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Data acquisition and integration 4.
module DAI4
Laser Scanning

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Chapter 4. Laser Scanning

4.1 Introduction

Laser scanning is an emerging data acquisition technology that has remarkably broadened its application field and has been a serious competitor to other surveying techniques. Due to rapid technological development, the increased accuracy of global positioning systems and improving demands to even more accurate digital surface models, airborne laser scanning showed significant development in the 1990s.

Somewhat later terrestrial laser scanning became a reasonable alternative method in many kinds of applications that previously by ground based surveying or close-range photogrammetry.

Along with the penetration of laser scanning, significant paradigm change can be observed in geodesy, e.g. direct orientation instead of indirect orientation, surface detection instead of point measurements, complex 3D model product instead of simple coordinates etc. Laser scanning nicely demonstrates how these new paradigms work in practice.

In the last years, due to the sensor fusion techniques, navigation solutions including inertial measurements and the improving demand for urban modeling, mobile laser scanning is gaining more and more momentum, as it can be seen even in the sensor manufacturers’ product lists.

All the technologies above based on the same principle: the scanner emits a laser beam through the ground/object, and computes the distance by measuring the traveling time or the phase difference of the laser beam. The emission rate of the cutting edge sensors is in the 100-200 kHz range. The direction of the beam is determined by different types of rotating or oscillating mirrors that enable the scanning of the area of interest. In case of airborne and mobile laser scanning, the position of the sensor is given by high accuracy GNSS and INS.

The following chapters discuss laser scanning technology from the sensors, through the data acquisitions to the data processing and visualization. Note that the primary goal of this material is to provide a general overview about laser scanning technologies and definitely not going into the details or discussing specific applications.

The first chapter deals with airborne laser scanning, and clarifies the basic principles. Some of them are also valid for the forthcoming chapters dealing with terrestrial and mobile laser scanning.

As in many sources, laser scanning here is often referred as LiDAR (Light Detection And Ranging). ALM (Airborne Laser Mapping) or ALS (Airborne Laser Scanning) abbreviations are also widely used for airborne laser scanning, whilst term "terrestrial laser scanning" is used for ground-based laser scanning.

4.2 Airborne laser scanning

Airborne laser scanning is an active remote sensing technology that is able to rapidly collect data from huge areas. The resulted dataset can be the base of digital surface and elevation models. Airborne laser scanning is often coupled with airborne imagery, therefore the point clouds and images can be fused resulting enhanced quality 3D product.

The basic principle is as follows: the sensor emits a laser pulse through the terrain in a predefined direction and receives the reflected laser beam. Knowing the speed of light, the distance of the object can be calculated, see Figure 4.2.1.

![Figure 4.2.1. Time of flight laser range measurement](image-url)
Airborne LiDAR systems are composed by the following subsystems:

- Laser sensor and computing, data storage unit,
- INS/IMU (Inertial Navigation System / Inertial Measurement Unit),
- GNSS (Global Navigation Satellite System),
- GNSS ground station(s).

The components are shown in Figure 4.2.2.

4.2.1 Sensors, equipment

Sensors can be distinguished based on the scanning method, i.e. how the laser beam is directed through the surface. The four most widely used sensor types are shown in Figure 4.2.3.
As it is clearly seen in Figure 4.2.3, different kinds of mechanisms are applied by the different types of sensors; each has its advantages and shortcomings, e.g. number of moving parts, type of rotation etc. that lead to different kinds of error sources.

The capabilities (repetition rate, scan frequency, scan angle, point density) of the above scanners are very similar; the main difference lies in the scanning pattern, as seen in Figure 4.2.4. The most widely used oscillating mirror scanners produce the zigzag pattern. Spacing along the line depends on the pulse rate and scanning frequency, while spacing along the flight direction depends on the flying speed. To avoid too wide spacing of points along flight direction, LiDAR flights are usually slower (e.g. at 60-80 m/sec) compared to that of photogrammetric flights (even 120-160 m/sec). Careful planning of the measurement results in rather homogenous density, however, due to technical and microelectronic reasons (regarding the operating mechanism of the mirror, especially in case of oscillating mirrors), higher point density can be observed at the edges of the scan swath. Previously, critics were addressed to the fixed optic scanners, i.e. the parallel scan lines along the flight direction can miss sizeable objects, but vendors successfully responded and modified the mechanism in a way that produce the wavy pattern (Fig 4.2.4) and hence homogenous point density.
Not only scanner patterns make difference, the method of receiving the return signal can also be different. In the simplest case the scanner measures the traveling time of the emitted pulse and calculates a single distance value for one emission.

