Literature Review Focused on Data Processing Techniques for the Selective Filtering of Light Detection and Ranging (LiDAR) Data for Enhanced Surface Representation of River Geomorphology

Project ID: 657, Bureau of Reclamation Science and Technology Program

INTRODUCTION

Earth scientists and hydrologists throughout the Bureau of Reclamation routinely use LiDAR data in geomorphic studies and hydraulic modeling. Practical use of the data has revealed several data quality issues including inaccurate representation of landscape features such as stream banks, levees, and water surface. Additionally data file size can exceed processing capabilities of software used in generating and analyzing surface models. These data quality issues are not necessarily tied to quality assurance and quality control of data processing but rather widely recognized limitations of standard filtering procedures (Axelsson 1999 and 2000, Bowen and Waltermire 2002, Bretar and Chehata 2007, Brovelli and Lucca 2011, Chen et al. 2007, Evans and Hudak 2007, Goepfert et al. 2008, Kraus and Pfeifer 1998 and 2001, Meng et al. 2010, Raber et al. 2002, Schickler and Thorpe 2001, Silvan-Cardenas and Wang 2006, Sithole and Vossleman 2004, Wang and Glenn 2009). In this context, filtering refers to processes used in separating terrain and off-terrain data points (i.e., separation of the LiDAR point cloud into a landscape surface dataset, representing elevation values of vegetation and man-made objects, and a terrain surface dataset of bare-earth elevation values). It is the terrain surface dataset that is used to generate the digital terrain model (DTM); a continuous surface model for use in the geomorphic studies and hydraulic modeling.

Ideally, a DTM is generated from a combination of a well distributed sample of elevation values (mass points and spot points) along with breaklines. Sample points have traditionally been collected through field survey or photogrammetry. Terrain surfaces are deliberately sampled when using these methods; taking more samples where the terrain is more complex and fewer where the terrain is more uniform. Sample points collected in this manner can also be located at local maxima/minima to more precisely model surface elevations and shape. More recently, LiDAR has become recognized as a cost-effective means of sampling terrain surface, particularly over extensive areas. However, the LiDAR system is an undiscriminating sensor; it collects data for all returns (e.g., vegetation, birds in flight, and man-made objects in addition to unobstructed terrain). The initial data capture is a collection of range measurements and sensor parameters which are processed into a three-dimensional collection of points in geographical space. This is followed by filtering processes to identify outliers and classify data points as terrain or non-terrain objects. The classification and separation of LiDAR data into terrain and off-terrain datasets is critical in providing a dataset to develop accurate surface models. Accordingly, many studies have been conducted on filtering methods to process LiDAR data.

A literature review was conducted to identify methods and available tools for processing LiDAR data for use as surface models. LiDAR data have many applications in both rural and urban settings. This literature review focused on current scientific knowledge and technical advances that could be applied to filtering LiDAR data for use in geomorphic studies and hydraulic modeling. The intention is to use this information to: (1) adopt practical processes that can be applied in creating optimized LiDAR datasets for use in geomorphic studies and hydraulic modeling, and (2) identify areas for further study.

FILTERING TECHNIQUES

Various approaches have been explored in developing algorithms for filtering LiDAR data. The most commonly used can be categorized as elevation difference, slope-based, morphological, and multi-scale. With elevation difference, distance is calculated between an interpolated surface and measurement points. Each point is given a weight according to distance from the surface and, on the basis of weights, a new surface is computed. Slope-based filters are based on the relationship of height difference to distance between points (i.e., local slope). High local slopes imply the point of higher elevation is not a terrain point. Morphological filters work on gray-scale images, processing the images on the basis of spatial structure and not on the numerical value of data cells. The fundamental operators are dilation and erosion and used in combination produce opening and closing operators. In the context of processing LiDAR data, local minima and maxima can be found and used to classify points as belonging to the terrain or off-terrain. Multi-scale filters work on the basis that surface properties are scale-dependent and a multi-resolution approach is required to analyze surface variation. A multi-scale approach operates across the range of variation of the terrain surface; filters described above are applied at a smaller range of scale encompassing variation of objects on the landscape.

The following are example filters that have been developed within each of these categories.

