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*Review of 20 Years of Range Sensor Development ***

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Abstract. *We review 20 years of development in the field of 3-D laser imaging. An overview of 3-D digitizing techniques is presented with an emphasis on commercial techniques and systems currently available. It covers some of the most important methods that have been developed, both at the National Research Council of Canada (NRC) and elsewhere, with a focus on commercial systems that are considered good representations of the key technologies that have survived the test of years.* © *2004 SPIE and IS&T.*
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1 Introduction

The past 20 years have seen enormous progress in the development of noncontact optical surface digitizers. The large number of companies that are now offering commercial 3-D range sensor systems shows that 3-D-based technology has successfully passed the initial stage of research curiosities in laboratories of the 1980s and the numerous demonstrations of applications of the 1990s. Powerful algorithms and data processing software gradually complements 3-D sensing, demonstrating that dimensional applications are often better performed using reliable 3-D images than 2-D. However, 3-D vision systems are still in their infant stages when compared to their equivalent 2-D counterparts. In general, 3-D is still several years behind in terms of image quality, rendering, and ease of use.

During the last decade, much research has been published describing ''novel'' range sensors. Among this research are truly innovative works in the development of ranging methods, and a large majority brings important key ingredients that refine the knowledge in the field, but unfortunately many are also reinventing the subject. Furthermore, specialization of research and the presumption that software can solve all the problems often creates erroneous expectations based on extrapolations that break the laws of physics.

Various methods for acquiring range images were surveyed by Jarvis in 1983.[1] Besl in 1986 presented an overview of different range measurement techniques and commercial sensors.[2] At the time, the number of commercial systems was much smaller than today. He also proposed a

merit function to compare sensor performances. More recently, Tiziani[3] and Chen, Brown, and Song[4] presented comprehensive surveys focusing on a few techniques used mostly for object modeling, and although 3-D object modeling applications are today quickly growing, they are only one facet of 3-D sensing. This work presents this vast subject from a more industry-oriented perspective that includes applications ranging from inspection to 3-D object modeling.

The aim of this work is to quickly review the past 20 years of research and work in the field. To avoid the possibility of drawing historically false conclusions, it focuses in part with research that was done at the National Research Council of Canada (NRC) and on the evolution of key technologies and components that were used to build range sensors. This evolution is not unique to NRC and similar conclusions can be drawn for other groups. Furthermore, it helps explain some of the current industrial trends. Considering that prototypes usually take 5 to 10 years from the initial research laboratory to commercialization, while incremental innovations are implemented more quickly, industrial systems are therefore a good indicative of past and recent work.

Although far from being complete, the tables include descriptions of nearly 80 companies, most of them offering many variants of 3-D range camera systems. Obviously, not all the companies can be listed, and this selection was based on a combination of innovation, design particularities, demonstration of ranging methods, or specific applications. The appendices contain more technical information to support the comments and conclusions drawn.

