TERRESTRIAL LASER SCANNING –
NEW PERSPECTIVES IN 3D SURVEYING

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ABSTRACT

Laser scanners are used more and more as surveying instruments for various applications. With the advance of high precision systems, capable of working in most real world environments under a variety of conditions, numerous applications have opened up.
In the field of surveying laser scanners open up a new dimension with data capturing. Different industrial sectors require precise data of the environment in order to be able to have a as-build documentation of the facility. Especially as build documentation of plants (automotive, chemical, pharmaceutical etc.) has become a very sensitive and important new segment, as companies need to document their facilities. This is a basic requirement to plan and evaluate emergency situations (evacuation scenarios etc.) but also for simulation purposes of specific manufacturing cycles (car assembly etc.) as well as design studies. Having the environment in 3D as a CAD model ("digital factory") open up design studies without changing anything in the real environment and therefore causing no down time of production lines.
This paper reports about several systems and physical technologies used for measuring distances and presents several products available in this area. Furthermore it presents technical specifications of different systems and summarises with a comparison of achievable results.

1. INTRODUCTION

The market of laser scanners for terrestrial applications has developed over the last years quite successfully and the laser scanners are seen as surveying instruments which meet the requirements of industrial applications. At the moment several companies are offering products to the market. A direct comparison of these systems is difficult because of their technical specification and their physical measurement principle being different. Most systems are a combination of a one dimensional measurement system with a mechanical deflection system, directing the laser beam into different directions and measuring for each direction the distance to the closest object. The recent developments of terrestrial laser scanners open a wide variety of applications and therefore the adaptation of laser scanners is increasing.

In contrast to traditional geodetic instruments (e.g. total stations, GPS), most of the available laser scanners are not well specified regarding accuracy, resolution and performance as well only a few systems are checked by independent institutes regarding their performance and to confirm manufacturer specifications. A comprehensive investigation procedure has not been developed yet, so individual tests show results of the available systems.

The paper introduces technologies available with laser scanners. It reports the design of a laser scanner, consisting of a range measurement system and a deflection mirror and shows results of tests performed with the systems. It presents software for modelling purposes and compares three packages available by scanner manufacturers. It concludes with a summary of available systems and their performance data and gives an outlook to future developments needed for terrestrial developments.

1.1 Classification of terrestrial laser scanners

A classification of terrestrial laser scanners is difficult to be done. There are several possibilities to do this, either based on the measurement principle (i.e. triangulation, phase or pulse) or based on the technical specifications achieved. First of all, there is no one universal laser scanner for all conceivable applications. Some scanners are suitable for indoor use and medium ranges (up to 100 m), other scanners are better for outdoor use with long ranges (up to some 100 m) and there are also scanners for close range applications (up to some meters) with a high precision. Dependent on the application the suited laser scanner has to be selected.

Terrestrial laser scanners can be categorised by the principle of the distance measurement system. The distance measurement system correlates to both the range and the resulting accuracy of the system. Three different technologies for range measurements are used with laser scanners:

- Today, the most popular measurement system for laser scanners is the time of flight principle. This technique allows unambiguous measurements of distances up to several hundred of metres. The advantage of long ranges implies reasonable accuracy.

- Beside the time of flight principle, the phase measurement principle represents the other common technique for medium ranges. The range is restricted to one hundred metres. Accuracy of the measured distances within some millimetres are possible.

- For the sake of completeness, several close range laser scanners with ranges up to few meters are available. But, they are more for the use in industrial applications and reverse engineering (online monitoring in construction processes). The used distance measurement principles is optical triangulation. Accuracies down to some micrometers can be achieved with this technology.

Table 1 summarises a possible classification of laser scanners, based on the measurement principle. As a result, classification can be seen more in a general way. In addition, classifications by technical properties are more useful as they indicate the possibilities and the performance of the individual system. This is exactly, what the user is looking for.

