ADVANCED LIDAR DATA PROCESSING WITH LASTOOLS

C. Hug [a,*], P. Krzystek [b], W. Fuchs[c]

[a] GeoLas Consulting, Sultenstraße 3, D-85586 Poing, Germany – hug@geolas.com
[b] Department of Geoinformatics, Munich University of Applied Sciences, Karlstraße 6, D-80333 Munich, Germany -
krzystek@geo.fhm.edu
[c] fpi fuchs Ingenieure GmbH, Aachener Straße 583, D-50226 Frechen Königsdorf, Germany -
w.fuchs@fpi–ingenieure.de

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ABSTRACT:

This paper introduces LasTools, a new software suite for the operational processing of data from advanced airborne lidar sensor systems.
LasTools provides the tools required to generate DSMs and DTMs from raw or basically preprocessed lidar data in a stand-alone application. It features intelligent management of project data, import and geocoding of raw lidar and image data, system calibration, filtering and classification of lidar data, generation of elevation models, and the export of the results in various common formats. Special emphasis is laid on an intuitive graphical user interface and streamlined workflow to enable efficient and rapid production. Additionally, LasTools provides features for the handling and processing of advanced lidar data like return signal waveforms and true surface color, as well as the rapid integration of lidar and digital image data into digital orthoimages.
The paper describes the approach taken by LasTools to efficiently organize and handle the large amounts of data generated by emerging advanced lidar systems with waveform sampling and digital image registration. It discusses the segmentation-based object-oriented filtering technique at the heart of the LasTools classification engine that achieves a high degree of automation for lidar point classification and feature extraction. The user interface philosophy for rapid data visualization and highly efficient interactive editing is highlighted. Finally, the instruments for quality control incorporated into LasTools at all stages of the processing workflow are presented.

1. INTRODUCTION

1.1 Motivation

Airborne lidar mapping has been gaining widespread acceptance during the last several years. While there are a number of established manufacturers offering standard lidar instrumentation, lidar data processing is mostly still done using proprietary in-house developments of the service providers. Obviously, service providers have little interest in making their developments available to the general market, and thus potentially to competitors in their own field. Therefore, the market of commercially available lidar processing software is to date quite small, with Terrasolid Oy of Finnland offering the only lidar-specific products that cover lidar processing in some breadth. Other remote-sensing software packages are beginning to include limited lidar data support. However, most of these only provide tools for the regularization of lidar points (e.g. gridding) and for bare-earth filtering/classification but do not address typical tasks specific to lidar data processing like geocoding and strip adjustment. A framework that handles the entire production workflow is so far not available.

Furthermore, we have had to observe shortcomings in user interfaces of most of the currently available lidar processing systems and lidar add-on components to other remote-sensing software packages with regards to intuitivness and efficiency, which put high demands for training and education on the potential users and make the production process unduly tedious.

Finally, new requirements for lidar processing software are on the horizon due to new hardware capabilities (integrated high-resolution digital cameras, or waveform digitization). They demand flexible data and processing structures to handle the explosively expanding data volumes efficiently and to make best use of the additional information that becomes available through these technologies.

Our goal with LasTools is to provide a "next-generation" integrated lidar processing environment that addresses these issues and puts an emphasis on *ease-of-use* and *efficient production*.

1.2 Overview

In its first incarnation, LasTools handles lidar data processing from the egg (raw data) to the chicken (elevation models, orthoimages), integrated with a project management and quality control framework.

Following processing features are available:
- raw data geocoding
- calibration and strip adjustment
- model adjustment and ground control
- classification
- model generation
- orthoimage generation
- datum transformation and projection

On the project management side LasTools provides
- workflow management
- storage resource management

- quality control
- documentation and report generation
- simultaneous multi-user and network capabilities
- flexible process scheduler for running time-consuming tasks automatically during suitable periods

The user meets a consistent, easy-to-use interface, including
- graphical project organizer, process scheduler, and workflow monitor
- fast and flexible data viewer giving visual access to the data in a variety of display modes in multiple synchronized windows and with efficient display control mechanisms,
- intuitive and efficient data editor with instant visual feedback for interactive operations
- comprehensive online help features on several levels.