Elevation Difference

Kraus and Pfeifer (2001) assess the LiDAR point cloud against an approximate terrain surface interpolated using a method similar to kriging. Residuals (the distance from the surface to the LiDAR data points) are calculated and applied to a weighting function. Negative residuals are assumed more likely to be terrain points and are assigned high weights whereas positive residuals are assigned low weights as likely non-terrain points (Kraus and Pfeifer 1998). A new surface is computed based on weights. The process of assigning weights and computing a new surface is performed iteratively until all gross errors or a maximum number of iterations are reached (Kraus and Pfeifer 2001).

Zhang and Cui (2007) developed two polynomial fitting filters to improve filtering results on interpolated surfaces. The first of the two polynomial filters is applied to try to recover missed ground points by comparing elevation differences of LiDAR points to what is considered the final interpolated surface. Candidate points are selected based on elevation thresholds and incorporated into a new, proposed surface. The second polynomial surface filter compares the new proposed surface with the previous surface to find the best fitting curve between the two.

Slope-based

Vosselman (2000) presents an approach that filters points on the basis of height difference relative to distance between the points as the filter method; i.e., a function of slope or gradient. This approach assumes that a large height difference between two neighboring points is unlikely to be a natural terrain slope and the higher point is unlikely to be a terrain point. Applied as a filter, height differences exceeding a height threshold are classified as non-terrain points. The threshold is defined based on knowledge of height differences in the terrain (Vosselman 2000).

An adaptive TIN filtering process developed by Axelsson (2000) operates by densifying a sparse TIN created from seed points. The filter is applied iteratively, adding one point at a time in each TIN facet if it meets threshold parameters. Parameters are based on median values estimated from histograms of surface angles (slope) and elevation differences (Axelsson 2000).

The adaptive TIN filter was modified to improve point classification in areas of steep slope (e.g., cliffs) with the addition of a "mirror point" to assess LiDAR points against surface angle (Zhang and Cui 2007). The candidate point is horizontally mirrored and the distance between the mirrored point and the surface is also taken into account in classifying the candidate point.

Roggero (2001) approximates a terrain surface using local minima to calculate local slopes against which to compare the point cloud in classifying terrain and non-terrain points. Threshold values are assigned in classifying ground, non-ground, and non-classified points based by vertical difference from the approximated surface (Roggero 2001).

Sithole (2001) compares slope between neighboring LiDAR points against an assumed terrain slope map generated from the minimum values within the dataset. If the point slope exceeds a threshold the point is classified as a non-terrain point. This filtering method is a modification of Vosselman (2000) in that it uses a slope threshold that adapts to the slope of the surrounding terrain; threshold varies between flat and steep terrain.

Whereas the previous slope-based methods use TINs, Wack and Wimmer (2001) interpolate randomly distributed raw lidar data into a regular grid (i.e., raster dataset) to which a slope-based algorithm is applied. Slope information is derived from a grid of the lowest data points and used to filter raster elements based on a maximum height difference threshold. Additional processing is performed using a Laplacian of Gaussian filter. Similarly, Zhang and Whitman (2005) create a regular grid based on minimum elevation points for use with the elevation threshold with expanding window (ETEW filter). Slope and height differences are compared between the surface and LiDAR points, similar to the process developed by Vossleman (2000). Points that do not meet threshold values for slope and height are removed from the dataset. The process is repeated with increased cell size and continues until there are no further points removed.

<u>Morphological</u>

Pursuing a morphological approach to filtering LiDAR data, Zhang et al. (2003) investigated applying morphological filters (e.g., dilation and erosion; opening and closing operations) to remove non-ground data points and preserve ground points. The filter is applied in iterative processes, gradually increasing filtering window size to detect objects across a range of dimensions. An elevation difference threshold, based on window size, was incorporated into the process in order to manage incorrect removal of measurements at the top of high relief terrain (Zhang et al. 2003). Parameters for data rotation angle and number of rotations were later added to improve filter performance (Zhang and Cui 2007). A similar filter was developed to be more adaptive to local terrain and perform better in rugged areas (Chen et al. 2007). The approach includes processes to fill no-data area and remove outliers in addition to extracting terrain points. Another approach developed by Zaksek and Pfeifer (2006) uses trend surfaces estimated from the first and last LiDAR returns. The trend surfaces take position of a candidate ground point into account and elevation thresholds for identifying ground points.

