METROLOGICAL ASPECTS IN TERRESTRIAL LASER-SCANNING TECHNOLOGY

Hilmar Ingensand
Institute of Geodesy and Photogrammetry
ETH Zurich
Email: hilmar.ingensand@geod.baug.ethz.ch

Abstract: Within the last years airborne and terrestrial laser-scanning (TLS) has become a dominant technique for fast and efficient three-dimensional data acquisition of complex objects. Aerial and kinematic terrestrial laser-scanning follow an approach by combining GPS and inertial navigation systems (INSS). In such mobile multisensor systems the error budget of all sensors - positioning and attitude sensors - has to be taken into consideration. Therefore, the parameters in accuracy of laser-scanning will be discussed. The recent developments of high precision laser-scanners widened the field of applications such as monitoring tasks in engineering geodesy and geotechnics. A topic in research is the three-dimensional calibration of laser-scanning systems. Despite the importance of investigating and analyzing each component of laser-scanners separately, most users are only interested in resulting accuracies of single points or of derived objects.

1. Introduction

Laser-scanning and its synonyms LADAR (laser distance and ranging) or LIDAR (Light Detecting and Ranging) have become a major technology for the three-dimensional geometrical data capture of complex structures. In contrast to classical photogrammetry, which requires a minimum of two images and delivers image coordinates which have to be scaled and transformed to generate a 3D information, laser-scanning generates directly a metric 3D information, the so-called point cloud, with just one single setup of the scanner. Each point of this cloud has three-dimensional coordinates with accuracies up to a few millimetres. Additionally the intensities of the received signals give valuable indicators for post-processing. In most cases laser-scanning has to be combined with other coordinate determining technologies such as totalstations, GPS and INSS. A wide range of specific laser-scanner types have the ability to determine the geometry of objects in the distance range from a few centimetres up to several hundred metres within a few minutes.

2. Technologies and main applications

2.1 Electro-optical distance technologies in laser-scanning

In general, laser-scanning corresponds to other three-dimensional vector measuring system as fast reflector-less measurements using totalstations. The radial component bases on electro-optical distance measurement (EDM) using various technologies. The most widespread technology is the Time of Flight (TOF) approach, which enables two-target detection by "first-last pulse" evaluation. High precision laser-scanners follow the Amplitude- Modulation of Current Waves (AMCW) and the Optical Frequency Modulation of Current Waves (O-FMCW) technologies. The last mentioned technology uses the principle of radar technology transformed to laser wavelength modulation. It is also named "Chirp" technology. A new approach, represented by Leica's Pinpoint technology [1] emits laser radiation with structured signals and analysis of the reflected signal structure in the time domain. This technology enables multi-target determination.

2.2 Direction determining technologies

In laser-scanners the direction of the laser ray is controlled by high-resolution angular encoders attached to rotating mirrors, oscillating or rotating polygon-mirrors. The deflection technology is related to the angular working range and allows a categorisation into profilers, camera-view type and panoramic scanners, which rotate 360 degrees around the vertical axis.

2.3 Static and kinematic laser-scanning

Another aspect is that laser scanning can be used statically or kinematically installed on cars, trolleys, helicopters and aircrafts. This approach combines laser-scanning with tracking totalstations, GPS and other attitude sensors [2]. Mobile mapping systems additionally add Inertial Navigation Sensor Systems (INSS) and optical positioning systems basing on optical correlation (Corrsys).

The following diagram depicts some typical applications of terrestrial static and kinematic laser-scanning.