LasTools is able to manage, process, and visualize 3D-point, vector, 2D-raster, and volume data simultaneously. Therefore, it is ready to handle the output of advanced lidar systems recording echo waveforms. An open data interface architecture allows LasTools to be easily expanded with additional processing capabilities in the future, as well as giving third-party developers and users with special requirements access for customized applications.

Within the scope of this paper, we will focus on two aspects of LasTools in more detail: project management and classification.

2. PROJECT AND DATA MANAGEMENT

2.1 Project Organization and Data Management

A project in LasTools is organized as one or several *regions*, each of which contains one or more *blocks*. Blocks are considered elementary coherent survey areas. Data is acquired in *flights* (between one takeoff and landing) collecting one or more *tracks* of data that may cover a single or multiple blocks. While flights and tracks result from *sequential* data acquisition and thus represent the temporal structure of a project, regions and blocks reflect its *spatial* organization. A flight will usually be done with a single lidar sensor and one set of calibration values. A block may, however, contain data from several flights with different sensors and calibration sets. LasTools maintains a database that relates flights, tracks, blocks, and regions with the relevant sensor descriptions and calibration data sets.
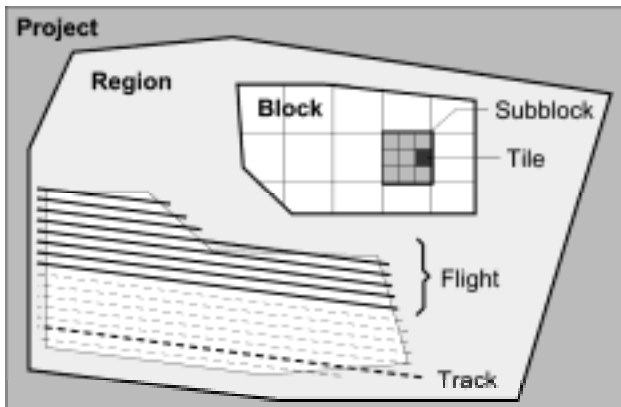

Figure 1. Project layout

Regions and blocks are defined by their perimeters (outline polygons) that are imported when a project is created. During import of track data (or its creation in the process of geocoding), outline polygons of tracks are generated to allow easy access to track-related information at later processing stages when data of multiple tracks has been merged.
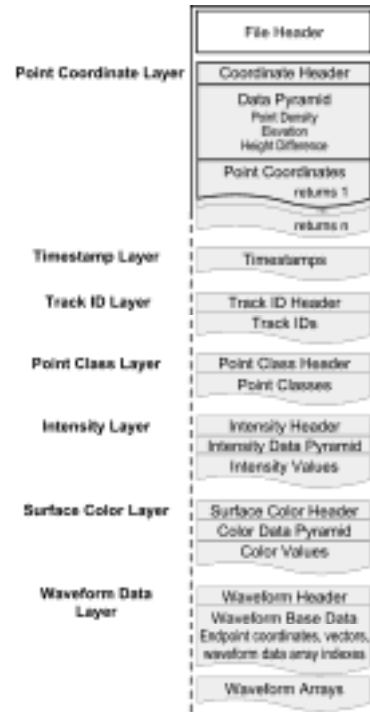

Figure 2. Subblock file layout

The geocoded lidar measurement points are held and organized in blocks. Blocks are subdivided into square subblocks for manageable file sizes (subblocks are the storage units) which themselves are divided into tiles for rapid location-based access. Subblock files hold in a meta-data structure basic lidar data (point coordinates) and attribute information (time stamps, track identifier, return signal intensity, surface point color, point class, etc.) in multiple segments or layers. The sequence of data in all layers is identical allowing the relevant information of any point to be accessed directly and rapidly by indexing from the layer start while maintaining a fully bi-directional relationship between coordinates and attribute values on the level of single measurements. This organization also makes it easy to include additional attributes without having to change the basic file structure and access mechanisms.