In datasets of current systems, multiple reflections can be distinguished from a single emission. Receiving multiple reflections or even digitizing the entire waveform enables specific applications. Since the laser footprint is sizeable from a distance (e.g. footprint ellipse axes can be 2-3dm, which is altitude and beam divergence dependent), from a single emission many distances, thus many objects can be measured. For example in a forest, part of the beam reflects from the top of the canopy, the next from a branch, the third from the bushes and the last pulse from the ground (Fig 4.2.5). Note that detecting the ground in wooden area makes LiDAR a highly capable technology in forestry applications (especially compared to photogrammetry).
The two most widely used airborne platforms are the fixed wing aircrafts and helicopters. Airplanes can fly at high altitudes at high speed that enables affordable measurements about large areas and ideal for corridor mapping (e.g. mapping motorways, power lines). Helicopters can fly at very low speed or even are able to hovering. Therefore extremely high point density can be achieved by sensors mounted on helicopters. Of course, sensors can be mounted on specific platforms, interesting researches and projects have been carried out with hot air balloons and airships.

4.2.2 Lasers

Lasers are categorized by their wavelength; laser scanning devices operate with lasers in the visible and in the near infra-red range. Lasers can be focused and easily absorbed by the eye; the maximum power has to be limited to make them ‘eye-safe’ [10].

Airborne LiDAR systems generally use 1064 nm (or 1550 nm) diode pumped YAG (yttrium aluminium garnet) lasers while bathymetric systems use 532 nm double diode pumped lasers which penetrate water with much less attenuation than the lasers with 1064-1550 nm bandwidth. Better resolution can be achieved with shorter pulses [10].

4.2.3 Positioning and error budget

Positioning is a key issue of airborne laser scanning. Georeferencing is exclusively supported by GNSS and INS systems. Better accuracy can be achieved by differential GNSS techniques that require careful measurement campaign planning by deploying ground stations along the flight lines. Recent laser scanning systems are capable of more than 100 kHz pulse (repetition) rate resulting more than 100 000 points in a second. An IMU is used to determine the attitude (position and orientation) of the aircraft as the sensor is taking measurements. These are recorded in degrees with extremely high accuracy in all three dimensions as roll, pitch and yaw, along with the vertical and horizontal movements of the aircraft in flight. From these two datasets the laser beam’s exit geometry is calculated relative to the Earth’s surface coordinates at very high accuracy [10].

Note that the particular positioning system is responsible for the 80% of the entire airborne LiDAR error budget. Considering accuracy, cutting edge systems are capable of 1-2 dm horizontal and 0.5-1.5 dm vertical accuracy according to manufacturer’s claims. Other components of the error budget are coming from the laser range finder error and that of the scanning mechanism, and from the atmospheric disadvantageous effects.
The error budget of a LiDAR system is a quantitative evaluation of the random and systematic error sources that contribute to the overall positional \((x, y, z)\) accuracy of the post-processed LiDAR point cloud. The major contributors to a LiDAR system error budget are:

- GNSS accuracy,
- INS accuracy,
- LiDAR system noise,
- Timing resolution,
- Mechanical tolerances (temperature, atmospheric pressure variations),
- Atmospheric distortions (extreme ground temperature, haze) \[5\].

These factors typically add up to an error budget of ±12 to 15 cm for a LiDAR data collection flown at 1500 m altitude \[5\].

There are additional factors which may affect LiDAR data accuracy, such as invalid coordinates for the GNSS base station(s), misalignment of the INS with the LiDAR scanner (boresight misalignment), or a software failure at coordinate conversions. These error contributions are causing systematic errors, and may be identified by sensor calibration, comparing LiDAR with known reference data or additional control operations \[5\]. For example, boresight misalignment, the spatial relationship between the IMU body frame and the LiDAR body frame is of high importance as it could be the largest source of systematic errors in airborne mobile mapping systems, and thus must be determined before the system can be effectively utilized \[19\].

