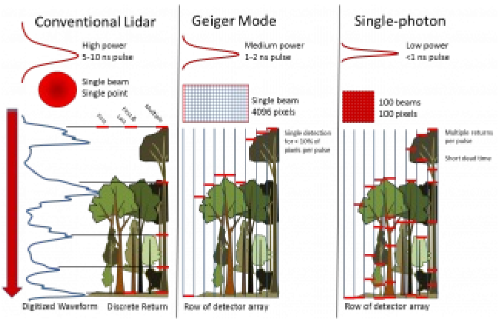
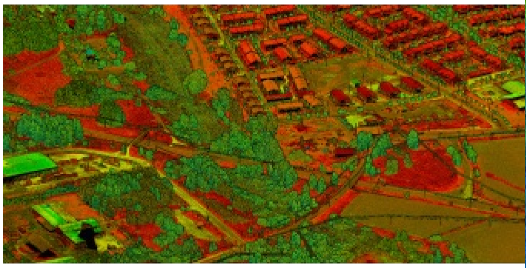
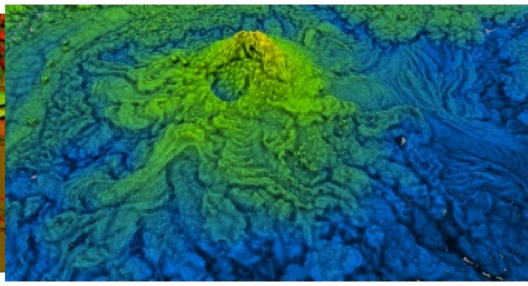
BUILDING THE CAPABILITY FOR HIGH-DENSITY 3D DATA

Technologies for the Future: A Lidar Overview







Which technologies and processes are building the capability for high-density 3D data? [Point clouds](#) can be captured by an ever-increasing number of means to understand the surrounding reality and detect critical developments. Diverse applications of 3D laser scanning or ‘Lidar’, which is a technology on a sky-rocketing path to be used for mapping and surveying, are changing the way we collect and refine topographic data. This article outlines the latest industry developments.

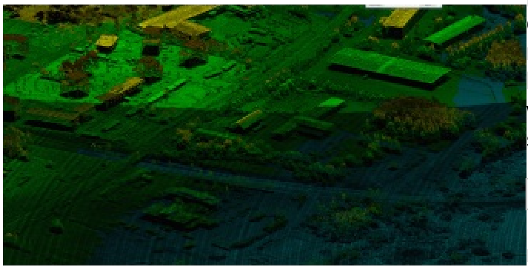
National topographic databases store data refined from field measurements, imagery and laser scanning data at certain specifications and purposes, but lack the ability to adapt to ever-changing needs and situational awareness. ‘Data on demand’ is a recognized megatrend in the geospatial industry.

Point cloud data can be captured with an ever-increasing number of means – e.g. ground-based, airborne and spaceborne platforms – to understand the surrounding reality, from grain scale to global overview. Different scales and viewpoints can provide comprehensive multimodal data for environmental analysis, assessment of natural resources, development of urban infrastructure, and critical services. Semantic point clouds, temporal coverage, multimodal data sources, and automated processing form the framework for the future topographic data.

Lidar Technologies

Laser scanning is based on the use of optically directed Lidar beams to collect object information in direct 3D measurements. This allows the system trajectory (i.e. position and attitude), to be produced robustly and accurately. Prior to the mid-1990s, GNSS-IMU technology was not affordable for commercial use. Since then, however, the market for devices has exploded, especially with the development of fibre-optic gyroscopes (FOG) and microelectromechanical systems (MEMS) technologies. Also, the buildup of nationwide GNSS base station networks has contributed to the success of Lidar in surveying and mapping in all its variety.

What makes Lidar so effective in topographic mapping is the capability to direct 3D measurements for the target and penetration of the beam through vegetation to collect information from objects and the ground beneath. The light wave front passing through the vegetation



produces information on the vegetation as a side product. To yield such information, certain principles of laser ranging have to be deployed. The traditional way to gain long-range measurements is to shoot powerful laser pulses towards the target and collect the backscattering signal. The signal is then processed to detect objects at distinct ranges within the beam illumination area. These systems are the current mainstream and use a selection of spectral wavelengths to convey the data collection.

Dense and geometrically accurate point cloud offers photographic 3D capture of the reality for mapping, modelling and monitoring. Spectral information from Lidar will have significant implications on automated data interpretation.