These technical specifications are
- scanning speed, sampling rate of laser measurement system
- field of view (camera view, profiling, imaging)
- spatial resolution, i.e. number of points scanned in field of view
- accuracies of range measurement system and deflection system and overall for the systems
- combination with other devices, mounted on the laser scanner (e.g. camera, GPS)

Measurement technology	Range [m]	Accuracy [mm]	Manufacturers
Time of flight	< 100	< 10	Callidus, Leica, Mensi, Optech , Riegl
	< 1000	< 20	Optech, Riegl
Phase measurement	< 100	< 10	IQSun, Leica, VisImage, Zoller+Fröhlich
Optical triangulation	< 5	< 1	Mensi, Minolta

Tab. 1: Classification of laser scanners

1.2 System components of laser scanners

Laser scanners consist normally of a range measurement system in combination with a deflection for the laser beam, directing the laser beam into the direction to be measured. The deflection system points the laser beam into the direction to be measured, the laser beam is emitted and the reflected laser light is detected. The accuracy of distance measurements depends mainly on the intensity of the reflected laser light and therefore directly on the reflectivity of the object surface. The reflectivity depends on the angle of incidence, and surface properties. Multiple investigations [1, 2, 3, 4] have been made and correspond with physical constraints and laws.

For calibration purposes of laser scanners and total stations, specific procedures were developed in the last years. Instrumental errors as well as angular resolutions and distance accuracies can be defined. Unfortunately, the mechanical design of some laser scanners is different to total stations and therefore multiple investigations on accuracy and system calibrations have still to be made. At the moment, many manufacturers do specify the accuracies on the range measurements but not on the system at all, which implies many different accuracy specification (ranging, mirrors, temperature etc.). This can be clearly seen, as all manufacturers have no common specifications defined yet, as typical for geodetic instruments.

1.3 Laser scanners available

For a precise, long-range and fast 3D surveying of the environment and its visual image, measurement systems are used in the industrial field which are based on an active measuring principle. Commercially available are systems by Riegl, Optech, Trimble (Mensi), Minolta, iQSun, Callidus, Leica (Cyra), Visimage and Z+F. These systems differ by physical measuring principles.

Fig. 1: Laser scanner overview

a) Riegl LMS-Z210i

b) Optech ILRIS 3D

c) Trimble (Mensi) GS200

d) Minolta VIVID 910

e) IQSun IQSun 880

f) Callidus CP 3200

g) Leica HDS 4500

h) Zoller + Fröhlich IMAGER 5003

The systems of Riegl and Optech are pulsed systems with an accuracy in the centimeter area. The field of view of these systems is in the range of 360° (horizontal) x 60° (vertical) for Riegl and 60° x 60° for Optech. The advantage of these systems lies in the wide measuring range of over 100m, with the disadvantage of a long duration for the measuring of the complete field of view. The Riegl system offers a combination with a color camera and therefore results in colored point clouds at the end of a measurement cycle. Measuring the total field of view at a reasonable point density takes relatively long. The systems are used world wide successfully for surveying tasks in open environments (outdoor) and applications in rough environments. Especially the Optech system is also used in airborne applications and is very advanced in this field of application.

The systems of Trimble (GS100, GS200) and Leica (HDS3000, HDS2500) are also based on the pulse method and are suitable for distances up to about 70 m. These systems show a restricted field of view (typ. 360°x60°; HDS3000: 360°x270° in two separate windows) and a measuring period – depending on the density of points – in an area between minutes and hours for a complete 360°x270° field of view. The HDS systems of Leica are used quite successful over the world for all surveying tasks, mainly in the construction and GIS field.

Pulsed systems have measuring rates of 20kHz maximum which results in a long surveying period for large environment sections. Especially when surveying a field of view of 360°x270° with a high point density, these systems need unacceptably long if details are to be detected as well. Due to long measuring periods as well as the restricted vertical field of view these systems are only partly suitable for the given environment as especially the vertical field of view means a big challenge when surveying tree tops.

Phase based scanners are existing on the market since more than 10 years already by Zoller + Fröhlich in Germany, starting with systems for railway applications. The systems are offering high sampling rates and therefore are the solution for data capturing and surveying with a high speed. This is especially required with dynamic applications (moving platform like trains, cars, etc.) and plant applications, where access time to certain areas is only restricted. Phase based scanners are at the moment produced by the companies iQSun, VisImage and Zoller + Fröhlich. The visual laser scanner IMAGER 5003 by Z+F (HDS 4500 by Leica) is based on the AMCW principle (phase difference method) where a two frequency modulated (AMCW) laser beam is lead over the scene to be measured by means of a mechanical beam deflection unit. The result are range and reflectance images which correspond pixel by pixel, with an accuracy of the single points in an area of mm.