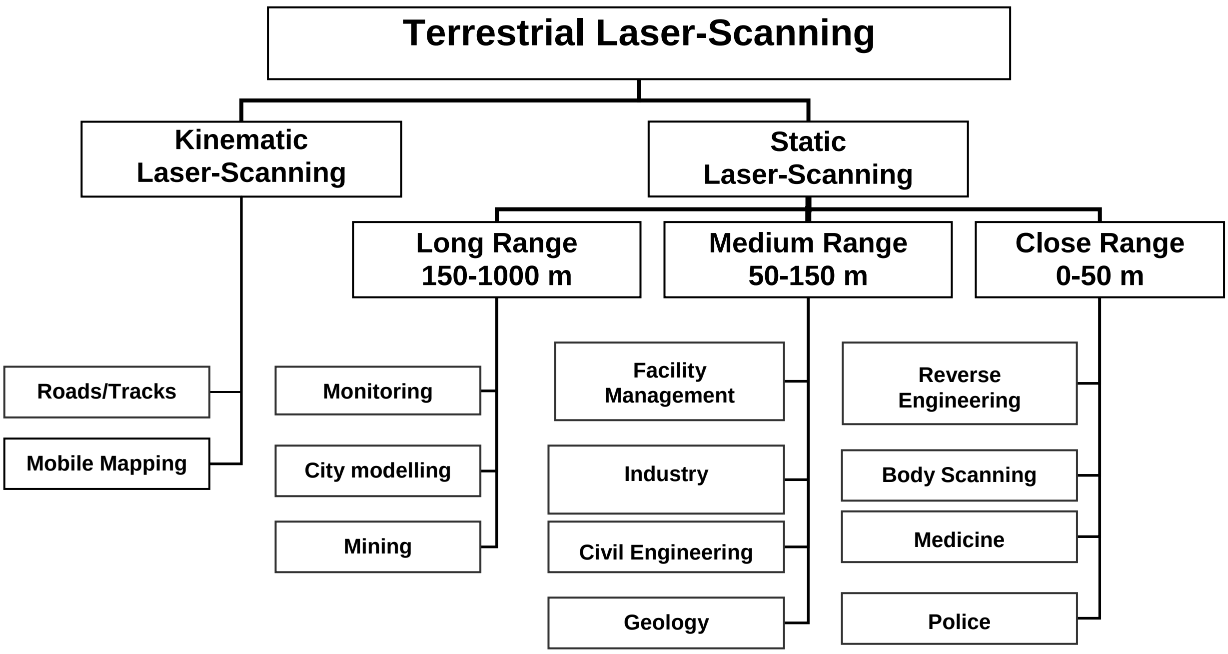

Table 1: Typical application areas of terrestrial laser-scanning

For the different applications there is now a variety of laser-scanners which have to be individually selected to meet the requirements of the specific application.

Manu-facturer	Feature	Range tech-nology	Wave-length [nm]	Min. /Max. range [m]	Range accuracy @50m [mm]	Field of view [VxH]	Scan speed [points/s]	Weight [kg]	Incli-nation sensor	CCD-Camera	Software
3rdtech	Delta Shpere-3000	TOF	670	0.5/12	7mm @ 12m	360°x300°	up to 25'000	10	no	Yes	SceneVision-3D
Callidus	CP 3200	TOF	905	1/80	5mm	360°x280°	1'750	17.9	yes	Yes	3D-Extractor
Faro	FARO LS 880 HE40/HE 80	Phase	785	--/35 resp. 70	3mm @ 10m	360°x320°	up to 120'000	14.5	yes	No	FARO Scene
I-SiTE	I-SiTE 4400	TOF	905	3/400	50mm @ 400m	360°x80°	4'400	14	yes	Yes	I-SiTE Studio
Leica	HDS 3000	TOF	532	1/200	4mm	360°x270°	up to 2'000	16	no	Yes	Cyclone
	HDS 4500	Phase	780	1/25 resp. 53	≤6.5mm @ 25m	360°x320°	up to 650'000	16	no	No	
	Metric Vision	Chirp	1550	1/60	240µm @ 24m	360°x90°	1000	40	no	No	
Optech	ILRIS-3D	TOF	1'500	3/1500	7mm	360°x220°	2'000	12	no	Yes	diff. software
Riegel	GX	TOF	Near infrared	4/400	typ. ±10mm	360°x80°	up to 12'000	13	no	Yes	RiScan Pro
	LMS-Z210i	TOF	Near infrared	4/400	typ. ±10mm	360°x80°	up to 12'000	13	no	Yes	
	LMS-Z420i	TOF	Near infrared	2/1000	typ. ±15mm	360°x80°	Up to 12'000	14.5	no	Yes	
Trimble	GS101	TOF	532	1/200	3mm	360°x60°	up to 5'000	12.8	no	Yes	Real Work Survey / 3Dipsos
	GS200	TOF	532	1/350	3mm	360°x60°	up to 5'000	12.8	no	Yes	
	GX	TOF	532	1/200 up to 300	1.4mm	360°x60°	Up to 5'000	12.2	yes	Yes	
Zoller+ Fröhlich	IMAGER 5003	Phase	780	1/25 resp. 53	≤6.5mm @ 25m	360°x320°	up to 650'000	16	no	No	Z+F Viewer / LFM Modeller

Table 2: Overview of TLS manufacturers and features
(TOF = time of flight; Phase = phase based; Chirp = optical frequency modulation)

The overview demonstrates the missing standard in the definition of the accuracy of TLS. All manufacturers state the accuracy of the distance but not the angular component. Environmental and surface properties are not mentioned.