For example, the inclusion of digitized waveform data from the advanced lidar systems is easily accomplished as an additional layer of data. For each laser measurement, a variable-length array of waveform samples plus azimuth and incidence angle values of the beam direction and the coordinate of the last sample is appended to the subblock files. While file sizes increase substantially by including waveform data, the layered organization of the files does not require the entire file to be read for performing geometric operations, so processing speed is not compromised.

To further speed up data access and display at coarser levels, each subblock contains aggregated surface height, height difference, intensity and color information at several resolutions in a data pyramid.

LasTools manages subblocks invisibly to the user, who may select any area (rectangular, polygonial or linear) within a block for display and processing and may pan and zoom the display freely over the entire block without having to work with subblocks or even encountering their traces in the displayed data.

2.2 Workflow

LasTools handles all steps of the lidar data processing workflow from project setup to output of products and provides guidance and support to the user on required steps, production progress, quality control, and report generation.

The first step in the workflow is project preparation. It involves
- setting up a project by defining its location in a computer environment, and creating the required directory structures (which happens automatically); a new project may be created from scratch or as a copy of an existing project if some of the parameters used in the old project also apply to the new project,
- importing project-defining data (perimeters, target coordinate system(s) and projections, flight plans, products, output formats and tiling requirements, accuracy requirements, tie-points and control surface information, geoid, etc.),
- definition of the processing steps and timeline for processing milestones.

In the second step the data to be processed is imported:
- import of pre-processed trajectory data
- import of raw or pre-processed lidar along with sensor description and calibration files – the import process includes geocoding of raw lidar data, generation of track outlines, conversion and storage of lidar data in the meta-data subblock files,
- import of digital camera images and associated exposure location and calibration information.

The next step covers lidar and image processing:
- calibration – if not available from an earlier project LasTools assists in deriving sensor calibration parameters (sensor-specific parameters, boresighting, range- and angular offsets) for both lidar and simultaneously acquired digital camera data from a calibration flight pattern over an airfield,
- strip adjustment using data from cross-track intersections and overlap of adjacent strips; adjustment of roll- and scanangle-scalefactor deviations is done using trajectory data, or if not available by an approximate reconstruction of the trajectory from strip data. The availability of track numbers as an attribute to each lidar point is, however, required.
- verification of internal geometrical accuracy at strip overlap and intersection areas,
- classification of lidar points into classes ground/bare-earth, vegetation, buildings/artificial structures, etc.,
- control of classification quality by statistical analyses and visualization,
- transformation into target system,
- geometrical adjustment on the model level using reference surfaces, tie-points, and geoid data,
- verification of absolute geometrical accuracy,
- generation of digital elevation models and lidar data imagery (IR intensity images, RGB/CIR images),
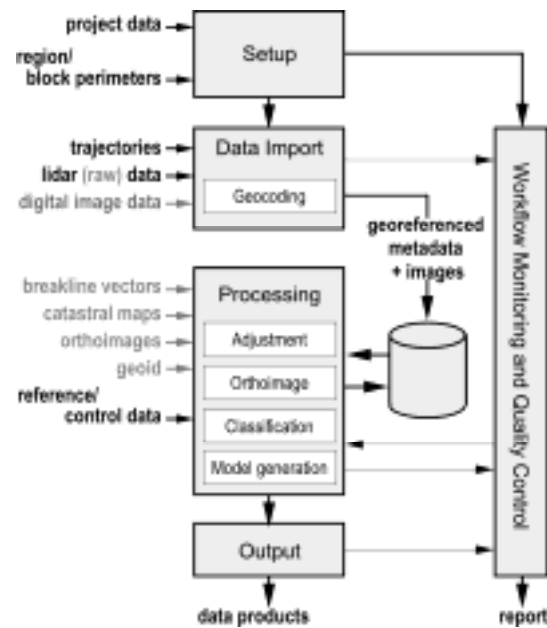- orthorectification of digital imagery using lidar DSM, mosaiking and tone balancing.