2 Range Sensor Development

The practical development of 3-D laser range sensors closely follows the availability of new electronic components and electro-optical emerging technologies. The principle of range measurement based on triangulation is centuries old. This principle was demonstrated by the Greeks for navigation and by astronomers. Erastothenes used the shadow created by the sun to measure the circumference of the earth, with impressive results considering this was done more than 2000 years ago. During the two world wars, intensive use of passive optical range finders by the military was common practice. During the 1970s and beginning of the 1980s, the availability of low-cost light position and
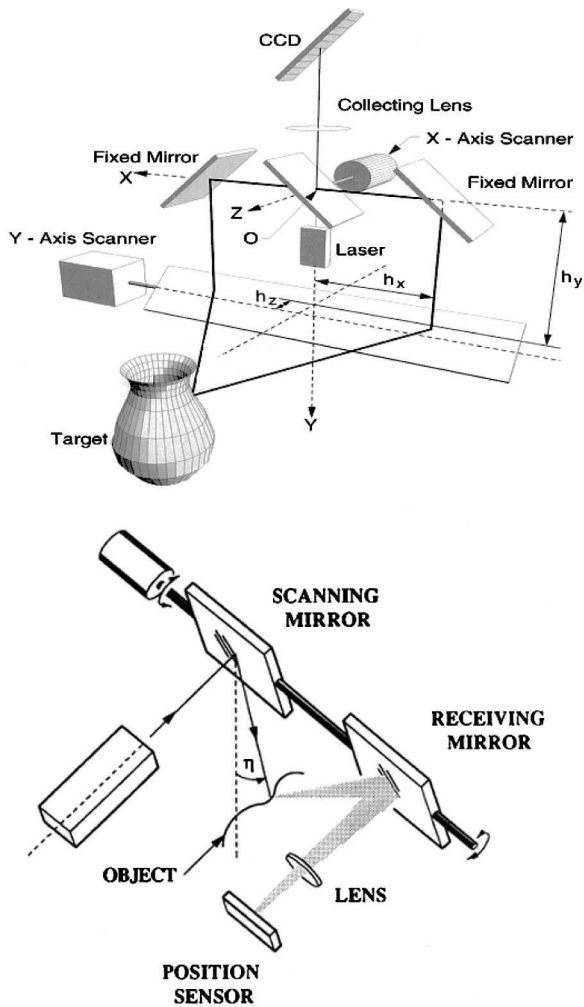
Fig. 1 Single-point laser scanning using longitudinal synchronization (top) and lateral synchronization (bottom). Range magnification and immunity to ambient light is obtained without compromising the field of view of the 3-D camera.

other electro-optical devices, and the introduction of the microcomputer, made possible the development of cost-effective automated range sensor systems for industrial applications. At first, position sensitive devices were mostly analog in nature. For example, the lateral effect photodiode (LEP) and Vidicon-type cameras were used to convert optical information to an electrical signal that was then processed to extract range information. These technologies were difficult to use and quasi-impossible to calibrate, limited by inaccuracies and drifts in the electronics.

2.1 Single Point and Laser Scanners

During the 1970s, a few research laboratories were already involved in 3-D. The plane-of-light and pattern projection methods were known practice. In 1983, Jarvis[1] published a survey of some of these works. In the early 1980s, the NRC initiated a research program in 3-D, focusing on the development of high-accuracy triangulation-based 3-D range sensors.[5] The synchronized laser scanner principles using fast scanning mirrors, as shown in Fig. 1,[6,7] were introduced by the NRC and other laboratories. The advantage of synchronizing the optical detector with laser projection en-

abled the use of long focal length lens zoom configurations (see Appendix A in Sec. 5). The extra cost of using mechanical scanners was minimal compared with a tenfold increase in performances. Gas lasers were used and acquisition rates to 200 kHz were obtained, and later pushed to 10 MHz video-rates[8] with newer LEPs.[9] Other research with different optical principles and scanning methods produced similar quasi-video rate systems[10] still used today for the automatic inspection of electronics packaging, and soldering paste (e.g., Sec. 3.1).

During the following years, several concepts of detectors using geometrically shaped LEP or specially designed masks were presented. The introduction of the CCD array created an important breakthrough in 3-D active triangulation-based range sensors. The NRC's first prototype used a linear 2048-element CCD from Fairchild. An all-digital solution to the laser position measurement was possible, bringing accuracy and stability to the range data. Although slower, CCD devices were much more accurate and stable.[11–13] When coupled with real-time subpixel digital peak detection algorithms,[12,14] range resolution in the order of 0.1% was obtained compared to 1% with analog detectors. Reduced acquisition speeds also allowed the use of slower but more accurate galvanometer-based scanning devices rather than fast polygonal rotating mirrors.

Faster and larger CCD pixel arrays, initially developed for spectroscopy applications (e.g., Reticon), were commercially available. Coupled with better processing, these devices pushed the range accuracy to 0.01%, which consequently created the need for new and more accurate galvanometers and control to obtain 0.01% in pointing precision.[15,16] Laser position detection is now mostly limited by physical and optical limits[17,18] and the performances of the sensors quickly exceeded the range of the merit function that was proposed by Besl.[2,19] Other prototypes were developed to support eye-safe lasers (1.5 μm), initially using optically pumped fiber lasers and later with laser diodes;[20] time-of-flight (TOF) measurements; and color detection with the addition of a white laser source (RGB), color separation optics, and multiple peak position and color intensity detection.[21]

Several triangulation principles, devices, and techniques were published mostly during the 1980s: lateral and longitudinal synchronization, electroacoustic and piezodeflectors, micromirrors, prisms, and holographic scanners.[22] Research also focused on algorithms for the detection of laser spot position,[14] new linear detectors, parallel arrays, detectors with masks, the use of the Schleimpflug condition, and other optical and numerical methods to increase accuracy and to reduce laser speckle noise while preserving the overall shape information.