As a minimum the following specifications should be stated:

- resolution = points per steradian (according to the resolution of flatbed scanners or CCD cameras).
- ray divergence which is related to the spot size (footprint) in a certain distance. This also has an impact to the resolution.
- scanning rate = measurements per second.
- accuracy (uncertainty of measurements [3]) of the 3D coordinates.

3. Calibration of laser-scanners and environmental effects

There is now an ongoing intensive discussion about the calibration of laser-scanners [4]. In order to get first experiences at the ETH Zurich we followed primarily the approach of component calibration.

3.1 Calibration of the direction component

Using theodolite–type scanners, as the Zoller&Fröhlich, Faro or I-Site scanners, the direction-affecting instrumental errors of the laser-scanner could be calibrated by procedures known from theodolites [4]. Theses are:

- vertical axis wobble, which acts as a lever effect, if the scanner does not correct this influence by inclination sensors
- eccentricity of scan centre
- collimation axis error
- horizontal axis error

3.2 Calibration of the distance component

The test facilities at the Institute of Geodesy and Photogrammetry, a 52 m laser interferometer controlled track, guarantee a one-micron accuracy. Intensive tests demonstrated the high-distance accuracy of laser-scanners under lab conditions. Especially AMCW-based-technologies are known for systematic cyclic effects which can be calibrated and corrected with the look-up table method.

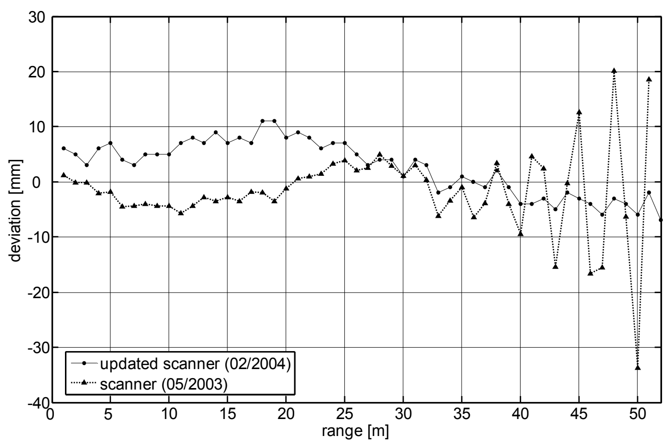

Figure 1: Calibration of the distance component of a phase measurement system before and after update

3.3 Environmental and surface effects

As in other optical 3D technologies at longer distances the atmospheric influences have to be taken into account to correct the distance and direction component.

In contrast to classical EDM with appropriate reflectors, laser-scanning accuracy is highly correlated with the angle of incidence of the laser ray at the surface, the optical design of the scanner and the distance itself. As in GPS measurements, the surrounding object geometry can affect the result systematically by multipath effects, if there are objects in various distances in the scanning area.

To enable a high scan rate, the signal-to-noise ratio (SNR) of EDM in laser-scanners is not regulated and optimised. This can cause an over-steering of the receiving avalanche diode and generates systematic errors [5].

In general, the sensitivity of reflectorless range finding can be estimated as [1]:

$$S = \frac{D}{\sqrt{A \cdot T}} \tag{1}$$

S = sensitivity
D = distance
T = time of the measurement
A = total scattered power/incident power

In all reflectorless laser technologies - including laser-scanners - the performance is affected and limited by the physical laws of reflection and the optical properties of materials. The surface reflection of monochromatic light normally shows reflected rays in many directions.

This type of isotropic reflection can be described in general by Lambert's cosine law:

$$I_{reflected}(\lambda) = I_l(\lambda) \cdot k_d(\lambda) \cdot \cos(\theta) \tag{2}$$

$I_{li}(\lambda)$ = the incident light intensity as a function of wavelength (colour)
$k_d(\lambda)$ = diffuse reflection coefficient which is also a function of wavelength
θ = angle between the incident light and the normal vector to the surface.