<u>Multi-scale</u>

Silvan-Cardenas and Wang (2006) investigated using the multiscale Hermite transform (MHT) as an approach to separate terrain elevations from feature heights. The LiDAR point cloud is interpolated into multi-resolution grids and multi-scale thresholds are applied at the MHT is computed to adaptively remove above ground points using an erosion operator. The MHT is a scale-space filter based on the Gaussian pyramid with properties of wavelet theory.

The Multiscale Curvature Classification (MCC) is an iterative multi-scale algorithm for classifying LiDAR returns as ground and non-ground (Evans and Hudak 2007). The algorithm incorporates curvature filtering with a scale component and variable curvature tolerance. A surface is interpolated at different resolutions using the thin-plate spline method and points are classified based on a progressive curvature threshold parameter; the curvature tolerance parameter increases as resolution coarsens to compensate for slope effect as the data are generalized.

FILTER ENHANCEMENTS

The filtering approaches, as described so far, only use surface geometry in classifying terrain and off-terrain LiDAR returns. Modifications made to filter algorithms to improve filter performance were adaptive to local changes in slope or spatial scale.

Schickler and Thorpe (2001) applied the surface estimation methods developed by Krauss and Pfeifer (1998) using a triangular irregular network (TIN) and included independently measured breaklines and land cover type to derive a bare-earth model from a LiDAR point cloud. Algorithm parameters in the elevation difference filter were assigned based on the land cover type.

Other studies used information contained in the LiDAR dataset. Raber et al. (2002) classified vegetation based on vertical distribution of LiDAR elevation points. A histogram of the multiple-return LiDAR was used to classify six (6) land cover classes (coniferous, deciduous, mixed, shrub, and high and low grass). The algorithm parameters were adjusted based on the vegetation map. In this case, the histogram was a surrogate for full waveform LiDAR data. A similar approach used intensity information and distribution of multiple echoes for adaptive weights in the same iterative surface fitting procedure (Goepfert et al.

2008). Bretar and Chehata (2007) also used the approach of applying vegetation information in assigning algorithm parameters. LiDAR intensity values were combined with true color aerial imagery to generate a “Hybrid” Normal Difference Vegetation Index (HNDVI) and used to classify land cover type. The intensity values were used as an infrared channel. A morphological-based filtering algorithm was applied, adapting window size to presence of vegetated areas. Another study used Gaussian distribution of two vegetation classes derived from intensity image (Wang and Glenn 2009). Rather than generating a vegetation map to aid in filtering LiDAR data, Liu et al. (2009) used skewness and kutosis of intensity data values to classify terrain and off-terrain LiDAR data points (Liu et al. 2009)

TOOLS

Many of the above mentioned filters are implemented in software readily available to process LiDAR data. A brief description of the software implementation and capabilities is provided below. In addition, other software and tools used for general processing or data manipulations are also presented and described.

Airborne LiDAR Data Processing and Analysis Tools (ALDPAT)

Software developed by the National Center for Airborne Laser Mapping (NCALM) implements a progressive morphological filter (Zhang et al. 2003), an elevation threshold with expanded window (ETEW) filter (Zhang and Whitman 2005), iterative polynomial fitting and polynomial surface filters (Zhang and Cui 2007), maximum local slope (MLS) filter (Vosselman 2000), and modified adaptive TIN filter (Zhang and Cui 2007). It also provides tools to thin, tile, interpolate LiDAR points to grids, convert ellipsoid to orthometric heights, and extract points by polygon.

ALDPAT is available through free download from the National Oceanic and Atmospheric Administration Coastal Services Center (http://www.csc.noaa.gov/digitalcoast/tools/aldpat/download) or the International Hurricane Research Center (http://lidar.ihrc.fiu.edu/lidartool.html)

ArcGIS

Esri ArcGIS is a full-featured Geographic Information System (GIS) software program with numerous tools available for processing LiDAR point data and interpolation. The Terrain data model allows for point thinning. The MCC algorithm is implemented in ArcGIS.

ArcGIS is readily available throughout the federal government.