Note that manufacturer’s accuracy specifications are derived from statistical sampling of the LiDAR data and are generally quoted as a 1 sigma spec, meaning ~68% of the data will fall within this limit \[15\].

### 4.2.4 LiDAR work phases and data processing

According to the particular application or specific requirements of a project, different work flows are to be executed. However, the main steps are often the same for many applications, a typical LiDAR campaign has the following work phases:

- Planning (coverage, point density, flying parameters etc.),
- Deployment of GNSS base stations (if needed),
- Calibration of equipment (e.g. for determining certain misalignments),
- LiDAR surveying.

LiDAR data processing can be grouped in many ways. Assuming a typical airborne LiDAR project for deriving digital surface model, e.g. for mobile communication companies to support precisely deploying base stations and antennas, the following data processing steps are to be discussed:

- Georeferencing: transforming the point cloud (usually from WGS84) to the local coordinate system.
- Noise removal: filter out points that are not reflected from the surface (e.g. reflected from a bird or can be found below the ground because of multipath reflection or faulty time measurement).
- Coarse classification (e.g. ground points, above ground points, water), point density adjustment, interpolation.
- Modeling: DSM/DEM generation, feature extraction (segmentation and/or classification).
- Data fusion (e.g. warp airborne images onto DSM).
• Measurements on model, advanced feature extraction.

Many of these data processing steps can be automated, there are procedures built into processing software that are capable of classifying features, recognizing building roofs, trees, etc.

LiDAR data is usually stored in LAS format; however, many manufacturers apply self-developed file formats as well. The LAS file format is a public file format for the interchange of LiDAR data between vendors and customers. This binary file format is an alternative to proprietary systems or a generic ASCII file interchange system used by many companies [6].

4.2.5 Intensity data

Recent LiDAR systems are capable of measuring the signal strength (i.e. intensity) of the reflected laser pulse. Different objects have different reflectivity, therefore the intensity values can support object recognition and identification (Fig 4.2.6).

Note that LiDAR intensity values vary based on light and weather circumstances, therefore barely can be used alone, without additional data for classification.

4.2.6 Applications

Typical airborne laser scanning applications are the ones that can exploit the strengths of the technology, for example:

• Forestry: due to multiple reflection or full waveform digitizing, several reflections can be recorded from a single emitted laser beam. The high LiDAR point density enables refined tree detection (Fig 4.2.7).
• Coastal survey: no ground control, neither checkpoints are needed for LiDAR measurement, therefore is an ideal technology for surveying ice-covered terrains, deserts, sea shorelines.

• Urban modeling: LiDAR provides high density, accurate 3D point cloud that is capable of generating precise urban models that can be used e.g. by mobile communication companies in planning base station locations (Fig 4.2.8).

• Disaster management: LiDAR produces datasets rapidly from wide areas therefore can be used in various disaster management applications, e.g. flood detection.

• Topographic survey: LiDAR technology needs less manpower than conventional geodetic and photogrammetric techniques. Robust procedures are available for removing vegetation and man-made objects from the ground and hence providing accurate digital elevation models.

• Line-of-sight analysis (e.g. for modeling cell-phone signal propagation).

• Corridor mapping (e.g. roads, power lines) (Fig 4.2.9.).
Bathymetric LiDAR needs more explanation. This hybrid LiDAR system uses both green and infra-red laser. While the infra-red beam reflects from the water, the green penetrates through the bottom of the sea. As a result, the topography of the seabed and the sea level can be mapped from the same measurement. Bathymetric LiDAR is capable of measuring the sea depth up to 40 m.

4.2.7 Comparison with other technologies

LiDAR is generally compared to photogrammetry (due to the overlapping application fields) and to IfSAR (Interferometric Synthetic Aperture Radar) (due to similar data acquisition principle).

Considering LiDAR, the 3D point cloud is available immediately after the flight. The main shortcoming of LiDAR compared to optical sensing is the breakline detection. The result of LiDAR survey is a point cloud where the points are not necessarily reflected from the edges of the objects that are to be mapped. This problem can be resolved by detecting the breaklines in the model, but in this case the errors of modeling will corrupt the results.