Directed reflections occur when the roughness of the surface is small in comparison with the wavelength of the reflected radiation. Additional speckle effects affect the image of intensity and are related to the carrier frequency λ. As known from experiments with reflectorless measurements using totalstations, the properties of the surface, as reflectance of the surface, also affect the distance determination. The reflectance, defined as the relation of the reflected radiation power to the incident radiation power, gives the signal-to-noise ratio and influences the precision of the distance measurement (see Figure 2).

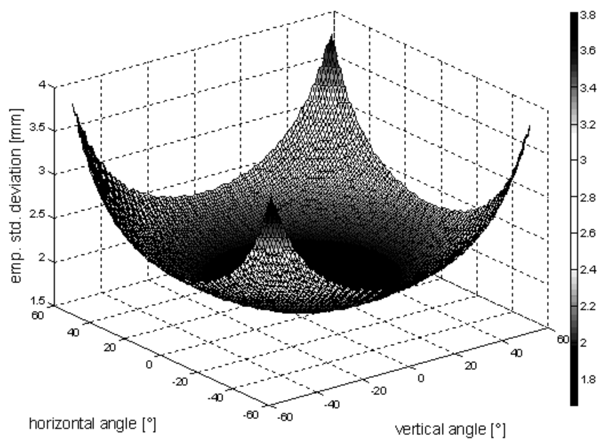

Figure 2: Standard-deviation of the distance component related to the angle of incidence upon a flat homogenous surface in a distance of 10 m

Additional effects are caused by the optical layout of the emitting and receiving system which is not really coaxial to prevent optical cross-talks. In most cases the laser shape is more or less elliptical with additional secondary maxima. In addition, several materials are invaded by the laser ray and the ray is also refracted and reflected in the material itself. This causes an addition constant in distance measurements, which has to be regarded in the computation. Experiments at the ETH Zurich and other geodetic institutions [6] have shown a dependence on these superimposing effects which generate material-related systematic effects in the distance of about 1 cm.

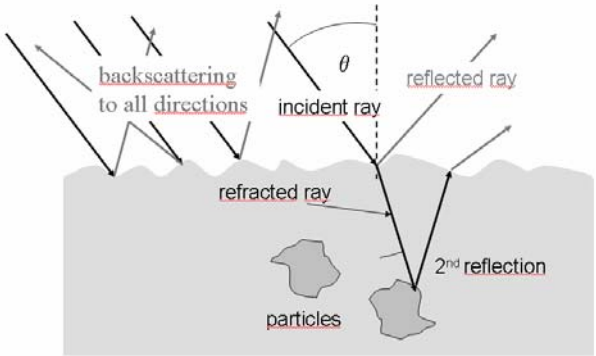

Figure 3: Surface backscattering and refractional effects in inhomogeneous semitransparent materials (Styropor, wood, marble).

In addition to the instrumental effects the whole error budget of the single coordinate s_{xyz} of a point cloud can be summarised as a function of:

- distance(D), which is related to the parameters of the atmosphere
- reflectance/reflectivity of the object ,which affects SNR
- ambient light , which affects the SNR
- angle of incidence (θ)
- wavelength (λ), which has a correlation with the roughness and generates speckles
- surface colour
- roughness of the surface
- geometry of the object which may cause multipath-effects

Out of long-term experiences with laser-scanning we can state that the physical threshold in accuracy in monochromatic laser-scanning is in the range of a few millimetres.

4. High precision static and kinematic laser scanning applications

Besides the nowadays applications as cultural heritage, façades etc. there is now a focus on high-precision applications in engineering geodesy. The question is how far laser-scanning can replace or be added to high-precision surveying technologies. One approach is monitoring of structures as concrete dams. In 2005 the concrete dam of Nalps, Switzerland, has been scanned. Its height is around 100 m and the length of its capstone is 478 m. Due to construction works of AlpTransit there are settlements and deformations to be expected. Until now this dam has been permanently monitored by tacheometry and GPS. The measurements were done with the Leica HDS3000 system.

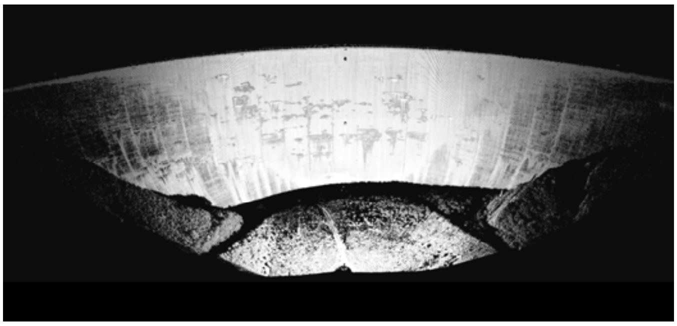

Figure 4: 3D point cloud of concrete dam Nalps (Sedrun).

