An Overview of LIDAR: collection to applications

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A group of planners, engineers and concerned citizens look down a city street, discussing how a new development on vacant land will integrate with the existing fabric of people, cultures, and infrastructure. Their words carry weight but communication is limited by different understandings of the problems faced during development. So they turn to a laptop placed on a nearby truck hood...

Geographic Information System software on the laptop shows plan maps for the area drawn by planners and engineers, rough three-dimensional models of the street as it is now and as it may be in the future. A visualization tool shows photo-quality models of the same street with fly-overs. A discussion evolves, and changes are noted. The design lead passes around a card with a Web address that links to Google Earth, where the citizens can look at a lower-resolution plan for the area complete with real and simulated photographs.

Where does the data for such models come from? Does someone go out and measure each and every feature on the street manually? Do we have such data for our infrastructure at present?

LiDAR is one key technology that makes the construction of city-wide data sets of this type feasible. This document provides background and context for understanding how LiDAR supports present and future modeling and planning efforts.

LiDAR data collected in Oslo, Norway, using a Leica HDS6000, February 2009: every feature has not only a reflectance value, but also a mm-accurate 3d position relative to the scanner

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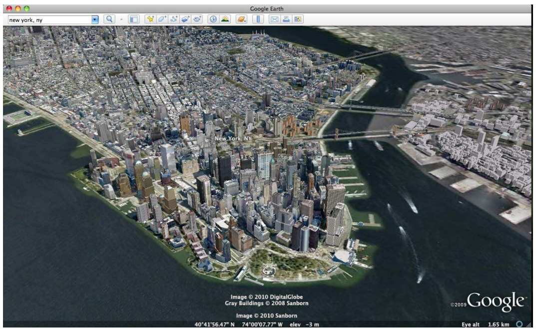


Google Earth - Three-dimensional GIS visualization, free on the Internet. Where does the 3d data for all these features come from? Can one method provide it all?

Overview

LiDAR is a technology for measuring positions of physical objects, rapidly. In the urban case, the scanner measures the positions of most of the features along the street. LiDAR stands for Light Distance And Ranging; LiDAR uses a laser beam to measure the distance from an object to the scanner, and mechanical-optical mount to scan the laser across a scene accurately. To know where features are in the world, the scanner also needs to know where it is.

LiDAR is useful not only because it can provide accurate positions over large areas, but also because it is fast: LiDAR can collect tens of thousands to over a million positions per second. Collecting location based data at this level of detail through traditional surveying would take years. LiDAR is thus a viable solution to the ongoing and daunting task of mapping our infrastructure to support maintenance, modelling, and visioning exercises.

LiDAR data can be collected from airborne or terrestrial vehicles, from fixed positions, usually on a tripod, and offshore platofrms. Airborne LiDAR has been used for some time as a source of models of the landform for engineering, disaster management, and other visualization tasks; fixed LiDAR has been used in infrastructure mapping of detailed sites such as chemical plants for a number of years.

In recent years the use of LiDAR has grown rapidly, both in terms of the number of application domains and in the prevalence of the method in real-world practice. This document provides background on LiDAR and illustrates where LiDAR appears to be heading as a tool to support urban planning and engineering.

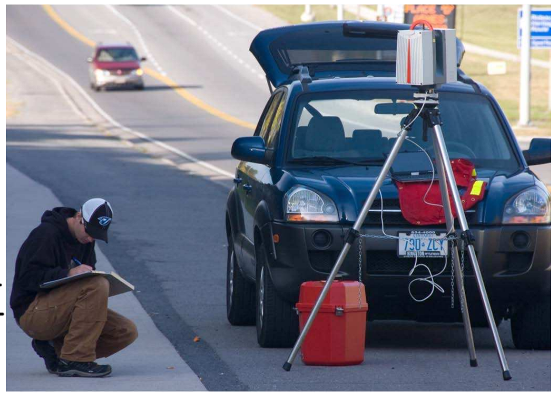
How It Works

LiDAR relies on two sets of measurements to generate a cloud of point locations for features around the known location of the scanner. First, the position and pointing direction of the laser must be known for each measurement. Depending on the physical mechanism of the scanner the points may be evenly or unevenly distributed on the target, and because systems normally operate on an angular offset between successive measurements, targets closer to the device will have a higher point density than those farther away.

The second piece of information needed is the distance. There are two approaches to measuring this: time-of-flight and phase-based. Time-of-flight LiDAR sends a laser pulse, waits, and measures the time of arrival of the return pulse(s). Given the travel time (the speed of light) and very precise time measurement, a distance can be derived. Time-of-flight systems are limited only by the need for a return signal, and so higher powered systems can 'see' out to multiple kilometers, as needed.