Airborne LiDAR point density may be in the range of 1 to 20 points/m². Aerial photogrammetry point density depends on ground sampling distance (GSD), thus pixel size. At a 10 cm pixel, 100 points/m² can be achieved, but these are not 3D elevation values and representing only the 2D resolution. The 3D sampling interval depends on the image overlap; if 50 percent of the pixels were to get matched for independent 3D elevation values, 50 points/m² ground resolution can be achieved from 10 cm pixels [17].
The difference between LiDAR and 3D image-based photogrammetry is more distinct when swath width and flight lines are considered (as time and cost issues). Table 1 presents some typical 2009 project values for a LiDAR system flying at 750 meters above ground at 60 m/sec [17]. Considering flying costs, under these assumptions LiDAR measurement takes more than 10 times longer than with camera to obtain comparable results.

Table 1. Project parameters for a LiDAR and a digital photogrammetric camera; status 2009 [17].

<table>
<thead>
<tr>
<th>LiDAR</th>
<th>Digital photogrammetry</th>
</tr>
</thead>
<tbody>
<tr>
<td>170 scans per second (190 kHz), 30° FOV</td>
<td>GSD 25 cm</td>
</tr>
<tr>
<td>8 points/ m²</td>
<td>16 points/ m²</td>
</tr>
<tr>
<td>Flying height 750 meters</td>
<td>Flying height 4 188 meters</td>
</tr>
<tr>
<td>Aircraft speed 60 m/sec</td>
<td>Aircraft speed 141 m/sec</td>
</tr>
<tr>
<td>Strip width 403 m</td>
<td>Strip width 4 328 m</td>
</tr>
<tr>
<td>20% side-lap between flight lines</td>
<td>60% side-lap between flight lines</td>
</tr>
<tr>
<td>Effective strip width at 322 m</td>
<td>Effective strip width 1 731 m</td>
</tr>
</tbody>
</table>

Usually images are also taken simultaneously with the LiDAR survey. The fused dataset integrates the advantages of both technologies: provide accurate 3D data about the surface and enables precise interpretation.

Comparing to IfSAR, LiDAR has better accuracy and point density, IfSAR has higher coverage and is capable of working even in cloudy weather. LiDAR sensors and additional equipment are more affordable than IfSAR. Considering market penetration, only few companies are dealing with IfSAR all over the world, while LiDAR penetration can be compared with that of digital photogrammetry cameras.

### 4.2.8 Factors affecting data acquisition

Most LiDAR systems apply laser in the visible light range that means dust and vapor/fog/clouds can affect the measurement. LiDAR sensors are usually mounted on small aircrafts that fly below the clouds, however, in bad weather conditions no flights are to be planned due to safety issues. Note that older sensors are sensitive to strong sunlight and surfaces with bad reflectivity.

Since LiDAR is an active remote sensing technology, it can be used even at night; however, surveys are usually planned in daylight due to navigation issues.

Photogrammetric surveys are often planned late fall or early spring in order to acquire data in leaf-off conditions (no leaves on trees). LiDAR is not as sensitive, much more ground points can be extracted from leaf-on campaigns, however, if possible and if needed (forested areas are to be mapped), LiDAR measurements also to be planned in the optimal period considering vegetation.

### 4.3 Terrestrial laser scanning

While airborne laser scanning is competing with photogrammetry and interferometric radar, terrestrial laser scanning is rather concurrent technology in the field of conventional surveying. Traditional close-range photogrammetry does not have wide application field and barely considered as competing technology in planning projects.

In the early 2000s, terrestrial laser scanning was used only for specific tasks, e.g. surveying and modeling complex (e.g. cooling/heating pipe-) systems of a factory. Recently, terrestrial laser scanning broadens its application area and used even in projects that are conventionally considered as field of traditional surveying (e.g. small-scale topographic survey, road construction works, in-door surveying of buildings etc.).

The principle of terrestrial laser scanning is very similar to that of airborne surveying. The sensor continuously emits laser beam towards the objects, receives it and computes the distance of object. The beam is directed by...
rotating or oscillating mirrors (usually the same mirror can operate both in rotating and oscillating mode). The main components of a terrestrial laser scanner are shown in Figure 4.3.1.

