department of Defense (DoD) combat and combat support agencies requires automated feature extraction (AFE) software for collecting very high-resolution 3D urban features from terrestrial LIDAR data to support the ground-based Warfighter operating in the urban battlespace. Advanced vehicle-mounted and man-portable terrestrial Light Imaging and Range Detection (LIDAR) systems capture accurate 3D measurements of the urban environment with spatial resolutions on the order of 5 centimeters or less (Blais, 2004). The 3D imaging capability of these systems is negated, however, by a lack of commercial software tools capable of exploiting terrestrial LIDAR datasets (Shiode 2001). Current approaches for creating high-resolution 3D urban models are expensive requiring thousands of man-hours to digitize feature geometries, assign textures to features and attribute features. The lack of robust AFE software tools for collecting *geospecific* urban features from terrestrial LIDAR systems directly impacts applications for facility reconnaissance, special operations planning and urban warfare decision-making. Visual Learning Systems, Inc. has developed a LIDAR AFE system capable of extracting over 1,000 buildings per minute as 3D Shapefiles from airborne LIDAR. In this presentation we provide an overview of the VLS solution for 3-D AFE from airborne and terrestrial LIDAR systems operating in urban environments.

INTRODUCTION

Over the past five years the Modeling & Simulation (M&S) community has shown tremendous interest in collecting 3D *geospecific* features directly from terrestrial and airborne LIDAR datasets. The weak link in using both terrestrial and airborne LIDAR data effectively, however, is the lack of commercial-off-the-shelf (COTS) software tools for extracting geospecific features for M&S applications. Visual Learning Systems, Inc. (VLS) has developed a LIDAR AFE system capable of extracting over 1,000 buildings per minute as 3D Shapefiles from airborne LIDAR. Automated geospatial data production processes are necessary in order to achieve timely production of high-fidelity 3D data that is (1) efficiently processed and (2) correctly formatted. Bottlenecks in producing "good" data result from manually-intensive processes used in extracting and/or registering features to newly acquired imagery and LIDAR, editing complex 3-D geometries (i.e. rooftops), and attributing features (Figure 1). VLS' automated feature extraction techniques for LIDAR require minimal human intervention and are highly-valued because the resulting output is both spatially accurate and automatically attributed.

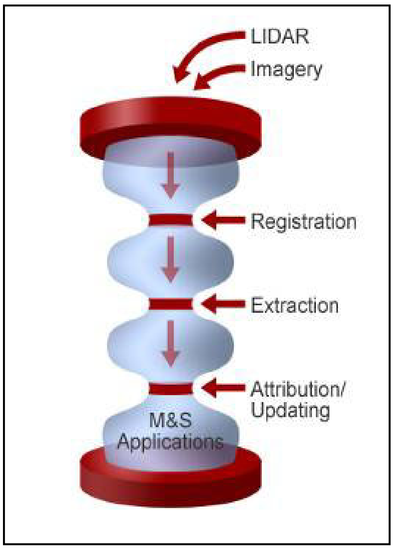

Figure 1. The production of high-quality 3D databases from LIDAR must overcome multiple restrictions in manually-driven geospatial data production workflows. Bottlenecks include the

Automated Feature Extraction (AFE) from LIDAR

The VLS commercial feature extraction software application Feature Analyst® is widely used through-out the military, civilian government agencies and commercial mapping organizations. In 2004 VLS was competitively selected by the DoD Advanced LIDAR Exploitation System (ALES) Consortium to develop a commercial LIDAR extraction toolkit in support of the U.S. Army's Urban Warfare initiative. In 2005 VLS released the commercial software LIDAR Analyst v3.5 as an extension for ArcGIS. LIDAR Analyst provides a highly automated solution for the extraction of bare earth, 3D buildings and trees from airborne LIDAR. VLS is currently researching the development of terrestrial LIDAR AFE tools to support the collection of 3D features from the urban environment.

Accuracy of Feature Extraction from LIDAR

Assessing the accuracy of surface feature extraction from LIDAR is an important task with respect to establishing the robustness of algorithms. In cooperation with the U.S. Army Engineering and Research Development Center (ERDC) Topographic Engineering Center (TEC), VLS compared the accuracy of its bare earth extraction from LIDAR Analyst against 3,141 surveyed ground control points. Ground control points were collected by ERDC-TEC engineers in open areas as well as beneath trees on the ERDC-TEC grounds. GSTI, Inc. collected two airborne LIDAR datasets over the ERDC-TEC facility, located in Alexandria, Virginia. The first dataset was collected during both leaf-on conditions and the second datasets was collected during leaf-off conditions.