In general AMCW systems (phase difference method) have their advantages in a very high measuring speed (the IMAGER 5003 up to 625.000 measurements per second, iQSun 240.000 and VisImage 150.000) and at the same time measuring of corresponding reflectance images. Disadvantage of these systems is the restricted area of unambiguity.

2. BEAM DEFLECTION UNITS

Beam deflection with laser scanners is performed by two main principles for environmental scanning.

2.1 Profiling System

By rotating a deflection mirror about the optical axis of the laser measurement system a 360° profile measurement is accomplished. Each profile consists of single data points where the system data sample rate of the laser measurement system determines the number of points reachable. The achieved angular accuracy is directly based on the encoder fixed to the rotating deflection mirror.

Using profiling systems, a large spatial coverage of an extended section of the environment (tunnel survey, etc.) is implemented by profiling perpendicular to the direction of motion, while driving through the environment. Consecutive profiles (Helix) are stacked to form an image, where the lateral distance between two profiles can be varied depending on the speed of the carrier vehicle.

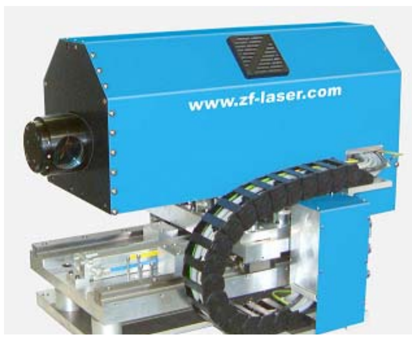

Fig. 2: PROFILER 6000-300

At the moment only a few systems - mainly measurement systems based on phase - are used for profiling applications. These applications require high data acquisition rates in order to have a gap less monitoring of the environment with high navigation speeds of the moving platforms. The system of Zoller + Fröhlich called PROFILER 6000-300 (Fig. 2) is the most advanced on the market and is used since 1994 in many different industrial applications. Especially service providers use the system for railway applications for the survey of tunnels and open track. The system is designed to measure up to 300 profiles per second with a max. data sampling rate of 625,000 points per second. Running the system on a train navigating at 120km/h allows a measurement of 300 profiles per second with a longitudinal measurement frequency of a few cm between consecutive profiles.

2.2 Imaging System

In order to implement a survey of a local 3-D section of the environment, a 2-D deflection unit is combined with a spot laser measurement system. The deflection unit enables imaging in azimuth (horizontal) and in elevation (vertical). For the deflection of the laser beam there are two different technologies available.

Camera view
A camera view field of view is achieved by using two synchronised mirrors (galvo), one for horizontal beam deflection and the other for vertical beam deflection. The benefit of this technology is that both mirrors can be positioned individually and – due to the mechanical set-up – a very high accuracy with angular measurement can be achieved. The disadvantage of this technology is that the field of view is limited to a camera view, normally in the order of 60° x 60°. Some systems are moving this limited field of view by positioning the mirrors automatically and result in a field of view by 360° x 60° maximum.

Panoramic view
A panoramic view is achieved by a single rotating (azimuth deflection) mirror and simultaneously rotating the system by the center axis of the system (Fig. 3). The set-up is similar to a total station which has multiple benefits. The field of view therefore results in 360° horizontally (azimuth) and up to 310° vertically (elevation). This restriction in vertical direction is due to the mechanical set-up of the system but is no major limitation for the system.

	FoV hor. x vert. [°]	**Manufacturer**
Camera View	60 x 60	Optech, Riegl
	360 x approx. 60	Mensi GS200 Callidus Riegl
	360 x 270, two windows	Leica HDS3000
Panoramic View	360° x 320°	IQSun
	360° x 270°	VisImage
	360° x 320°	Leica HDS 4500, Zoller + Fröhlich IMAGER 5003

Tab. 2: Deflection System of laser scanners

The two different beam deflection systems have different advantages and disadvantages. The panoramic view device, based on a total station approach, leads to easy and quick scanning, as the scene to be modelled has to be surveyed only from a few locations. Together with a high speed measuring device, this enables the user to survey the scene in a very short time.