Optech IlRIS long range time of flight LiDAR scanner. The scanner is set-up at a quarry to analyze the potential of rockfall hazards.

Phase-based LiDAR employs an amplitude modulated continuous waveform laser (AMCW). When the beam interact with a target, the phase is reset, and the returned shifted signal is processed to derive distance in combination with the duration of the flight. This measurement technique is faster than time-of-flight methods but has the limitation that there is a finite distance beyond which offsets cannot be converted into distances. For ex-ample, the Leica HDS6000 unit cannot image targets past 79 m. It can, however, collect 500,000 pts/sec. State-of-the-art phase based scanners such as the Faro LS120 can collect measurements to a distance of 120 m at a rate of 1,000,000 pts/sec.



LiDAR data collection using an HDS6000 in Kingston, Canada. Data collection time requires less than 5 minutes per tripod location.

Regardless of the type of LiDAR used, the combination of direction and distance is used to create a cloud of measured points located relative to the scanner. If the actual position and orientation of the scanner in real-world coordinates are known, these can be integrated with the scanner-relative measurements to produce a point cloud in real-world coordinates. Knowing where the LiDAR device is thus key to building data sets that can be integrated with other geographic information and information systems.

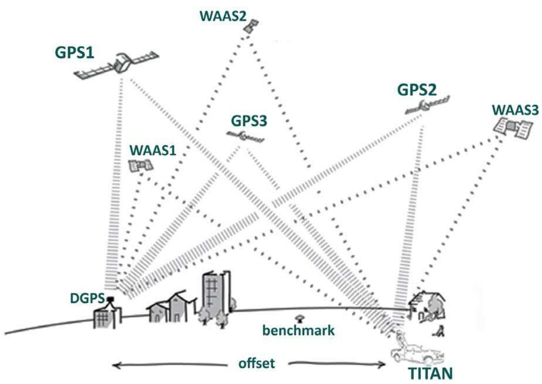
Navigation and Location

The accuracy of a LiDAR is limited by the accuracy to which we know its location. For a moving system we must track the position of the sensor for each pulse; this location is then used in combination with the LiDAR angle and distance information to place a position in three dimensions. For a static system the problem is somewhat simpler as all of the positions for one scan will be relative to the position of the sensor, which is not moving. In both cases, the overall accuracy of a scan relative to other geographic data (for example, existing GIS data for an area) is limited strongly by how well we can position the sensor.

Positioning is based on the Global Positioning System (GPS), augmented in the case of mobile systems by Inertial Movement Units (IMU, also known as INS). Together these constrain the location of the sensor at every instant, and if we accurately correlate times of LiDAR acquisition to positions then the overall scan will be accurately located in a georeferenced space, for example the UTM coordinate system.

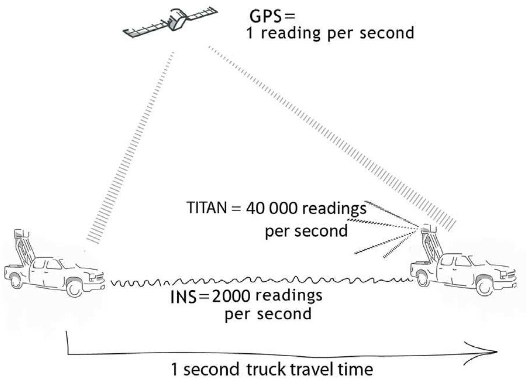
GPS is based on the measurement of position by the time of flight of radio waves. A number of satellites (at least 4, but usually more) contribute position offsets that, together, constrain where a GPS receiver is at any point in time. Operationally this is limited by the availability of satellites, by an unobstructed view of the sky, and by the fundamental physics of the satellites and receivers.

The use of static base stations, whose apparent motion can be used as a correction signal to offset clock and atmospheric physics limits on accuracy, is called 'differential GPS.' For mobile LiDAR surveys at least one and usually more base stations are placed at fixed locations in the survey area and provide correction signals for the position of the mobile unit; this typically takes GPS from meters of accuracy down to decimeter accuracy. Survey grade GPS uses advanced GPS receivers and processing to produce centimetre level accuracy.



GPS is a core technology for LiDAR - knowledge of the scanners location is essential when converting collected lidar data to useful point-clouds. GPS used in LiDAR is much more precise than systems used by consumers, but the principles are the same.