The LIDAR dataset, referred to as HECSA, along with the ground control points and building count data were used to assess the accuracy of the LIDAR Analyst bare earth and building extraction algorithms. The HECSA LIDAR dataset is 1 meter spatial resolution and imaged over an area with relatively gentle topography, roughly 60% forest cover, and buildings ranging from small houses in suburban neighborhoods to fairly large commercial complexes. Each image was divided into grids. The LIDAR Analyst contains tools for refining the extracted layers, but only the automated extraction techniques were used to evaluate results.

Assessment of Bare Earth Accuracy

Using the surveyed control points provided by ERDC-TEC, we calculated the accuracy of the bare earth layers that LIDAR Analyst created for both 'leaf on' and 'leaf off' LIDAR data. The points contained an attribute column with surveyed elevations, and we added a column of elevations extracted from the bare earth pixel underlying each point. We then calculated the mean absolute error (MAE) and root mean square error (RMSE) for the bare earth elevations [Hodgson and Bresnahan 2004]:

$$MAE = \frac{\sum \left| Z_{bareearth} - Z_{survey} \right|}{n}$$

$$RMSE = \sqrt{\frac{\sum (Z_{bareearth} - Z_{survey})^2}{n}}$$

Both methods give an estimate of uncertainty of the elevation of each bare earth pixel. The RMSE gives slightly more conservative results, but an advantage of the MAE is it provides a mean of a sample. It allows the use of a t-test to determine whether there is a significant difference in the mean of two sample populations. In this case, we used a two-sample t-test to compare the absolute errors for the bare earth rasters obtained using the leaf-on and the leaf-off LIDAR data.

The bare earth is a key data layer used in many different types of M&S applications; hence the accuracy of the bare earth surface is very important. VLS has developed a unique algorithm for automated extraction of bare earth from LIDAR that is extremely accurate based on comparison to surveyed ground control points. The results of the accuracy assessment include calculations of the Root Mean Square Error (RMSE) and Correlation Coefficient (R Square). Post processing of the bare earth surface includes adjusting the height of the Normalized Difference Surface Model (NDSM). A low-pass filter (LPF) was also used to process the bare earth surface to compare results.

The Optech LIDAR sensor flown by GSTI has a vertical accuracy (z-value) of approximately 12 centimeters. Bare earth extractions options with LIDAR Analyst include using Method 1 or Method 2. Method 2 is used for dense urban areas or areas of dense forests. The results of the accuracy assessment show that the VLS bare earth extraction for leaf-off conditions is equivalent to the vertical RMSE of the sensor itself (12 cm). Even more impressive is the extraction of the bare earth surface during leaf-on conditions. The RMSE for leaf-on conditions is 18 cm which is only 6 cm different than the RMSE vertical accuracy of the sensor. The VLS approach to extracting the bare earth surface from LIDAR showed the following:

- The approach is automated and very accurate with respect to the interpolated z-value (elevation) for both leaf-off and leaf-on conditions.
- The bare earth solution is fast with average processing speed of 86 seconds per square kilometer on a high-end PC.
- VLS provides two different methods for bare earth extraction including solutions for (1) densely wooded

terrains and urban areas and (2) rolling hills and flat areas.

The bare earth surface was extracted using first and last return as inputs to the LIDAR Analyst. LIDAR Analyst provides users with two different methods for extracting bare earth depending on terrain type. Terrain types for the 24 datasets included urban settings in major cities, coastal regions, suburban areas, small airports in densely wooded areas, international airports, etc.

Assessment of Building Extraction Classification Accuracy

The buildings vectors for the HECSA dataset are discrete class data output as Shapefiles. Accordingly, we randomly sampled 250 locations in the LIDAR images that were classified by the LIDAR Analyst as buildings and 250 that were classified as background. This number of samples is well above the minimum number of 50 per class that has been suggested by others (Lillesand and Kiefer 2000). We then visually determined whether each point was correctly or incorrectly classified and used the results to calculate User's Accuracy, Producer's Accuracy, and Overall Accuracy for the buildings class. We produced these values separately for the classification of the 'leaf on' and the 'leaf off' datasets.

Within each class, User's Accuracy is the percentage of the total number of classified points that are correctly classified. It represents the probability that a point classified as a building actually represents a building on the image. Producer's accuracy is the percentage of points that should have been assigned to a class that were actually classified correctly. It indicates how well the buildings on the image were classified. Finally, overall accuracy is the percentage of all of the sample points (for both classes combined) that were correctly classified (Lillesand and Kiefer 2000).

Assessment of Tree Points Accuracy

It is much more difficult to determine the accuracy of the tree points, because individual trees are difficult to see on the LIDAR images, particularly in areas of dense tree cover. Additionally, the user has a large amount of control in determining which features are classifies as trees, by setting minimum tree height and the degree of vertical curvature that a feature must have in order to be considered a tree. As a result, we only attempt a qualitative assessment of the accuracy of tree points. Ideally, we would have field survey information available with which to verify point placement, as well as the attributes of tree height, crown width, and stem diameter that the LIDAR Analyst estimates.