Figure 3. Workflow (gray=optional inputs)

In the final step data products are output:
- tiling, output conversion, and export in the required output formats (e.g. ASCII, LAS, Terrascan, Shape, GeoTIFF, JPG2000, etc.)
- generation of a processing report, including documentation of performed processing steps, used parameters, input and output data files, time, and manpower, computing capacity spent to reach milestones and checkpoints, statistics and results of quality checks.

2.3 Project Management

The project management features of LasTools cover the following aspects:
- user guidance,
- workflow and production status monitoring,
- resource management
- quality control.

User guidance assists the user by indicating which actions are necessary for the production process to proceed, and ensures project integrity. This is especially valuable for a novice user who is advised which parameters need to be set (and what they mean), which files need to be imported and in which sequence processing should be done to achieve the desired results most efficiently. This is implemented in form of an advanced "project wizard". Context sensitive online help functionality further assists users of all experience levels, ranging from brief "tool-tips" through more detailed item explanations to fully indexed user manuals and tutorials.

Workflow control ensures that processing steps are performed in the required sequence and are completed before proceeding. The project administrator may define a sequence of processing steps and set certain conditions/milestones that must be met before subsequent steps can be initiated. It also controls access to data in case of multi-user processing environments to make sure that actions of one operator do not interfere with actions of another operator on the same data set.

Project status monitoring maintains a detailed overview of which processing steps have been applied to which parts of a data set. This includes a graphical processing status mask showing areas of a project have been completed (e.g. filtered or classified), which areas are pending (currently being worked on), and which areas are still open. It also alerts the project administrator of delays with respect to the project timeline.

Resource management manages storage space on the designated storage devices, caches data locally in networked processing environments, to provide the user with fast access to the data he is working on, and maintains data integrity for the entire project. Automated data backup and mirroring may also be integrated into the resource management feature.

Quality control verifies that the quality criteria set forth in the project specifications are met throughout the processing workflow. Specifically, at the end of each processing task quality checks are performed before the task is closed and the user can move on to the next step. The results of the quality controls are automatically logged.

- During data import input data quality is verified regarding completeness of coverage within the block boundaries, raw point density, and a general data quality assessment is carried out through statistics generated during the import process (raw data noise and shot statistics, point distribution statistics),
- after strip adjustment the quality of alignment is controlled by analyzing residual deviation and height noise statistics,
- after model adjustment and transformation the statistics of residual planimetric and vertical errors at control surfaces/objects are checked against project requirements
- after classification, statistics are generated, ground point density and ground point distribution are analyzed for irregularities and for compliance with project requirements.
- For output generation the parameters used (e.g. tiling boundaries, grid sizes, file naming conventions, file size limitations, etc.) are compared with project requirements.

Part of quality control is also the documentation of the processing workflow including used input files, performed tasks, associated names of operators, used parameters, product lists, and their crosscheck with the project specifications. All protocols generated by the individual tasks are collected in the quality control report that is generated automatically at the end of the project.

Those steps of the quality control procedure that are interactive like the interpretation of point distribution statistics require the user to confirm that the quality criteria are met. His name, "signature", any remarks, and time and date are logged in the quality control protocol.

3. PROCESSING

While most of the lidar processing components in LasTools employ advanced approaches worthy of detailed discussion we will focus on classification in the scope of this paper.

3.1 Classification Workflow

Lidar measurements unqualified in that point locations are more or less evenly distributed over the reflecting surfaces, but no direct information about what type of surface was hit by each shot is available initially. In order to derive elevation models that only represent a certain type of surface (for example: terrain) the surfaces that reflected the laser beam must be distinguished. Classification is the process of distinguishing and assigning individual 3D measurement points to surface classes, so that in subsequent processing surface and object modelling may be based only on the points from relevant surfaces.