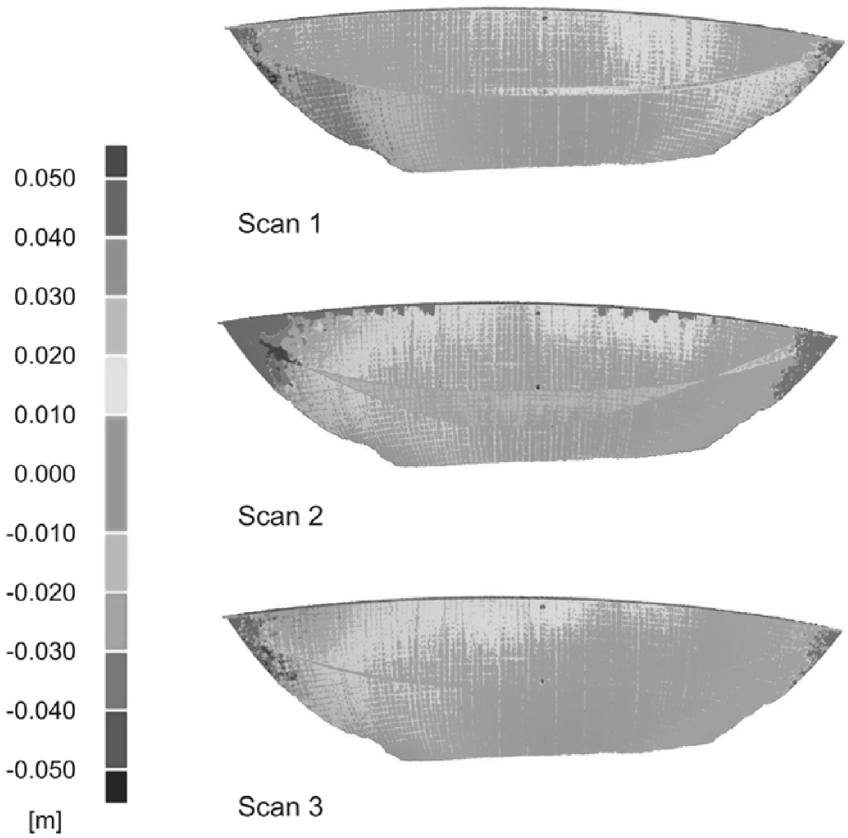

Figure 5: The greyscale represent the differences between as-is state and the CAD model.

Area-wide deformation monitoring can be done by laser-scanning systems. The re-measurement will be compared with the to-be geometry of the concrete dam. The modelling uses the Non Uniform Rational B-Splines (NURBS) mathematics.

In kinematic scanning the sensor platform is positioned and orientated in discrete, very short time intervals. Sensors to be applied are tracking totalstations, GPS and inclinometers. Within a joint venture project of scientific and private companies a track surveying vehicle has been developed - the so-called *swiss trolley,* which represents a platform of various sensors which is tracked either by GPS or tracking totalstations. For the geometric determination of the track environment, two laser-scanners are used. A further, essential feature of kinematic surveys is the synchronous acquisition of all involved sensors. For surveys with centimetre accuracy at velocities of several metres per second, synchronisation accuracies better than one millisecond are required.

The *swiss trolley* is successfully used for various tasks. Updates of databases of fixed assets, clearance inspections or contact free geometrical surveys of the overhead line are some typical applications in the field of railway engineering. For a customer, virtual scenery was created by means of the *swiss trolley* laser-scanners. Autonomous, circulating freight wagons equipped with laser-scanners compare the instantaneous environment with this nominal scenery. If differences between both models exceed thresholds, the wagon slows down [2].