However, for spaceborne applications, this has proved problematic due to the excessive power needed to reach the Earth's surface from orbit, because of the havoc heat causes for the optical components. A novel emerging technology is to harvest the energies at the single-photon level, reducing stress on the optics. Some single-photon devices available in the market promise high data-collection efficiency due to the high altitudes permitted by the sensitive detection. On the other hand, cloudiness sets limits for achieving the full potential in practice. The detector does not sample each returning photon but instead at detector-specific probability, and photons from other sources are detected in addition to those emitted by the Lidar source. This stochastic nature of detection forces adaptation of data processing methodology, because data characteristics and implications on data accuracy and processing are not yet fully commonly understood.

There are currently two techniques implemented for single-photon detection. In the Harris Geiger mode system, each detector pixel for a single pulse is occupied with the first photon received and no data beyond that is captured. Detection efficiency is less than 10%. Large-size detectors compensate these two characteristic features, and the data products typically give 8 or 32 points per square metre. However, penetration under vegetation remains somewhat uncertain. In the Leica SPL100 single-photon Lidar sensor, multiple targets are detected for each pulse per pixel after a short dead time of the detector when triggered by a photon. This gives penetration capability similarly to conventional Lidar. However, more analysis is needed to find out the pros and cons of these technologies unambiguously.

Airborne Lidar

Topographic surveys from the air form the firm basis of mapping. Information needs include ground elevation, building and network infrastructural assets and development. Airborne laser scanning is a two-decade old technology used to produce information for national mapping agencies, municipalities, and engineering companies, to fulfil the needs of communities, decision-makers and land-use planners.

Airborne Lidar data iscollected for projects and data needs exhibiting various scales. For maximum detail, the data is collected from low-altitude flights (50-300m) at millimetre-level accuracy for utility mapping and civil engineering (e.g. RIEGL VUX-240, or Optech ORION C300-1). The data densities at this level are at tens or hundreds of points per square metre. For road and urban planning, mid-altitude (400-1,000m) scanning is often used and the data density is typically around a couple of dozen points per square metre. Country-scale mapping flights are conducted using high altitudes (2,000m and up) for efficiency, and data densities are less than ten points per square metre, typically 1-2. The latest instruments for these applications on the market are the Leica Terrain Mapper, Optech ALTM Pegasus and RIEGL VQ-1560i.

Principles of certain Lidar modes. The most complete signal is recorded with full-waveform Lidar. On-the-fly detection and single-photon techniques reproduce discrete sampling. Increasing the scan angle has an effect on the signal as per the changing light path through the canopy.

Multi-platform Mobile Laser Scanning

Vehicle-mounted laser scanning systems have proven to be very efficient in measuring road and city environments. Multi-platform systems expand the use cases of MLS to natural environments, industrial installations and urban environments that cannot be easily accessed by a vehicle-mounted system. With the development of algorithms that allow simultaneous localization and mapping (SLAM), mobile laser scanning has also advanced to provide 3D data from global navigation satellite system (GNSS) denied environments, e.g. indoors and industrial sites.

In this field, sensor technology is still experiencing a significant reduction in size and price. Simultaneously, the performance and accuracy has been improved to provide detailed 3D structural information on tunnels, roads, urban scenes and industrial sites. While a few years back certain industrial scanners were not able to be synchronized to an external positioning system, current sensors are usually pretty easy to integrate on multi-sensor platforms. Small sizes and easy integration allow systems to be adapted for diverse 3D measurement needs. We have seen MLS mounted on cars, trains, all-terrain vehicles (ATVs), boats and tractors in the past, and new applications using kinematic data collection will no doubt emerge in the future.

In the future, increasingly detailed models and maps could be generated based on high-resolution airborne laser scanning (ALS) data. Multiple terrain and infrastructure features can be captured in a single flight to save cost. Complementary data can be collected with unmanned aerial vehicles (UAVs or â€˜dronesâ€™) and ground-based mobile laser scanning (MLS).

Drones and Lidar

Unmanned aerial systems (UASs) constitute an increasingly important segment of engineering. Mapping and surveying drones provide an easy-to-deploy platform for aerial views of an area of interest. Currently there are some factors limiting the use of drones regarding operation time and development of regulation in many countries. At best, drones contribute to the production of valuable 3D and image data for needs in various engineering projects, urban planning and scientific tasks. Sensor pools are expanding rapidly, and small sensors are already available for UAS-Lidar applications, depending on the drone scale, such as the RIEGL MiniVUX-1UAV and Velodyne Buck LITE in the conventional category, and the Cepton SORA200 in solid-state implementation. Longer ranges and faster data rates are becoming available for this segment to enhance the data products and broaden the application envelope.