Table 2 summarises different systems from different manufacturers and shows benefits of each system design. It furthermore shows, that there are no standards yet and that each manufacturer designs the deflection system for specific applications.
It furthermore shows, that camera view systems are normally combined with galvo based deflection units and used with pulsed measurement technology. As the system measurement rate is comparably slow and the long measurement range needs a very precise deflection of the laser beam, this approach is suitable to fulfil highly accurate measurements over a long measurement range. Panoramic view systems are normally based on high speed deflection systems and therefore used with phase measurement technology.
Especially the design of the Zoller + Fröhlich beam deflection system shows a promising approach, as it is similar to a total station set-up and therefore a lot of similarities can be used.

Fig. 3: Panoramic view scanner (IMAGER 5003)

3. THE GEOMETRICAL QUALITY OF THE MEASUREMENTS

The technical data of the actual scanners are listed in Table 3. The manufacturers give detailed technical information on their systems. But if we are looking at the quality of the measurements itself, this means the accuracy of the 3D-coordinates, respectively the measured elements, it is not easy to find appropriate information.

The judgment of the quality of the measurements cannot be realized by looking at single measurements (points), as we do for example with tacheometers; here we have to focus on derived elements (spheres, cylinders, etc.).

	System	3	4	Frequency	Range	Perform.
LEICA	HDS 3000	P	P	1000 Hz	>100m	*A*: 6 mm @ 50 m
MENSI	GS 200	H	P	5000 Hz	700 m	*R*:3 mm @ 100 m
OPTECH	ILRIS-3D	C	P	2000 Hz	800 m	*A*:3mm < 100 m 1-3 cm > 100 m
RIEGL	LMS Z 360	H	P	8000 Hz	800 m	*R*: 5 mm
Z + F	IMAGER 5003	P	A	500 kHz	52 m	*L*: 5 mm

Explanations:
row 3: P = Panorama-Scanner, C = Camera-Scanner , H = Hybrid-Scanner
4: P = Pulse-Measurement, A= Phase-Measurement

last row: *A* = Accuracy, *P* = Precision, *R* = Resolution, *L* = Linearity

Tab. 3: The technical data of the different scanners

3.1 Verification of the measured Distances

In order to estimate the achievable accuracy of distances and angles, 7 wooden spheres (with known diameters and known distances in one straight horizontal line) were scanned with a IMAGER 5003 (Z+F). In a first step the spheres and their corresponding center coordinates are estimated in a least-squares-adjustment. The second step is the comparison of the known distance and the calculated distance between two center points. The results of the deviations from the known distances, dependent from the density of the scan, are shown in Fig. 4.

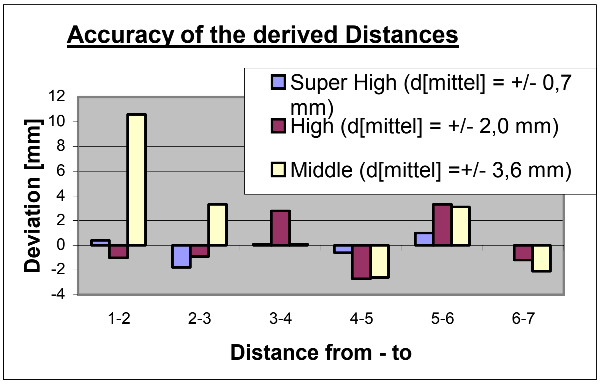

Fig.4: Distances derived from center coordinates of scanned spheres [4]

3.2 Verification of the Parameters of Cylinders

At the University of Essen, there is a work of art, consisting of 32 vertical cylinders (steel, diameter known, approx. 1200 mm, 5 m high) arranged in a square of 30 x 30 m. The cylinders were scanned with different systems and the results are presented for a subset of 10 cylinders in Fig. 5.

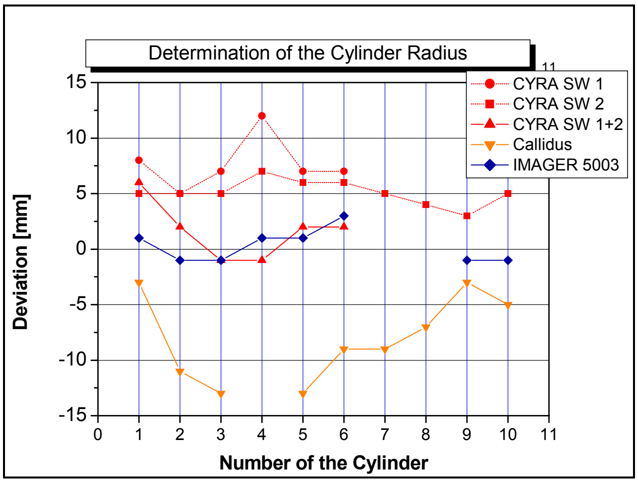

Fig. 5: Determination of the determined radius with different systems [4]