As so far no approach exists that can guarantee a 100% correct classification of lidar points automatically, the classification process is done in three steps:
1. Interactive parametrization
2. Automatic classification
3. Interactive refinement

3.2 Interactive Parametrization

The user selects one or several areas of a block that contain features typical for the surfaces and terrain shapes in that block. These areas are displayed simultaneously on the screen. The user then interactively varies the initial classification parameter settings such that the classification results in the displayed sample areas are optimized. Changes of parameters invoke an immediate reclassification and display update to show the effect of the current parameter settings. The set of parameters is associated with the block and saved. It may also be reloaded as a starting point for other blocks or later projects that have similar characteristics.

3.3 Automatic Classification

An automatic classification is performed for the entire data set (or selected parts) using the optimized parameters.

In LasTools, we implemented a contour/segmentation-based object-oriented approach to point and surface classification. Segmentation is performed by "contouring": contour lines are generated from the highest elevation in an area down to the lowest elevation in relatively small steps (for example 0.5 m). At each elevation level new closed contours are searched. The first occurrence of a closed contour seeds a new segment. A *segment* in this context is a coherent planimetric area delineated by a closed contour. On subsequent (lower) levels, segments grow until their contours merge with neighboring contours. A *primitive object* is constituted by all contours above this level, i.e. by all contours that contain at most one contour at the next higher level. *Complex objects* come into existence when multiple segments merge, i.e. a complex object contains more than one contour or object (both primitive and complex) at the next level. Complex objects are the "parents" of their complex or primitive "children". Obviously, at the lowest elevation (root) level a single complex object exists that contains all other objects and represents the entire block.

These objects are so far only abstract entities representing hierachies of enclosed contours and should, of course, not be confused with actual surface objects as they may contain any type of surface objects (vegetation, buildings) as well as ground. This hierachical description of the data set, however, facillitates searching for "real" surface objects significantly.
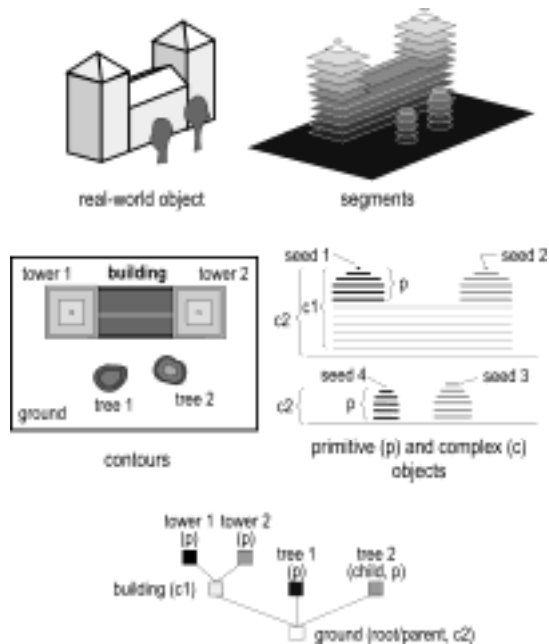
Figure 4. Object hierarchy

In the next step, the object family tree is analyzed from the leaves (the top/seed of the objects) to the root to determine, if an object is a real-world object sitting on the ground or if an object is part of a terrain structure (or an artificial structure that should be considered terrain like a dam). This is done by analyzing the shape of the object and the "growing behavior" of its segments from level to level. In a simple case, a seed may be a small spot that grows quadratically in area from level to level into a rectangular shape, stops growing for several levels and suddenly grows again in large but random steps. The real-world object described is a simple house with a rectangular floor plan. It is "completed" on the last (lowest) level before the segment starts growing randomly.

Numerous criteria can be used to determine real-world objects and on which elevation level they start: object geometry (area growth, contour/segment shape, relationship of area size and contour length, relationship of volume (height) and area size, etc.), object attributes, object context (shapes, sizes, growth behavior of "sibling" (adjacent) objects, and the parents and grandparents of multiple objects in the object tree), and several others. How a real-world object is detected from these criteria is controlled by a fuzzy-logic-based classification that may be parameterized by training.