![Figure 4.3.1.: Components of terrestrial laser scanner [7]](image)

The main difference is that the sensor is not moving but mounted on a tripod or any kind of structure. Therefore no positioning solution is needed; however, recent scanners are able to be directly connected to GPS receivers to directly obtain scanner station location.

### 4.3.1 Sensors, equipment

Sensors are designed to be easily transported and deployed; recent sensor houses/heads are even smaller and lighter. Sensors usually have built-in batteries (in some cases with optional additional batteries), in some cases in-built camera (e.g. Leica C10), in other ones commercial cameras can be solidly mounted on the sensor (e.g. Riegl VZ series), as shown on Fig 4.3.2. Previous sensors are usually to be operated by specific software running on a laptop, many recent scanners has an integrated display for setting up the parameters and executing the measurement (using a stylus with a touch screen or a keypad). However, even these scanners can be connected to laptops (or palmtops) that enable to exploit the full functionality of the device.
Considering the sensors, two major technologies have to be discussed separately:

- Time of flight (ToF) scanners (e.g. Leica, Riegl),
- Phase measurement scanners (e.g. Z+F).

ToF scanners measure the traveling time of the emitted laser pulse and calculate the distance of the object. In case of phase measurement the phase shift of the emitted and received pulse is measured and then the distance is calculated based on the number of phase shifts and difference. Phase measurement is limited in range (<100m) but is capable of higher repetition rate (up to 500 kHz); ToF scanners have enhanced range (up to 2000m) but lower frequency (~10 kHz). According to accuracy, phase scanners are capable of 3 mm compared to 4-6 mm of ToF scanners (at 50m distance).

Beside pulse rate and measurement range, scanners can be distinguished based on the resolution and scan density. Point density depends on the distance from the scanner and the angular resolution of the device; i.e. at a given distance, different point densities can be achieved by controlling the angular increment of rotating mirrors [16]. Some vendors specify angle measurement resolution (e.g. 0.0005° for Riegl VZ-400) and angular stepwidth (e.g. 0.0024° for Riegl VZ-400). Others provide point spacing depending on distance (e.g. min. 1 mm through full range for Leica C10).

Prior to purchasing or loaning a laser scanner, its technical capabilities have to be investigated. Even in case of ordering a laser scanning survey, information about the particular scanner helps the user in the final decision. Data sheets and technical specifications are available on the websites of the sensor providers. As an example, part of the data sheet of the Leica C10 laser scanner is shown in Figure 4.3.3.
The same information is available on other manufacturers’ (e.g. Optech, Riegl, Faro, Z+F) and vendors’ websites; therefore users can easily be informed before ordering measurements of purchasing devices. Note that technical specifications of vendors and suppliers are often valid only for specific circumstances. Many investigations and analysis have been conducted and are still running in this area (many times in cooperation with manufacturers), publications are already available if further information is needed about the certain device [23].

4.3.2 Data processing

The workflow of the terrestrial laser scanning procedure can be summarized as follows:

- Preparation (planning, preliminary geodetic measurements etc.),
- scanning,
- registration/georeferencing (if required and if preparation and scanning was done accordingly),
- selecting area of interest (optional),
- filtering, converting data,
- segmentation, classification,
- modeling (triangulation, rendering, fitting geometrical elements onto point cloud (see Fig 4.3.4) etc.),
- measurements on model
- visualization
- application-dependent products (e.g. cross-sections for architects).

As in most engineering projects strong emphasis has to be put on project planning and preparatory work that includes creating the geodetic network (if needed), checking field-of-view, planning scan station locations. Beside costs that can be saved by planning, optimal scan station locations are needed for achieving the required coverage, point density, visibility of dedicated parts of the object, and to ensure the desired accuracy.

Scanning usually starts with panorama scanning i.e. a low resolution surveying of the surrounding area. Then the area to be mapped can be selected on this point-cloud or, as alternate methods, it can be specified by corner coordinates or angular ranges. Specific points (e.g. control points or dedicated points of a structure of which displacement has to be measured) can be marked with specific targets. These are special stickers or objects (usually in a form of disc, cylinder or sphere) with extremely high reflectivity. The scanner software is able to recognize the reflectors in range and provide the coordinates of the middle of the reflectors. Careful planning of deploying the reflectors is crucial. If repeatability is an issue (e.g. in monitoring, quality control projects), the reflector locations have to be marked in a way that they will remain until the next survey. Scanning in open areas the protection of reflectors also has to be solved.