The clear development trends are towards automated systems and real-time data processing. Also, longer operation times for UAVs are achieved with improved avionics, battery life and indigenous ideas, such as the Avartek Boxer Hybrid drone with 2-4 hours' flight time. Small but high-performance sensors and real-time data are the most relevant needs for drones, and typically limited project areas do not necessitate the presence of a GNSS-IMU; data is processed to a local coordinate system using techniques prevailing within the robotics community. However, ever-smaller and more capable GNSS-IMUs, like the NovAtel CPT7 or SBG Ellipse2-D are available, and with decreasing prices, direct georeferencing reduces the effort for ground control.

SLAM/LOAM Laser Mapping

GNSS-free laser scanning is developing rapidly. Systems typically consist of low-cost laser scanners and inertial measurement units. Lidar data is used, and on some occasions augmented with visual odometry from cameras, to compensate for instantaneous movements of the sensor system, to calibrate low-performance IMU, and to keep track of the sensor and/or platform pose. These mapping solutions provide real-time or near-real-time 3D data for tasks with moderate accuracy needs. The development has been possible due to the miniaturization of sensors and SLAM, Lidar odometry and mapping (LOAM) and related algorithms. Multi-layer scanning in particular has proven to give sufficient information to estimate platform movements from single scans. Algorithms for scan matching with such data perform reasonably well and reliably to give good pose estimations, and are able to detect loop closures for global drift mitigation. A couple of examples are the Gexcel HERON, GeoSLAM Zeb Horizon and Kaarta Stencil systems, all based on Velodyne's Lidar Puck scanner. Notably, many companies are planning to bring similar sensor products on to the market, among them devices from RoboSense and Ouster.

In the area of terrestrial laser scanning, automated registration of scans has seen an interesting development implemented in the Leica RTC360. The scanner is implemented with image-augmented inertial measurements to compensate for movements between scan stations, thus speeding up the scanning work on site. Beyond that, use of Lidar for measuring submerged structures and objects is of increasing interest in the maritime industry, and kinematics-based localization systems using inertial and data-matching techniques are applied similarly to the counterparts on the ground.

Backpack Lidar mapped spatter cone and adjacent lava field. Such applications permit better understanding of natural processes and mitigation of hazards, but also bring possibilities in exploration and planetary research.

Multimodal Mapping

Affordable but high-performance systems are already changing the ways of producing topographic data. Unmanned drones are an emerging technology that, coupled with advanced systems featuring laser scanning and imaging sensors, allows for rapid aerial data for various purposes. Combining UAV-based airborne sensors and mobile laser scanning with imagery brings together the flexibility of mobile systems and allows for short response times and low mobilization costs. Use of these systems provides data with minimal occlusions enabled by easily accessed viewpoints. This data typically represents the objects of interest at a very high level of detail (LOD) down to a scale of a single railing, cable or sign.

Vehicle-mounted kinematic mapping systems are useful for road and street data capture for mapping and maintenance purposes. Such data provides high-density base map data for autonomous driving – an example of a new kind of mapping for the future. Backpack scanning is a suitable method of collecting 3D data from cultural heritage sites, buildings, streets and terrain.

GNSS-IMU and SLAM-based laser scanning systems can be mounted on virtually any kind of platform to carry out tasks in variable environments, and for variable data requirements and scales.

Autonomous Vehicles and Crowdsourced Mapping

Autonomous vehicles have attracted considerable industrial interest in recent years. Following the DARPA Grand Challenge competition for self-driving cars, several major manufacturers have announced their future goals of providing autonomous vehicles. This requires fitting the vehicles with highly capable 3D mapping systems, much like those encountered in contemporary MLS. For the geospatial information community, these future autonomous vehicles are a potential source of highly detailed and frequently updated 3D mapping data.

In addition to vehicles, 3D mapping capabilities are increasingly carried by consumers in their smart devices – simply put, smartphone camera images and positioning information may contribute to mapping. More capabilities are offered by other sensors such as depth cameras and 3D image interpretation. These technological developments hold the potential to replace the prevailing centralized mapping conventions with decentralized, distributed and frequent crowdsourced mapping.

Mapping and monitoring of power grid facilities and other structures critical to our everyday life and function is a prominent application of airborne and UAS-Lidar.

Multispectral Sensors – Colour Vision with Lasers

Multispectral laser scanning technology is currently in its technological adaptation phase in ALS, promising an increase of active spectral information for mapping and detection. The first example of this was the recording of laser backscatter intensity and the use of the intensity values in the visualization of point clouds and in certain classification tasks. The emerging multispectral laser scanning (e.g. Optech Titan for ALS) increases the amount and quality of spectral information obtainable. However, the current implementation is not optimal for acquiring spectral information due to distinct scan angles and patterns for each channel, and data needs to be interpolated for analysis. Alternatively, the RIEGL 1560i-DW provides a two-wavelength instrument.

Actively sensed radiometric properties of target objects do not suffer from illumination variations and anomalies caused by solar illumination present in passive imaging products. The autonomous driving industry is predicted to explore this opportunity in the future, as well as forecasting the availability of small form-factor sensors.