This approach has proven to work very well with a large variety of surfaces including mountainous areas with steep slopes and sharp ridges that often pose challenges to conventional approaches. We also found that discrimination of artificial structures like dams and ramps that are usually considered as belonging to the "ground" class are reliably classified as such while other artificial structures of almost any size and shape are reliably identified as non-ground (e.g. buildings).

Besides distinguishing surface objects from ground, contour-based object detection generates comprehensive information about the surface objects that can readily be used for further classification. Different types of surface objects (buildings, trees, etc.) can be identified and

geometrical object descriptions (building geometry, roof shape, ridge orientation etc.) can be derived with little additional effort by just evaluating the geometry of the abstract object. Complex buildings, for example, are represented in the object tree as a parent object with multiple child objects representing building primitives (see figure 4). The geometries of parent and child objects structure the building and describe its geometry in detail.

In the other direction a generalized surface and land use description may be derived by classifying lower-level complex objects according to their children (e.g. an area with many small-sized child objects of type "building" makes a housing area, similarly: industrial areas, parks, forest, agricultural areas etc.)

It should be mentioned that this approach is easily expanded to use attribute data like in form of 3D-points and raster images as well as any available a-priori information in object or structural from, and also including return waveform data, to increase the selectivity and robustness of the classification and to refine the object descriptions:

- 3D-point data within object boundaries, point density and the planimetric and vertical distributions of points within an object indicate its "transparency",
- lidar intensity, surface color, and raster image data provide radiometric information about an object,
- vectorized object descriptions from digital catastral maps, zone delineations, breaklines, or segmentation maps from digital imagery, etc. can be used as additional input to the segmentation process to refine the output or to define objects that cannot easily be recognized from geometry alone (administrative zones, for example)
- return waveform data describes surface attributes like "roughness" and "slope", and, representing reflectance within the volume (at each level inside an object), the content and internal structure of transparent and partially transparent objects.

3.4 Interactive Inspection and Refinement

Depending on the requirements to the quality of the classification LasTools contains an easy-to-use, flexible, and fast data viewer and editor for interactive verification and local refinement of the classification results.

Data Viewer

The data viewer enables the user to visualize all relevant aspects of the available data. It displays
- vector data (outlines of regions, blocks, strips of lidar data, planned flight line vectors and flown trajectories, imported breaklines and vector maps, profiles, contour lines, 1D and 2D histograms ...),
- point data (3D lidar measurements) colored by attributes (timestamp, line number, return number, elevation, spot height, intensity, surface color, ...)
- raster data (DTM/DSM color-coded elevation, shaded relief, intensity and surface color images, digital orthoimages, imported raster maps),
- volumetric data (volume reflectance from waveform data, slices, profiles, etc.)
simultaneously in a data (world) coordinate system. Multiple views may be synchronized to show different aspects of a data set in separate windows that are updated as the user pans or zooms one of them.

The user may select and manipulate the display area (pan, zoom, rotate), switch between data layers, superimpose and mix different layers, and select, modify and display profiles. Separate horizontal and vertical scaling is provided to view slight variations in the vertical direction over large areas and long profiles. The user may select specific data ranges to be displayed, having full control over the assigned color-coding, scaling, image, and gamma settings. Several color tables are available to color-code elevation, height differences, intensities, point and surface classes, etc. appropriately, and user-defined color tables may be created within LasTools.

Data can be displayed in plan, profile, and perspective views, as point clouds, wire meshes, contour lines, surface renderings, 3D-vectors, and 3D-slices. 3D display using appropriate hardware (LCD goggles) is in preparation. The data viewer also provides access to data statistics (histograms) and the object database, making the retrieval and output of information about any specific object a matter of point-and-click. Furthermore, information about multiple objects, either individually selected or by one of the selection functions can be extracted on selectable levels and output, for example to a text file or a vector graphics file.