Boise Center Aerospace Laboratory (BCAL) LiDAR Tools

BCAL LiDAR Tools are open-source tools developed by BCAL for processing, analyzing, and visualizing LiDAR data. The “Perform Height Filtering” tool filters LiDAR data into ground and vegetation. The tools were developed for use in shrub-steppe rangeland; it is not intended to filter buildings or large objects

The tools are available for free download from http://bcal.geology.isu.edu/tools-2/envi-tools [NOTE: these tools are add-ons to ENVI, a commercially available image processing software program. Pricing is not available]

FUSION

FUSION was developed at the United States Forest Service Pacific Northwest Research Station by the Silviculture and Forest Models Team. Its primary intended application is forest stand analysis but includes tools for more general application (e.g., conversion between data formats, point cloud statistics, and surface modeling, generation of intensity images). The feature to generate a bare-earth surface (GroundFilter) is adapted from Kraus and Pfeifer (1998) with the purpose of supporting other features such as determining vegetation heights. The GroundFilter feature carries a precaution that the model output is too coarse to use for bare-earth surface as a primary product. It does include an interesting switch that can be used to diagnose where the filter is not producing good bare-earth point sets.

FUSION is available for free download from: http://forsys.cfr.washington.edu/fusion/fusionlatest.html

Geographical Resources Analysis Support System (GRASS)

GRASS is a full featured GIS software product that covers a wide range of capabilities. Tools specific to LiDAR allow analysis for outliers, edge detection, surface generation, and data conversion. Brovelli and Lucca (2011) compared LiDAR modules available in GRASS against commercially available TerraScan. Comparison results indicated GRASS outperformed TerraScan in classifying vegetation, particularly better able to identify low vegetation points though Terrascan was more reliable in detecting man-made structures. Interpolation functions are also available (Cebecauer et al. 2002, Mitaosva et al. 2005); as is quad-tree segmentation (Cebercauer et al. 2002, Agarwal et al. 2006). NVIS is GRASS's n-dimensional visualization software. LiDAR 3-D point clouds can be colorized based on point data attributes.

GRASS is free and open source software that can be downloaded at http://grass.fbk.eu/download/index.php

LAS Tools

LASTools is a suite of LiDAR data processing tools programmed by Martin Isenburg. The more generalized tools for converting between data formats and extract header information or data precision are open use. More sophisticated tools for filtering, classification, and interpolation require licensing.

LASTools can be downloaded at http://www.cs.unc.edu/~isenburg/lastools/

Multiscale Curvature Classification

The algorithm developed by Evans and Hudak (2007) is implemented in AML (two versions) and C++. The AML can be set up as an ATOOL in ESRI ArcGIS (version 9).

The AML is available for free download at http://forest.moscowfsl.wsu.edu/lidar/MCC.aml and http://forest.moscowfsl.wsu.edu/lidar/MCC_IFD.aml (using the iterative finite differencing spline method). The C++ implementation can be downloaded for free from http://sourceforge.net/projects/mcclidar/develop

Quick Terrain Modeler

Quick Terrain Modeler, developed and distributed by Applied Imagery, was primarily created and optimized as a 3-D visualization and analysis software. The software program allows rapid visualization in 2-D and 3-D. LiDAR point clouds can be displayed with custom altitude coloration and lighting effects. Editing tools include manual removal of terrain features, area smoothing and cut, crop, and point deletion operations. The analytical capabilities of Quick Terrain are generally qualitative; advanced operations are not available.

Purchase price and annual maintenance costs were not readily available. A free trial license is available.

SCOP++

SCOP++ is a software package that offers several modules for processing and analyzing LiDAR data. The SCOP++ LiDAR module is used for filtering raw point cloud data into terrain and off-terrain points. This module implements the algorithm developed by Kraus and Pfeifer (1998).

Pricing was not available. A free trial license is available.

TerraSolid/ TerraScan

TerraSolid offers several software products. TerraScan is a software program for processing raw LiDAR data and data point classification. It runs in MicroStation, a CADS environment. TerraScan implements the adaptive TIN algorithm developed by Axelsson (2000).

Software and license costs approximately $6,400 with an annual maintenance cost of approximately $960.