Today, single-point 3-D laser scanners still offer many technical advantages. The whole CCD length can be optimized for a given volume of measurement, resulting in higher resolution and accuracy than slit scanners. Laser modulation and control can be optimized on a per-voxel basis to increase the SNR of the returned signal,[19] a must for metallic and other reflective surfaces. The cost is usually higher than slit scanners because of the use of scanning mechanical devices and specialized components, such as galvanometers and large pixel linear CCDs.
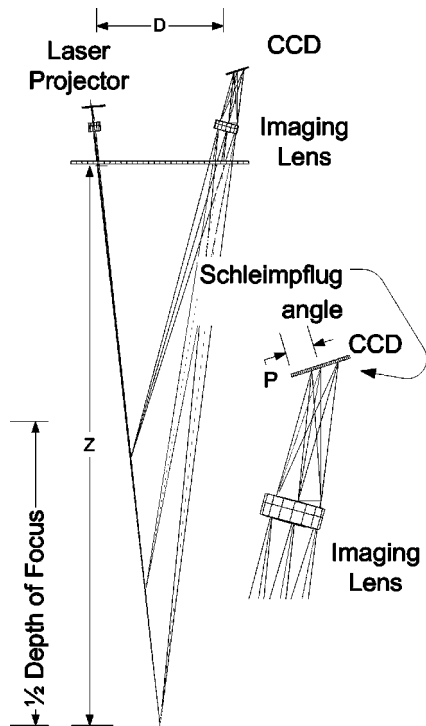
Fig. 2 Basic triangulation principle; the position of the image on the CCD is directly related to the range. Large depth of focus is obtained using lasers and the Schleimpflug condition.

Fig. 4 A dual-aperture mask produces similar advantages without requiring a second detector.

Figures 1–4 are examples of single-point triangulation sensor configurations. These figures were produced using a professional optical lens design and ray-tracing program, and show the basic principles as well as the subtleties of image formation and defocusing. The basic triangulation principle is shown in Fig. 2, where a narrow laser beam is projected on the surface of an object and imaged at different positions on the CCD, 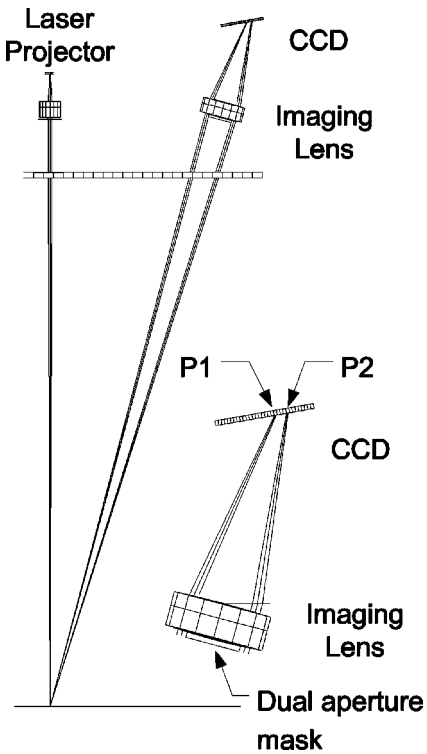depending on range. A closeup shows how the Schleimpflug angle provides optimum image focusing on the CCD, independent of range. The tilt of the detector guarantees that the light point projected on the

object will always be imaged in focus. The advantage of using a laser lies in the very large depth of focus defined by Gaussian beam propagation equations and high power in small packages at the compromise of increased laser speckle noise (more later in Sec. 2.3 and Appendix B in Sec. 6).