The interaction of the viewer is designed to be highly intuitive and efficient: only a minimum number of mouse actions and key-strokes are required to switch between different display manipulation functions (e.g. zoom in/zoom out/pan) and display modes, as it is also known from popular image-manipulation software. The display engine and the internal data organization are geared for flexibility and display performance using data pyramids and a multi-threading approach to provide a high responsiveness of the viewer at all times. The inefficiency and leaning requirements of typical CAD-based applications are avoided without compromising on accuracy and speed.

Data Editor

The graphical data editor expands the capabilities of the data viewer and provides features for manipulating certain aspects of the data. Its main function is to provide a way to interactively optimize point classification and to edit elevation models. The interaction concept puts emphasis on intuitive interaction and immediate feedback to make interactive data editing as efficient as possible.

Two approaches are implemented:
- the user selects one or more regions of interest (which can also be objects), and applies certain filtering or manipulation functions to the selected ROI(s). He can select the filtering/classification/ manipulation functions and vary the parameters interactively to find the best setting for the selected area, or
- the user defines a filtering/classification/manipulation function (or sequence thereof) along with the parameters and then selects the area(s) or objects to which the effect is to be applied.

Data Selection. Several types of selection tools are available: individual selection of points and objects by directly clicking them, selection of areas with rectangle, ellipsis, or polygon selection tools, selection of areas with similar characteristics using the "magic wand" locally or a property selection dialog globally, and a paintbrush tool for directly marking one or multiple areas of interest. The selection tools may be used in combination to define complex areas using include and exclude functionality.

Interactive Segmentation. The magic wand provides a tool for interactive segmentation by region growing based on data characteristics like elevation, intensity, and/or, surface color. Starting with the seed point marked by the user all connected points within given min and max values are selected. Instead of absolute limits it is also possible to define a bandwidth of *relative change* to for example select all connected points where the height difference from one point to the next does not change more than +20 cm or less than –50 cm. A combination of several data characteristics may be defined (e.g. min/max absolute elevation AND max. elevation change AND min/max intensity). This tool can be very efficient to locate extended connected areas like road surfaces or fields with a certain type of vegetation.

Interactive Re-classification. The paintbrush tool is especially useful for the second type of manipulation approach, as it provides on-the-fly data manipulation and display update. With this tool, it is for instance possible to define a surface class, and to apply (or "paint" this class to all points touched by the paintbrush. If the display shows a shaded-relief view, the re-classification immediately causes a local re-calculation and display of the modified surface model, so that the effect of the manipulation is seen as it is performed. The function of this tool is not only limited to changing the class of all points directly. It is also able to apply a local filter that effects a re-classification according to filter criteria (e.g. set class "ground" only to lowest points in a 5-m-radius). Similarly, the surface may be smoothed, lifted up or lowered, etc.

Elevation Model Manipulation. The data editor allows the user to edit elevation models (DSM, DTM) before output, to remove residual surface features that could not be removed by classification, or to blacken out areas of industrial or military installations that are classified and should not be present in the DSM product. It assists to approximate or smoothen areas that only have a very coarse representation due to, for example, low ground point density in dense forest. An "extrusion" tool, finally provides the possibility to shape the terrain by applying a profile along a user-defined path. This can help to approximate terrain along a heavily-vegetated ridge or cliff which initially appears heavily distorted locally due to missing ground points, but where it can be assumed that the terrain profile shape does not change substantially for some distance. A path along the (suspected) ridge edge is defined by the user, and one or multiple profiles that are taken from open parts of the ridge are placed along the path to define intermediate model points. This tool can also be used in classification, if instead of changing the model it is only used to select all ground points near the extrude profile that may not have been detected by the automatic classification due to the complexity of the terrain.

4. SUMMARY

LasTools provides a next-generation integrated lidar processing environment including multi-user, networked production process, workflow management, and quality control for operational and efficient lidar data production. While it currently does not provide all the application-specific features implemented in other products yet, its object-oriented modular approach with integrated point, vector, raster, volume, and model-handling capabilities facillitates its expansion with additional features to address customer requirements and upcoming technologies.