4. SOFTWARE FOR DATA EVALUATION

The software available for point cloud modelling is available from three scanner manufacturers and also some individual software companies like i.e. JRC and Bitwyse. The three packages from Leica, Mensi/Trimble and Zoller + Fröhlich are the most advanced available packages from scanner manufacturers, dedicated to physical hardware which is a big benefit due to physical constraints of measurement systems. All three packages support direct operation and control of the hardware connected as well as data evaluation afterwards. This enables the operator to use only one package so that it is easy to use without using multiple different packages.

4.1 CYCLONE

The cyclone software is developed from Leica since many years and is able to connect both, phase based scanners and pulsed systems as well as other GIS data measured by airborne scanners and other data capturing systems. Furthermore, the point clouds can be superimposed with color data from standard CCD cameras and therefore it is a kind of universal software tool. Different modules are available.

Cyclone™-SERVER
Cyclone Server is a standalone server module that enables individual members of workgroups to simultaneously access 3D point clouds, embedded images, and geometric surface models. This provides a powerful environment for collaborative design on large, complex projects and can significantly reduce project execution time.

Cyclone Databases
Each module of the Cyclone 3D point cloud processing software product line is based on a Client/Server Object Database foundation. Cyclone- SERVER supports the concurrent connection of up to ten (10) 'client' users to the same data server in a network environment. These clients can be licensees of Cyclone-SERVER, MODEL, SURVEY, VIEWER, or Cyclone CloudWorx™ for AutoCAD and Bentley® CloudWorx (distributed by Bentley Systems, Inc).

Central Cyclone Server for Efficient Database Management
Cyclone-SERVER eliminates data redundancy and related synchronisation issues, frees disk space on workstations, and provides more reliable access in network environments. A dedicated server, administered remotely by authorised users, can serve databases to Cyclone clients on the same network. Workstations with licenses of Cyclone software can also contain Cyclone-SERVER licenses, distributing the server load. Cyclone's PC-based server products are effective tools for computers with single or multiple processors.

Cyclone Modules
Cyclone is composed of individual software modules, allowing customisation for the individual client. Cyclone-REGISTER quickly and accurately aligns point clouds captured from different scanning positions to a common co-ordinate system. Cyclone-MODEL is the complete, full-featured tool set of Cyclone software for information extraction and 3D modelling. Cyclone-MODEL enables solutions in many applications including plant, survey, and civil engineering. Cyclone-SURVEY is a subset of the Cyclone-MODEL product and is an ideal module for surveyors. Cyclone-VIEWER is a free, view-only version of the Cyclone software.

4.2 3D IPSOS

3Dipsos from Mensi is a 3D modelling system used to reconstruct 3D models from large sets of point cloud data. 3Dipsos is a solution for as-built data capture and reverse engineering of large industrial sites including process, power, and oil/gas related plants. The software can also be used to reconstruct triangulated meshes directly from clouds of points, in order to model non-mathematical shapes like statues, bas-relief, historical monuments, natural scenes, and other irregular objects

Core Module
The core module allows for the manipulation point cloud data, the smoothing and the segmentation of the cloud of points. Segmentation allows for the cloud of points be separated into a unlimited number of groupings, which make up logical subsets. The lists of points are organized into a hierarchic table which create a universe using a tree with an unlimited number of levels.

Consolidation
The points of view are used to scan the hidden-parts of the object. The corresponding clouds of points are in their own and unknown referential. To consolidate means to put them in the same referential (which could be given by the application). This consolidation is interactively realized with the help of the common parts between several points of view. The common parts may belong to scanned objects or magnetic spheres installed in the scene by the user. The presence of spheres increase the speed of consolidation, but are not essential.
Reconstruction

Reconstruction
The operator interactively groups the 3D points (of the input cloud) into sub-clouds describing elementary parts of the environment. Then, there are a lot of methods to match these clouds to 3Dipsos primitives: 3D point, line, circle, ellipse, plane, sphere, ellipsoid, cylinder, cone, eccentred cone, torus.

Further modules like the engineering module for treatment of piping applications, the image module which applies 2D images into 3D space.