Registration and georeferencing means that the resulted point cloud(s) and images have to be transformed to a given coordinate system. In many cases there is no need for transforming the data into local coordinate system; measurements can be executed in the scanner’s own coordinate system. The images taken by the scanner camera or by a camera mounted on a scanner are usually warped onto the point cloud by the scanner software.

Scanners capture points reflected from all objects in FOV (field of view) and range, thus selecting the area of interest (i.e. points reflected from the object(s) to be mapped) has to be done prior to modeling and any kinds of measurements.

Before modeling, further pre-processing steps are needed, e.g. converting the point cloud in the required format (depending on the processing software’s requirements), filtering outliers, interpolating points into a pre-defined grid (if needed) i.e. achieve a clean dataset that meets the requirements of the further processing steps.

In some applications segmentation and/or classification of certain areas in the point cloud is needed, but in most cases the entire data set has to be modeled. Modeling can cover wide ranges of procedures, e.g. triangulating surface, fitting geometric elements on the point cloud, detecting edges and creating vector model etc.

Some applications, e.g. engineering survey needs to derive particular values, e.g. displacement between two or more dedicated points or measuring certain distances. In some cases these values can be obtained without modeling, simply executing measurements on the point cloud. Note that there are specific point cloud processing software packages available on the market.

Visualization is even more important part of laser scanning as it is in case of other geodetic procedures, i.e. present the results to the customers, users, decision-makers in an easily understandable form.
Specific applications may require specific products, e.g. cross- and longitudinal sections for architectural design purposes, specific distance and volume calculations of artifacts for archaeological survey, deformation measurement at special parts of structures, obtaining surface material features etc. These kinds of specific products often require intense consultation with experts from the particular area.

Practical note: it is recommended to include detailed description in the project contract about the end-product of laser scanning. The raw point cloud or even a 3D model can be useless for the user if the required measurements, evaluations or any kinds of assessments cannot be executed. There are many myths circulating about laser scanning and laser scanned point clouds. For cross-check, consultation with independent experts or, at least, gathering information from other projects are highly recommended.

4.3.3 Applications

Terrestrial laser scanning’s application fields are similar to that of conventional surveying and close-range photogrammetry. If the ensured accuracy (~3-5 mm) is sufficient for the particular project, and data from surfaces (instead of some dedicated points) is needed, then laser scanning can be a reasonable option. Some areas that can be considered as typical laser scanning applications:

- Surveying complex structures (e.g. difficult mechanical structures) (Fig 4.3.5),

- building surveying (surveying entire surfaces, e.g. façade reconstruction, in-door surveying),

- mining applications (surveying sizeable areas from safe distance, e.g. for monitoring extracted volumes in a mine),

- surveying in areas with difficult accessibility (e.g. caves, tunnels) (Fig 4.3.6),
4.3.4 Comparison with other surveying technologies

The main difference between terrestrial laser scanning and conventional geodetic survey that instead of only dedicated points, data is acquired about the entire surface in the visibility range. No special markers are needed, the laser beam reflects practically from all objects.

Some points can be marked by reflectors, but edges and specific points are to be recognized and identified in the point cloud. This procedure highly relies on the modeling techniques, while automation is difficult; much less in-built solutions are available in commercial software than in case of airborne laser scanning.

Current laser scanning technologies provide accuracy of 3-6 mm (at 50m distance), while submilimeter accuracy can be reached with traditional surveying (tachymetric and leveling) techniques. However, due to the vast amount of measured points, better modeling accuracy can be achieved through sophisticated adjustment techniques.

Laser scanners will replace neither total stations nor close-range professional photogrammetric devices, even though some rather aggressive opinions and advertisements can be seen in magazines, and can be heard at conferences. In many cases these technologies can be used as complementary methods, in other ones the best (i.e. the most suitable) one should be selected for the particular goal.

4.4 Mobile laser scanning

The most recent application field of laser scanning is the mobile mapping application, where the scanner (or scanners) is mounted on a mobile platform, mostly on a passenger car or truck. Mobile laser scanning is used in projects where big areas (or long corridors) should be covered on the ground and data is to be acquired about the road or its environment.