Classification results with the data from the first multispectral ALS systems have been promising. For example, a very high overall accuracy (96%) of land cover classification results has been achieved in some studies, with six classification categories (building, tree, asphalt, gravel, rocky, low vegetation).

GNSS-free SLAM and LOAM solutions could provide 3D data in almost real-time, which is a desired feature for time-critical applications such as emergency response. Could Lidar systems help firefighters to navigate in smoke and detect victims in limited visibility in the future?

Single-photon Systems

Single-photon technology is an emerging technological breakthrough for airborne laser scanning. Single-photon systems require only one detected photon compared to hundreds or even thousands of photons needed in conventional Lidar. As a result, pulse densities of ten to a hundred times higher can be attained compared with conventional sensors. In addition, the sensitivity of the detector to energies in the single photon range allows the systems to attain higher maximum ranges and remain eye-safe. This has also contributed to the recent launch of ATLAS, a spaceborne Lidar-based sensor for global monitoring aboard ICESat-2. Similarly, the single-photon technology will be used in autonomous driving and drone sensors before long.

Single-photon data are available currently from two sensors: Leica SPL100 and Harris Geiger-mode Lidar. The operational differences, albeit generally similar, can be deciphered in Figure 2 and compared to the conventional one. Both single-photon systems available are implemented to use green light (532nm) that makes them suitable for use in bathymetric mapping as well. There are also single-photon detectors available, both on the market and in research labs, allowing miniaturized systems for UAV scale in the near future. Sensitive detection is expected to improve the depth data, although it will still take some time to perfect the processing methodologies and harness the full potential.

High-density mobile laser scanning data permits cadastre, and urban planning and management. Reflectance data can be used in object interpretation.

Implications of High-resolution Lidar

The developments in acquiring point cloud and spectral data significantly increase the data volumes produced. Automation is needed in order to transform the increased measuring frequency and point cloud density into efficiency and a high level of detail in mapping. The emergence of national laser scanning campaigns, such as those in the Netherlands, Sweden and Finland, highlights the need for automated processing methods.

On a more limited scale, multi-temporal point clouds have been applied to change detection both in the urban and natural areas, for management of resources and coping with hazards, effectively showing the potential of multi-temporal 3D data. Combining these methods with automation and periodically repeated country-wide scanning campaigns would allow spectral and geometrical change detection in unseen detail for improved understanding of natural resources and the biosphere.

In addition to change detection, automation is required for various modelling tasks. In urban environments, automated generation of simple building models has become the default approach for 3D city modelling. Several algorithms for detailed building modelling have been introduced, potentially raising the level of detail in automated modelling. In a similar fashion, algorithms have been introduced for modelling road environment objects from dense mobile laser scanning point clouds. In natural environments and forestry, point cloud datasets have been applied both for producing parameter information over larger areas (e.g. for hydraulic modelling and flooding analysis or permafrost processes), and detailed modelling of individual trees for forest resource and biomass assessments.

Ideally, the change detection, mapping and modelling should be combined with periodical 3D data acquisition at intervals of just a few years. Based on multi-temporal data, possible changes can be detected, identified or classified based on spectral and geometric features, and modelling, maintenance or any similar action or effort can be focused based on data-derived signals or early warnings to save costs or avoid indirect damage.

Multispectral Lidar point cloud from Optech Titan representing the urban environment. Combined data at different wavelength regions helps greatly in classification and object recognition. Differing scan patterns for each channel become visible in the raw point cloud data.

Summary

Current topographic databases are commonly based on aerial images and maintained by national mapping agencies with a significant amount of manual work. Developments in laser scanning and point cloud processing could provide significant cost savings via automation of mapping processed with improved output and quality of data.

Multimodal Lidar data will increasingly be used in the future thanks to the development and availability of capable sensor technologies. Ever-smaller systems with similar or improved performance will provide applications using virtually any platform to operate Lidar for mapping and surveying. Aircraft, drones, vehicles, backpacks and handheld mapping systems all serve as means to gather complementary data for virtually any task imaginable.

Emerging single-photon technology has the most potential as a sensor solution for providing dense point clouds with low unit costs for country-level data acquisition. Multimodal laser scanning from airborne and terrestrial perspectives can be utilized for obtaining more detailed data from selected areas.

Dense point clouds with multispectral information provide a common starting point for automated modelling workflows and direct visualization applications, forming the future topographic core data. They represent a significant asset for business in improved forestry and infrastructure management, and provide a platform for developing several future applications.

Leica SPL-100 single-photon elevation data. In the foreground, only data points from the forward part of the scanning cone are shown revealing the scan pattern on the ground.