4.3 LIGHT FORM MODELLER

LIGHT FORM MODELLER (LFM) from Zoller + Fröhlich has been developed specifically to convert 3D point clouds into 3D CAD models. It is one of the most advanced packages for laser scanner data treatment and various modules for modelling, but also to export point clouds directly into CAD software packages.

Conversion from point data to CAD objects is achieved by the application of analysis algorithms which have been developed to facilitate swift points-to-primitives translation. Various modules are available.

LFM Register
This package enables users of LFM to be able to register or join together neighbouring scans in order to form a group of scans or a "point cloud". It also enables export data from the IMAGER 5003 scanner via DLL to a number of complimentary CAD packages (Microstation, AutoCAD, PDS, PDMS, etc.).

LFM GENERATOR
It generates a database of points from the registered scan data. This database of points can then be viewed directly in LFM SERVER or through LFM SERVER in a CAD package such as Microstation or AutoCAD. It is possible to generate a database of points comprising of up to 256 scans, or 13 million data points. This capability far surpasses other software on the market and enables the user to be able to hold all these scans in view and then zoom into the area of interest and then increase the resolution of the scan to view in normal mode.

LFM SERVER
Phase-based scanners such as the Z+F IMAGER 5003 produce extremely large amounts of 3-D data (typically 50 Million pixels per scan). This means that loading individual scans can be a time consuming process. It is not desirable to have a work process which continually involves the opening and closing of individual scans. The user of high resolution laser-scanned data wishes to access the area of interest within the point cloud quickly and be able to view high resolution data. Projects can reach 1000 scans or more, which can mean clouds of points containing 50 billion points or more. LFM SERVER is highly efficient at navigating these very large point clouds and serving the points data to view in high resolution.

LFM VIEWER
Where a customer is using a CAD package not linked to LFM SERVER then they may wish to compare an existing CAD model with the real world by reading the CAD model into the cloud of points. Where this function is required then LFM VIEWER can be used as it is CAD engine based. In this instance the number of scans that can be viewed simultaneously will be limited to a handful by the processing power and RAM of the computer but it will be possible to compare the real world with the design model by working around the model in this fashion.

LFM MODELLER
Where accurate and semi-automatic fitting of the point cloud data is required then LFM MODELLER is used. An example of this work is tie-in and work package modelling in the Process Industry or modelling of equipment detail close to the car-line in automotive plant. Modelling using the LFM SERVER with the CAD package can be used more for infrastructure where accuracy is not quite as crucial e.g. HVAC, Walls, ceilings etc.

4.4 Other packages

There are other software packages available but they are not related directly to modelling of point clouds. There are also a lot of CAD packages available with direct import of point clouds from laser scanners which enable a direct modelling in the CAD software (AutoCAD, Microstation, etc.). Especially the package of the JRC called RECONSTRUCTOR is a very advanced software package for modelling of cultural objects and, together with the tool for detecting changes in the environment (based on a reference model), this tool is very useful for many applications also in industrial environments.

5. CONCLUSION

With the developed laser scanners, the control software and the software for model generation, very powerful tools are available that are suitable for most industrial and cultural heritage surveying tasks. The developed laser scanners offer large field of views with relatively long sampling time for camera view scanners, based on pulse measurement principles. For panoramic scanners a short measurement time within an extended field of view is available due to the high speed phase based technology. Both technologies offer a high accuracy with measurements in conjunction with a large dynamic range in reflective properties of object surfaces (highly reflective to absorbing).
A comprehensive investigation of the systems has been done by independent Universities and Institutes. The different distance measurement systems and the deflection systems available with laser scanners were examined in detail.
Triangulation technologies are also available with laser scanners, but they are focussing not on a typical surveying market but more on re-engineering purposes.

At the moment it is a big lack that every scanner manufacturer has different technical specifications published which makes it nearly impossible for users to compare the systems based on this data. Therefore, standards have to be defined and individual working groups have to define benchmark tests, similar to computer vision.

As a summary of the results achieved with the scanners, the Riegl and the Leica scanners with pulsed technology as well as the phase based scanner IMAGER 5003 from Z+F are the most advanced systems available on the market for the moment. The systems are showing a professional attitude with rough environments and their use in industrial environments.
The software available has still to be developed, especially the established CAD software companies have to focus on this new technology and provide plug in modules in their existing CAD packages for their users.

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