Areas may have obstructed views of the sky, resulting in poor



Mobile terrestrial LiDAR data collection involves the dynamic collection of location information in conjunction with LiDAR data. The above schematic illustrates the complex relationship between onboard data collection devices

or absent GPS positioning. This is especially common in urban scanning. Inertial Measurement Units are used to address this issue. Inertial Movement Units (IMUs) rely on physical sensors to determine movement: very accurate determination of attitude and acceleration can be combined to provide a path through space which requires no external signals. IMU on airborne or terrestrial LiDAR allows the interpolation of positions between accurate GPS position fixes. In practice the accuracy of IMU-based position determination drops off quite quickly, and so, it is the combination of GPS and IMU together that allow accurate sensor-position determination for LiDAR surveys.

Note that since an IMU is capable of accurately determining position during a 'gap' in GPS signal acquisition, a mobile terrestrial scanner equipped with an IMU can drive through urban canyons and tunnels for a significant distance, with only gradual loss of position accuracy. Once the position from GPS is re-acquired the position during the gap can be forward and back-corrected. In practice gaps of minutes in duration are permissible, though not desirable.

Airborne Acquisition

In the case of airborne acquisition, the LiDAR is placed in an unobstructed location in a fixed wing aircraft or helicopter. This generally involves fixing a sensor pod to the bottom of the aircraft and putting in-flight controls inside where the operator will sit.

The aircraft is then flown to the target area and flies a series of paths across the area in a grid pattern. The density of the measurements is determined by the LiDAR data collection rate, the elevation and ground speed of the aircraft.

Given the requirement of eye safety for people on the ground, higher power systems must be operated from greater height. As a result, systems are often divided into 'high range' and 'low range' systems for different applications.

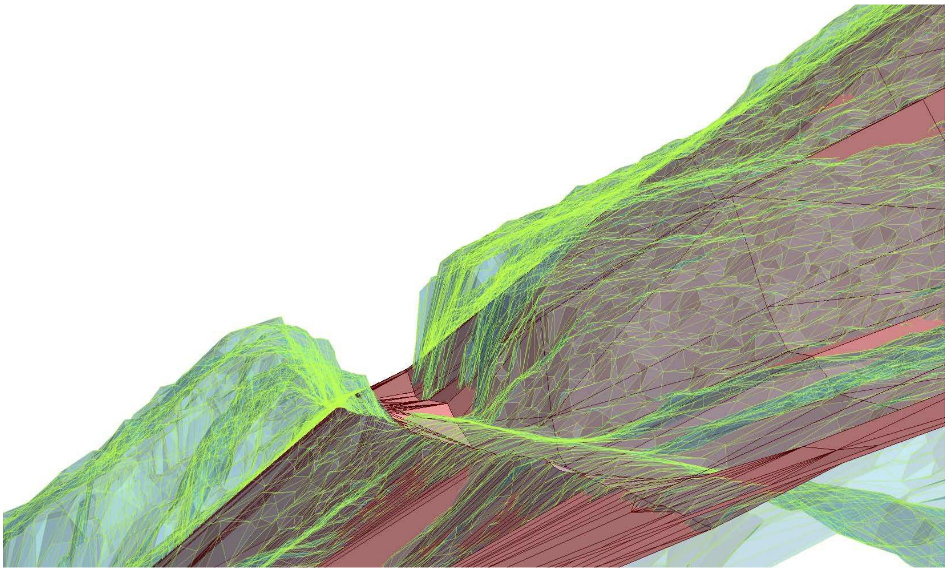
Data from airborne scans is corrected for position and then processed for various output products. One typical product is the generation of a bare-earth elevation model; in this case the 'farthest' return for each orientation is used and features such as buildings are removed by an operator using specialized software. Such bare-earth models are useful for flood mapping, construction planning, and other visualization needs.


Airborne LiDAR data collected in forested terrain is an excellent means of gathering information regarding tree type, canopy density, as well as investigation for road design and urban expansion. The above data illustrates a mountainous terrain with a railway about 1/4 of the elevation from the bottom of the slope

Terrestrial Acquisition

In terrestrial acquisition, the LiDAR unit is mounted either on a tripod or on a vehicle. Since the range to the target is dramatically less than for airborne surveys, the point density will be much higher, as great as a few points per square cm. This is pragmatically limited by the diameter of the beam on incidence – if the intersection is 5 mm across, collecting a point every millimeter is of limited use.