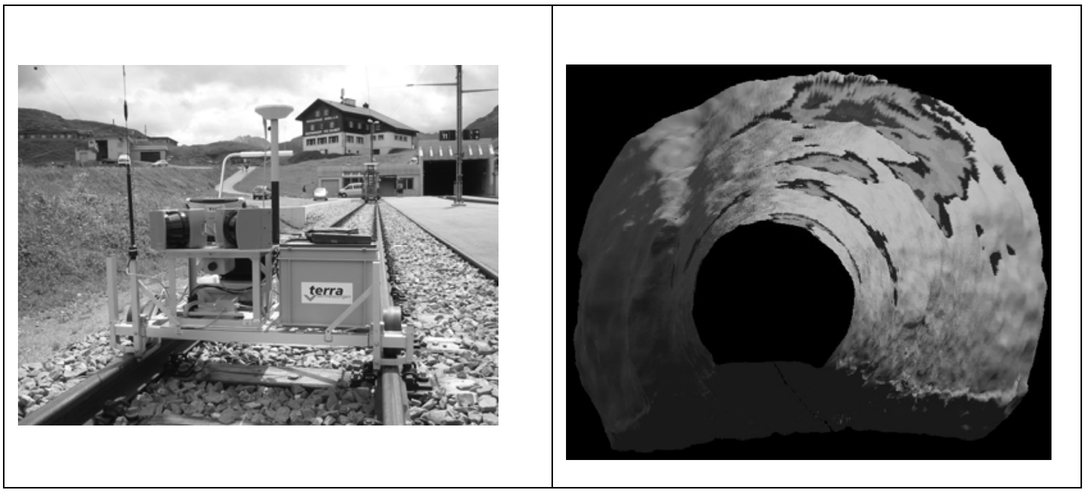

Figure 6: The *swiss trolley* equipped with two Sick laser-scanners
Clearance violations can be detected by the comparison of kinematic surveys with nominal data (high-lighted grey zones)

5. Outlook and Future 3D technologies

The investigations of high-precision scanners at the ETH Zurich have demonstrated the capability of the scanning technique for applications in engineering geodesy. This will encourage the use of this technology for high-precision kinematic applications. Terrestrial kinematic scanning using GPS or tracking total stations shows a tendency towards centimetre accuracy. Combination with other imaging techniques, as high-resolution CCD cameras, will give an opportunity of powerful 3D data capture system using the strengths of each technology.

In addition, new CMOS-CCD technologies - called Range Imaging (RIM) - integrates distance technologies and image capture in a single chip [7; 8].

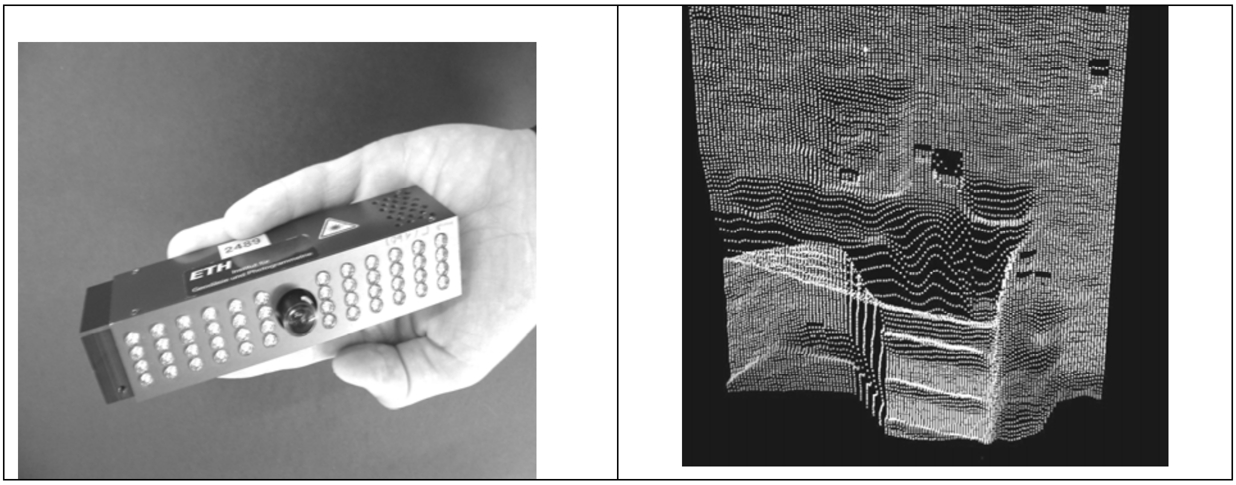

Figure 7: The SwissRanger and point cloud of an office scenery

The SwissRanger is equipped with a custom build combined CMOS/CCD-semiconductor array which has the ability to measure distances with every pixel. At the moment this new technology is in an experimental state but within the next years this technology could be used for scanning applications.

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