DISCUSSION

Numerous LiDAR filtering algorithms have been developed using a wide variety of approaches. Several comparative reviews of some of these existing filters report strengths and weaknesses of each. One very broad and simple conclusion is there is no single best filter; the “best” filter algorithm may vary from landscape to landscape and algorithm parameters vary by landscape (Sithole and Vosselman 2004). Results between filter algorithms tend to be comparative in low relief areas but show more variable results in areas of more complex terrain. Filters that performed best in areas of variable terrain and discontinuities (e.g., streambanks) were ones developed by Axelsson, Pfiefer and Kraus, and Wack and Wimmer (Sithole and Vosselman 2004, Meng et al. 2011). Yet another review found that Zhang’s progressive morphological preserved features better than the distance-based and slope-based algorithms tested (Zhang and Whitman 2005). The comparative reviews identified in this literature search are not individually inclusive of filtering algorithms that show promise in classifying terrain in areas of most interest for hydraulic modeling and studies related to stream geomorpholgy; those areas near the active stream channel and streambanks, levees, or low terraces covered in dense vegetation (Bowen and Waltermire 2002, Sithole and Vosselman 2004, Meng et al. 2011). Further study comparing the Pfeifer and Kraus, Wack and Wimmer, MCC, and PM filtering algorithms with emphasis on filtering LiDAR for hydraulic modeling and stream geomorphology studies is warranted. The reviews evaluated the performance of filters that used only surface geometry as input.

Filter enhancements that adapted parameters to the presence of vegetation and intensity value statistics showed improved results. However, accuracy of land cover classifications and reliability of intensity values was problematic. A more straight forward approach may be to use a combination of structural properties of the point cloud such as number of returns per pulse, range of elevation, and neighborhood density to adapt parameters to conditions that may affect filter performance.

A two-part study is proposed. The first being a review of filters (Kraus and Pfiefer, Wack and Wimmer, MCC, and PM) comparing them against delivered commercial products as the reference dataset. Filter performance would be assessed on the basis of two criteria: (1) minimization of Type I and Type II errors relative to the reference dataset, and (2) representation of surface shape relative to field surveyed transects. The second part of the study would be the development of meaningful cloud metrics and investigation of potential relationship to parameters and filter performance. The cloud metrics should be reflective of surface complexity. In conjunction with slope variables, cloud metrics could be used as supplemental information to guide assignment of parameters.

The objective of this literature review was to identify methods and available tools for processing LiDAR data for use as surface models. The emphasis was finding approaches to selective filtering of LiDAR to enhance surface models for use in hydraulic modeling and stream geomorphology studies. Selective filtering is better referred to as adaptive filtering; adapt filter algorithm parameters to surface conditions. A broader goal is to improve surface representation and improve data efficiencies. This involves more than identifying terrain points. Studies have investigated automated delineation of breaklines, decimation of terrain surface points, and interpolation of terrain points into a continuous surface. All these elements contribute to building reliable and economical surfaces. The focus of this literature search centers on the filtering of the LiDAR point cloud. However, further study of other surface elements and processing approaches is also recognized as an important pursuit. It should also be noted that this review did not pursue studies related to full wave form applications. Though this field of research appears promising, full-wave form data are not readily available. Commercial providers of LiDAR data have not received sufficient demand to develop full-wave form products and are not fully equipped to produce near-infrared LiDAR full-waveform datasets.

CONCLUSION

A wide variety of filtering approaches for separating LiDAR point clouds into terrain and off-terrain points exists. Available comparative reviews of filtering algorithms do not provide a full assessment of performance in landscape areas along active stream channels, heavily vegetated streambanks, low terraces, and levees. These areas are of particular importance in hydraulic modeling and stream geomorphology studies. A more current and focused comparative review is proposed.

Several studies have shown that surface information in addition to surface geometry (i.e., slope and elevation difference) improve filter performance. Intensity values and land cover maps have been used for this purpose. An approach using cloud metrics is proposed to represent surface complexity and guide selection of algorithm parameters in the filtering process.

Other areas of study including automatic breakline detection and point decimation/thinning deserve further investigation. All these elements combined can contribute to developing reliable surface models for use in hydraulic modeling and stream geomorphology studies.

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