With terrestrial mobile systems, a coupled GPS-IMU solution is needed to track where the device is during data acquisition. This



Airborne LiDAR - derived DEM (green) compared to traditional 1:50 000 DEM (pink) for an area along a rail line in northern Ontario, Canada. Note that the DEM does not 'see' the rail line or rock cut at all. LiDAR data collected with Ambercore's ALMIS system.

is in principle similar to airborne systems but has the added complication that it is much more likely that GPS visibility will be reduced so that reliance on IMU control will be larger. Ground control GPS locations are also used with mobile systems both for calibration and quality assessment.

With tripod mounted systems, GPS control can be either from a GPS on the unit, plus one or more control points on the ground to provide geometry, or from multiple GPS targets on the ground. Multiple scans can be combined as long as three or more common and distinct points exist between the scans. It is common practice to place targets in the scene that are highly reflective and have precise scannable markers in order to guarantee a minimum of the common points. These points, ideally, would be collected using GPS as well.

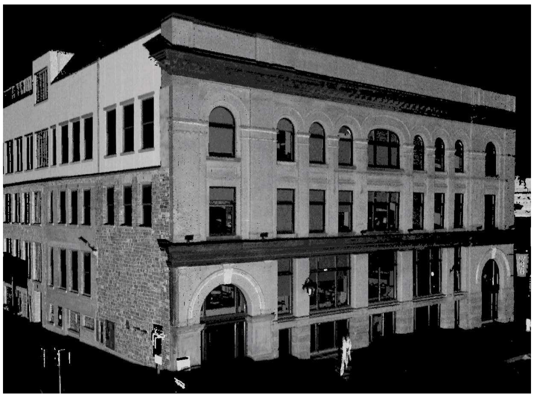
Photos collected from axial cameras on a mobile terrestrial unit or collected with a digital camera from the position of the LiDAR device can be combined to create image domes that can be integrated with LiDAR data to provide colour for point clouds.

Mobile terrestrial scanning technology is evolving rapidly, with several scanners available for purchase or rent. Notably, the TITAN scanner from Ambercore and the Lynx scanner from Optech. Both systems can be purchased, vehicle mounted (truck, atv, boat), and used for high speed data acquisition. Both systems use time-of-flight lidar scanners and are capable of producing point clouds with sub 5 cm of global accuracy. Both systems are capable of generating survey grade point clouds of sufficient density at flow of traffic speeds.

The Terrapoint TITAN scanning solution mounted on a truck. The box mounted on the scissor-lift contains multiple LIDAR and IMU units as well as a GPS receiver. The operator sits in the passenger seat in the truck.

LiDAR Processing: Basic Models

Once collected, LiDAR data is post-processed for geometric correction as needed. This can be simple, as in the case of a fixed scan from a tripod-mounted scanner, or highly complex, as in the case of IMU position correction for a mobile scanner. The result of this stage is a geometrically accurate collection of points, or a 'point cloud,' typically coded with intensity of return and in


Kingston Whig-Standard building and area, scanned November 2007 with a Leica HDS6000 phase-based, tripod-mounted LIDAR.

some cases with the normal vector (the vector to the scanner).

Multiple scans for an area can be combined, resulting in even larger data sets to increase either the scan area or the scan density. In the case of scanning using targets on the ground, these targets are the control points for combination. In the case of scanning using targets in the scene, as discussed earlier, these targets provide geometric reference for combining multiple scans since they are either GPS located or remain fixed between multiple scans.

Processing to spatial products then proceeds. Since LiDAR will produce complex signals, often including multiple returns for one pulse, processing can produce a 'first' or 'last' return product. In the case of airborne surveys, the last return from many of the pulses will be the ground or built infrastructure such as buildings. The first return may be vegetation. A skilled operator can produce a 'bare-earth' model from last returns, using editing tools to remove buildings or forest canopies, if desired.

Currently there are two daunting problems with LiDAR point cloud processing. First, there is no one software tool that does all of the necessary steps from input to model creation, and so files must be transferred between tools and formats. Second, the data volumes are so large – often in the hundreds of gigabyte range – that even the fastest workstations are hard-pressed to render, let alone process the data in reasonable times. Typically a large data collection project will involve division of an area into zones, or 'tiles,' simply to provide smaller working targets that are of manageable size.