4.4.1 Sensors, equipment

Mobile laser scanning equipment usually composed of regular terrestrial laser scanners, GNSS/INS positioning/navigation system, optical sensor(s), and the mobile platform. Nice example can be seen in Figure 4.4.1 that shows the sensor platform of the StreetMapper system.
Due to enhanced accuracy, differential GNSS technology is used that requires careful preparatory planning of routes and deploying base stations, and (if needed) real-time transmission of corrections.

The sensors are usually mounted on a van, SUV or truck that able to provide sufficient power for the sensors and room for the additional equipment and personnel (Fig 4.4.2).

4.4.2 Data processing

The main work phases of processing mobile laser scanned data are as follows:

- calculating position and orientation of the sensor platform,
- georeferencing the point cloud and registering the images,
- coarse classification of points (e.g. ground, vegetation, building, and other),
- measurements, evaluation and modeling according to the particular application.

Sensor position/trajectory and orientation is generally supported by Kalman-filtering. Obviously, georeferencing and registration of point clouds is the main difference between terrestrial and mobile laser scanning. Since in urban environment there are area where no GNSS signal is available (or only with less accuracy), and INS provides sufficient accuracy only for limited range, careful planning of measurement is needed, and these factors have to be considered during the accuracy assessment.
4.4.3 Applications

The main application fields of mobile laser scanning are as follows:

- 3D urban modeling,
- road surveying (pavement, road furniture etc.),
- vegetation classification,
- tunnel surveying (Fig 4.4.3).

During planning and preparing projects the following issues has to be considered:

- mobile laser scanning systems apply terrestrial laser scanners but the overall 3D accuracy is lower, since the error budget contains the errors of the positioning system,
- positioning accuracy is not homogenous all over the route, since GNSS constellation (especially in urban environment) is always changing,
- complicated post processing period has to be planned and considered: georeferencing the point cloud and fusing with images needs remarkable computing capacity and skilled personnel.

4.5 Summary

Looking at the ongoing researches and industrial projects, it can be concluded that laser scanning is a rapidly emerging remote sensing technology used in many applications. Current airborne surveys apply multiple sensors that enable integrating the advantageous features of each technology.

Terrestrial laser scanning and especially mobile mapping systems using laser scanners are continuously broaden the application areas and providing accurate 3D data about the real world.

Scientific papers are dealing with and arguing on the comparison of laser scanning and other data acquisition methods. All technologies have their advantages and shortcomings. Sensor selection and final decision has to be made considering the particular application and project. Fortunately, current trends are about fusing data from different sources, integrating sensors on the same platform, resulting enhanced 3D data products satisfying various demands. These trends lead to the wide application of remote sensing technologies.

Developments are running, researchers are working on sophisticated processing methods and automation techniques, while sensor providers are introducing sensors that are even more accurate and rapid at more affordable price.

Glossary

Glossary is usually given before the introductory part of a document. The reason the glossary has been put at the end that a general overview is needed about the entire topic. Different sources, educational materials and
papers often use confusing expressions and terms, it is worth to sum up the basic terminology relevant to laser scanning, thus support to avoid misunderstandings.

Accuracy: accuracy is the degree of agreement between a measurement and the conventional true value of the object being measured [14].

Modeled accuracy: the modeled accuracy is derived from the primitive model of an object that has been generated using multiple point measurements on the object surface. While the single measurement accuracy of a system may be 10 mm, the use of a least-squares algorithm to generate the primitive model can result in accuracies of 1-2 mm [14].

Precision: precision is the degree of agreement between two or more measurements collected on the same point from the same position. In short, it is the degree of repeatability in the measurement [14].

Resolution: resolution is the size of the smallest feature discernible by the system. It consists of two subgroups: depth resolution (z-axis) and planar resolution (xy-axis) [14].

Field-of-view: Laser scanners are similar to cameras in that each instrument scans over a field-of-view (FOV). Scanners are characterized by both horizontal and vertical FOV [16]. For example, Leica C10 (terrestrial) laser scanner has 360° horizontal and 270° vertical FOV.

Control questions:

1. What are the main components of airborne LiDAR systems? (p. 3)
2. What are the main technical parameters of an airborne LiDAR sensor? (pp. 4-6)
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