Building Extraction Results

VLS completed building extraction experiments on all 24 LIDAR datasets using the LIDAR Analyst software. Experiments focused on optimizing algorithm parameter settings to improve the accuracy and speed of the extraction. Parameters settings include minimum height, minimum area, maximum slope of building rooftops, and texture variance. The VLS approach to building extraction is unique in that it provides a completely automated solution for collecting multi-component buildings as 3-D Shapefiles, including attributes, from LIDAR. Table 3 summarizes the results of experiments including statistics on building count and processing speed.

Accuracy Assement of Building Extraction

The accuracies for the buildings classification from the HECSA LIDAR dataset are shown in Table 1. The producer's accuracy in particular is quite high, indicating that the buildings that exist on the LiDAR images were classified as such quite accurately. User's accuracy is slightly lower, suggesting that the software tended to slightly over-classify buildings (create commission errors). However, because buildings occupy a relatively small portion of the image, missed buildings might have been somewhat under sampled.

The differences between the 'leaf on' and 'leaf off' results are probably not significant. Most of the buildings in the images are relatively unobstructed by tree canopy, but in images with more buildings in wooded areas, we would expect 'leaf off' images to produce better results. In general, the balance between user's accuracy and producer's accuracy is controllable by the user during the LIDAR Analyst setup. Adjusting the *Maximum Slope for Buildings Roofs* parameter determines the sensitivity of the software to buildings detection. During testing we tried to visually obtain a good balance between commission errors and omission errors.

Table 1. Percent Accuracy for Classification of Buildings

	Overall accuracy	Producer's accuracy	User's accuracy
Leaf on	97.4	100.0	94.8
Leaf off	96.2	99.6	92.8

Building Rooftop Extraction Results

VLS has developed a novel approach for automatically extracting complex 3-D rooftop geometries from LIDAR. The VLS approach does not use a brittle and complex expert systems approach for 3-D modeling of buildings; rather it uses adaptive shape modeling techniques that do not require any input from the User. Extensive testing with ERDC-TEC show the LIDAR Analyst automated building extraction algorithm is accurate - over 97% accuracy on the HECSA LIDAR dataset. In addition to being very accurate, the building extraction process is also very fast – over 11,000 buildings in 9 minutes of processing time for the LAX East LIDAR dataset. Building footprints are extracted as 3-D Shapefiles and include multiple attribute such as height, area, perimeter, roof type, etc. Furthermore, LIDAR Analyst can precisely model the shape of complex roof types (pitched, domes, gabled, etc.) (See Figure 2). Before LIDAR Analyst, this was an immensely time-consuming task for analysts to do correctly. The VLS approach does not require complex programming or expert systems (which traditionally have never worked); rather it extracts 3-D rooftops in a completely automated approach.

Tree Extraction Results

LIDAR Analyst extracts trees as vector point features and forests as vector polygon. Attributes that are automatically extracted for trees include tree height, crown width, and stem diameter. Table 5 summarizes the processing results of the tree extraction algorithm. Test results show the LIDAR Analyst tree extraction provides very fast processing of trees as vector point files or entire forested regions as polygons. Over 100,000 trees were extracted from the Stafford LIDAR dataset in approximately 6 minutes. Auto-attribution of tree points includes values on crown width, tree height, and stem diameter.

Road Extraction Workflows

VLS conducted numerous road extraction experiments using a combined set of tools and from LIDAR Analyst and Feature Analyst. The semi-automated workflow created includes the following steps:

1. For surface streets bordered by vertical features such as buildings and trees, we extract the ground mask using the LIDAR Analyst. This raster layer delineates vertical features from the second return LIDAR image.
2. We can then use this layer as a region exclusion mask when extracting streets with Feature Analyst. This eliminates any confusion of buildings and trees with streets, making cleaner (less clutter) results possible. Feature Analyst