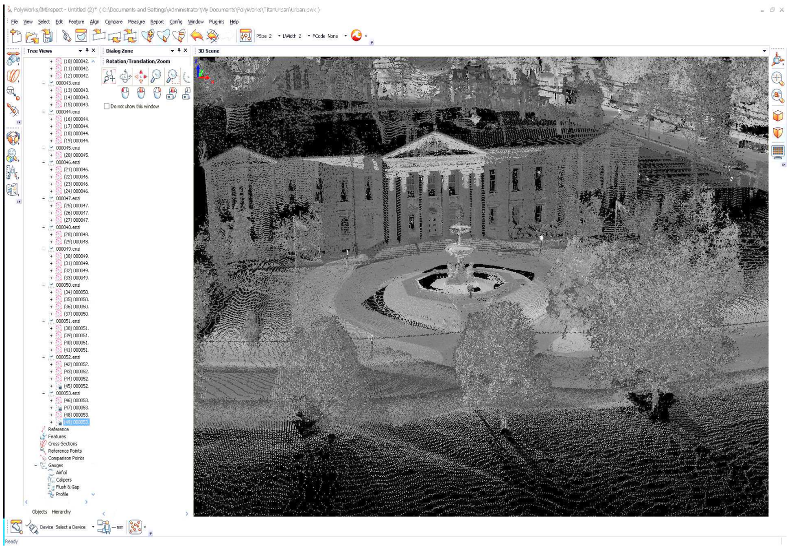
Processing: To Features

Engineers, urban planners, and other spatial data users do not want point clouds. They have neither the tools nor the interest in processing data in this format – they want spatial features such as 'roads' and 'trees' and 'buildings.' In a LiDAR point cloud, these urban features will be part of the overall cloud, and will at best be partially captured since obstruction during scanning and the position of the scanner limit what portions of features are measured. For parts of features scanned there is usually a correspondence between the material type and the intensity of signal return. Ideally processing should replace many points with few objects, and these objects should be from a standardized library (such as standard park benches, or standard hydrants) rather than being unique.


Although this resembles a LIDAR point cloud, this is a surface representation of the edge of the Kingston Whig Standard building constructed using surfacing tools in Leica's CYCLONE LIDAR processing package.

To date the process of converting point clouds to attributed spatial features is operator driven. There is abundant computer science research on this general topic but it has not yet trickled down into truly automatic tools that can 'look' at a point cloud and 'recognize' common features.

Two general approaches are taken. First, points can be converted to surfaces with geometry and then corrected, with the source points being removed from the point cloud. As this process continues the point cloud will eventually consist of only features that have complex and irregular geometry (like grass, trees) or are unrecognizable. Alternatively a matching tool can



Processing of LIDAR point clouds requires specialized software and very fast computers. This point cloud of the region around the Kingston Courthouse, shown here in PolyWorks from Innovmetrics, consists of hundreds of thousands of points. To use it in a traditional visualization tool it would have to be reduced to geometric features such as polygons, lines, and textures.. To use it in applications such as Google Earth the buildings would need to be reduced to a few dozen polygonal patches at most.

look through the point cloud and to recognize features by comparison to a library of known features.

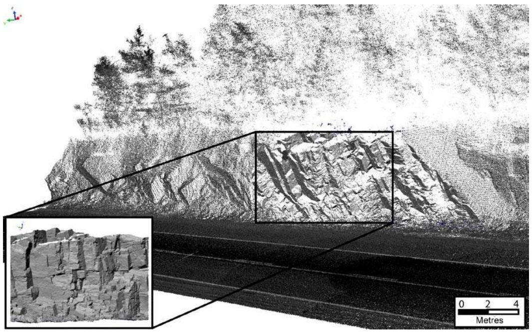
Even the process of building simple surfaces is problematic. How smooth should a surface be? Can we tell instrument precision issues apart from feature texture? To date, LiDAR processing tools are reasonably well suited to surface building and object tracing for highly regular features like pipes, but less well suited to complex features such as building fronts.

Output To GIS and Visualization Tools

Ideally geometric output from LiDAR processing, as features where possible, should be passed to more general mapping and visualization tools for further work. For example, building shapes from a mobile terrestrial lidar (MTL) scan might be processed to building features at a desired resolution, brought into a modelling environment such as Autodesk's 3dStudioMax for refinement, and then exported as components for use in movie making. MTL data might also be used to build out a large urban area at meter-level of detail for export to an open visualization platform such as Google Earth.

The real issue encountered here is of data set size. LiDAR data sets in the gigabyte range just do not transfer into 3d visualization tools effectively, and for Google Earth, even moderately detailed and textured geometric features are an issue. For example, Google Earth engineers recommend representing a large building as images (up to about 200 kb in size total) and features (a few dozen flat shapes total) for a total size of about 250 kb whereas a LiDAR scan of the same building might have 500 million points or correspond to a few tens of megabytes of

This urban data from the Terrapoint TITAN system shows how drive-by LIDAR can map infrastructure, buildings, and vegetation rapidly.