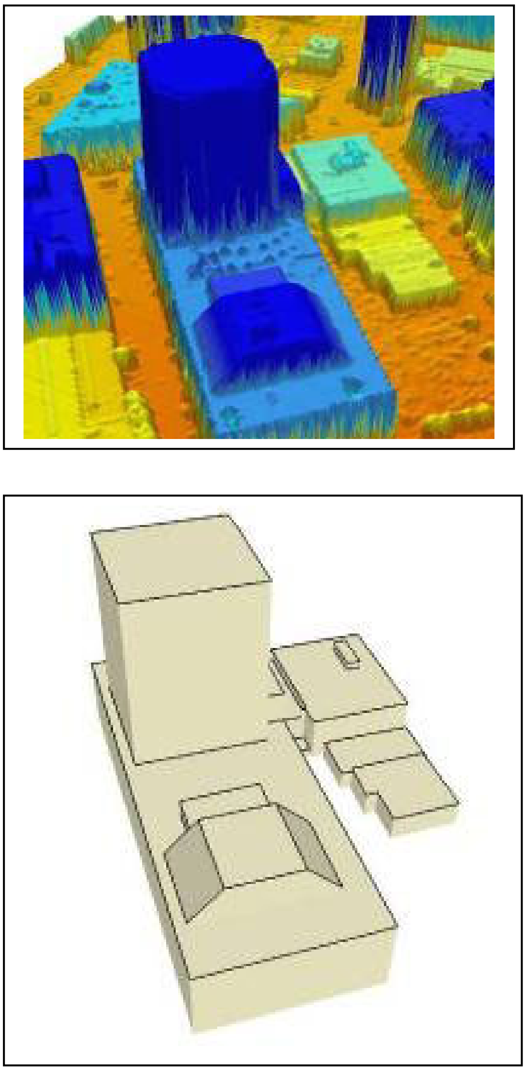

Figure 2. Clips from LIDAR images showing the results of VLS' proprietary shape modeling algorithm for 3-D building rooftops. The images shown on the left-hand side are LIDAR DEMs and the images on the right are the extracted 3D vector Shapefiles.

3. uses a supervised feature extraction approach for features such as roads.

Figure 3 shows the centerlines for surface streets after one hierarchical cleanup pass before which the user specified some correct and incorrect examples. The current workflow for roads extraction problem is semi-automated. VLS will develop solutions that automate the extraction of roads, which would more closely match the current LIDAR Analyst workflow. Possibilities for reducing the supervision include developing specialized Feature Analyst Learning Models for use with LIDAR data, or pursuing new types of automated road extraction such as line-following algorithms that would leverage the types of data presented above. VLS will continue to explore these and other options for improving and streamlining the roads extraction process.

Figure 3. Streets centerlines automatically created from the polygons. During the convert-to-line process, small dangles are removed, gaps are jumped, intersections are cleaned, and the lines are smoothed using a line snake algorithm.

Feature Analyst uses data fusion to extract roads, airport features, and many other types of geospatial information using LIDAR intensity bands, first and last return DEM bands, and electro-optical (EO) imagery. Feature Analyst provides Analysts with a wide range of automated and semi-automated workflows and tools for feature extraction, vector clean-up, and attribution.

Vertical Towers and Airport Features

The extraction of towers from LIDAR data can fundamentally be thought of as being just a special case of buildings where the height-to-area ratio is greater than a specified threshold value. The LIDAR Analyst currently extracts and attributes all buildings (or sections of buildings, as desired), so finding towers will simply be a matter of filtering buildings by their attribute information. VLS is currently working on tests for auto-extraction of towers including highly-accurate representation of their 3-D geometry. As with towers, domes are extracted along with other buildings, and can be filtered based on their shape. Airport runways are difficult to extract using only LIDAR data because they are typically quite similar in tone and elevation to their surroundings. However, the white lines that appear on all runways are typically quite visible on intensity images and can therefore be extracted reliably with Feature Analyst. The resulting line features can be used as is (Figure 4) for visualization purposes, or can be merged into a large polygon for each runway and then collapsed into single runway centerlines.

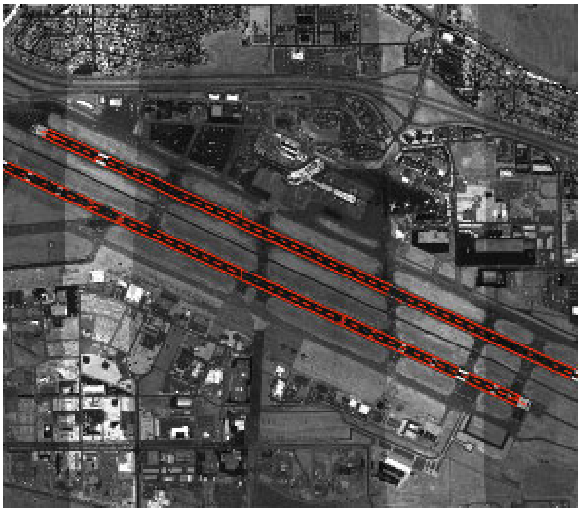

Figure 4. White runway lines (shown in black) extracted from the Boise airport LIDAR intensity image. The lines are shown on top of a hillshaded LIDAR return

FUTURE WORK

VLS is currently working on new research in the application of AFE techniques for terrestrial LIDAR including the extraction of building facades, doors, windows, ground space and other urban features. This capability is being merged with our existing airborne LIDAR AFE technology to provide a holistic approach to the generation of 3-D urban models.

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