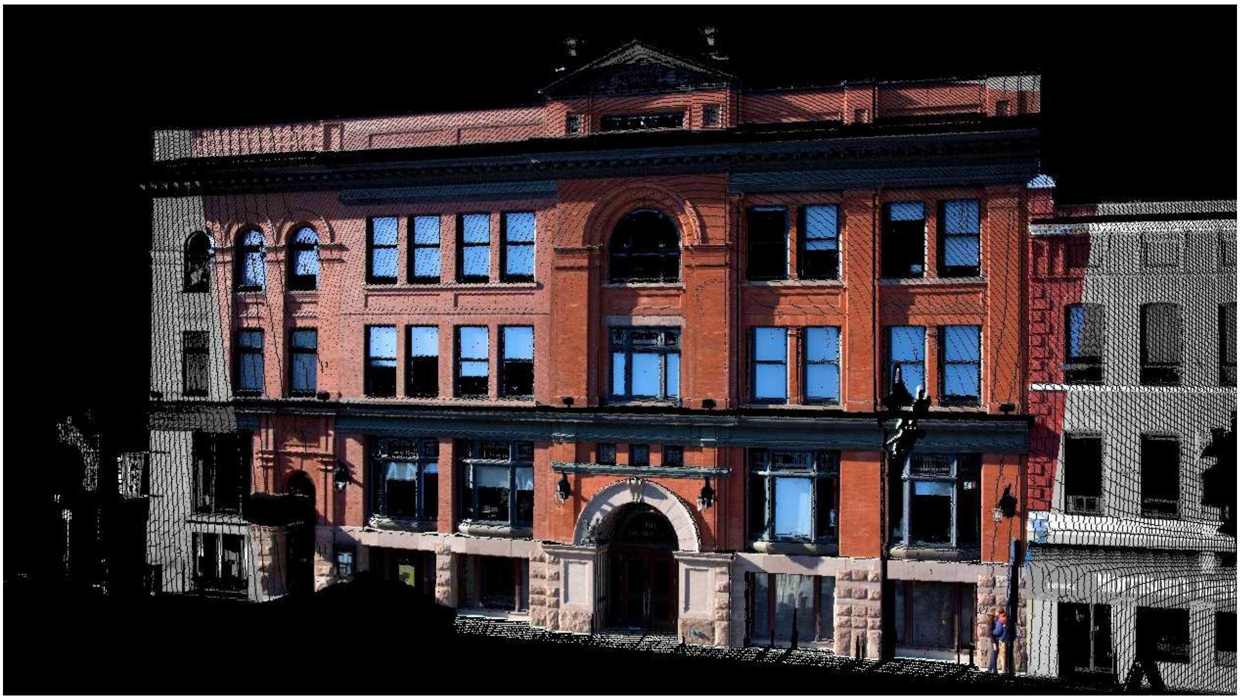
A potentially unstable rockmass adjacent to Highway 15 in Ontario, Canada. LiDAR data were used as an alternative to conventional field work to assess the stability of the rock-mass and determine a hazard level. This image illustrates mobile terrestrial data (TITAN) fused with high resolution Leica HDS6000 static LiDAR data. The data are merged and visualized in real-world UTM coordinates.

detailed building geometry. Clearly the workflow from LiDAR to Google Earth needs some research and pragmatic choices.

Conclusions and the Future

LiDAR scans, whether mobile or static, can be used to build models and to map urban infrastructure accurately. There is no alternative technology that allows thousands of measurements on geometry per second and can scan all features in line-of-sight to roadways. The fusion of LiDAR with digital photography, as seen in the adjacent figure, produce life-like virtual models.

Research on LiDAR processing, especially on feature extraction and spatial analysis, is ongoing. As computers get faster and cheaper, handling large data volumes will be less daunting and the penetration of this technology into urban planning, architecture, and civil engineering will accelerate. While it may be some time before LiDAR-level models are used in online tools like Google Earth, in the near future features in online environments, games, and visualization tools are based on LiDAR.



High resolution Leica HDS6000 LiDAR data pixel mapped using an image captured with a DSLR camera

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3D representation of a Viking Church in Oslo, Norway. The LiDAR data collected with an HDS6000. Data merged from 8 scanning location totally over 300 million points. Data were merged using InnovMetric’s PolyWorks software