The dual-view principle of Fig. 3 serves two purposes: the redundancy in the measurements improves the accuracy of the sensor by a factor of $\sqrt{2}$ and at the same time validates ranging; and an image of the laser will be symmetric on the two CCDs while an outlier (e.g., specular reflection of sun interference) will be asymmetric. The Biris principle of Fig. 4 provides equivalent advantages using only one CCD. A dual-aperture mask (Bi-Iris) inserted next to the diaphragm of the lens creates two spots P1 and P2 on the CCD detector and a unique peak-position/peak separation relationship. Figure 1 shows two examples of synchronized scanning that use galvanometers and mirrors to sweep a single-point laser beam on the surface of an object. The imaging and projection optical paths are mechanically synchronized.

2.2 Slit Scanner

The slit scanner is by far the most widely used triangulation-based 3-D laser camera because of its optical and mechanical simplicity and cost. The slit scanner is a natural extension of the linear single-point detector, allowing the projection of a laser line and the simultaneous detection of a complete profile of points in a single video frame. Rather than using a multitude of single-point probes or costly mechanical scanning devices (galvanometers, polygonal scanners), a laser line is projected on the object and

Fig. 3 Dual-view triangulation creates measurement redundancies that increase accuracy and remove erroneous reading.
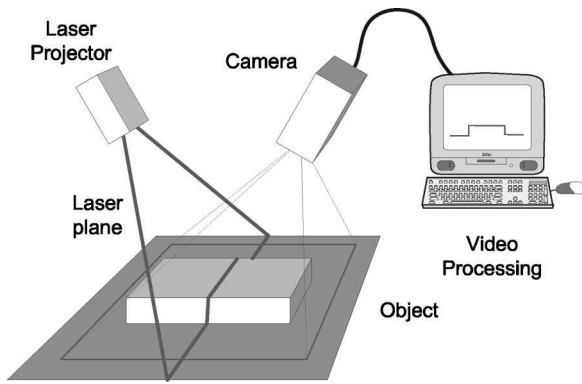
Fig. 5 Slit scanners are a direction extension of the basic triangulation principle of Fig. 2. Simplicity of the design results in a compromise between accuracy and field of view (see Appendix A in Sec. 5).

Fig. 6 LCD pattern projection systems create a magnified image of the projector pixel on the object, limiting lateral resolution but providing simultaneous measurements in a single video frame. Depth volume is limited by the defocusing of both projection and detection.

imaged at an angle. The deformation of the profile is a direct function of range, as shown in Fig. 5.

The introduction of CCD arrays in the early 1980s eliminated the inherent problems associated with tubes, and the Vidicon camera became quickly obsolete. Low-cost laser diodes in the late 1980s eliminated the need for gas lasers and allowed the creation of very compact sensor heads. Recently, the introduction of a low-cost complementary metal-oxide semiconductor (CMOS) detector that incorporates digital conversion and on-chip processing, high-speed digital bus interface, and powerful computers further removes the need for dedicated acquisition frame grabbers and specialized electronics.

The main inconvenience of a slit scanner is the compromise between the field of view and depth resolution (see Appendix A in Sec. 5).[19] Field of views in the order of 20 to 30 deg are usually published. To increase the field of view, anamorphic optical designs were introduced; cylindrical lens add-ons gave an interesting 60-deg field of view.[23] The second disadvantage associated with slit scanners is their relatively poor immunity to ambient light. Optical signal-to-noise ratio is reduced because of the spread of the laser power along the projected line, and because the sensor must image the whole scene. Strong ambient light will perturb the measurements even if narrow-band optical interference filters are used. Although not that critical for indoor environments, this is particularly important for outdoors, and some robotics applications.[24] Several methods have been proposed, such as dark frame subtraction and range redundancy using optical principles, such as those illustrated in Figs. 3 and 4. These partial solutions do not eliminate the problem of detector saturation.

Cost reductions are directly associated with the introduction of smaller detectors and the possibility of integrating more pixels and more functionality on a single IC. From the 1-in. Vidicon-type detector, the 2/3- and 1/2-in. CCD, the newer CMOS arrays are 1/3-in. and now 1/4-in. in size. Although lateral resolution increases because of the larger number of pixels, overall optical and range performances are expected to remain relatively the same or even decrease with these new CMOS detectors. Assuming perfect optics, speckle noise and optical resolution are physical limits that were already reached with the 2/3-in. CCD (see Appendix
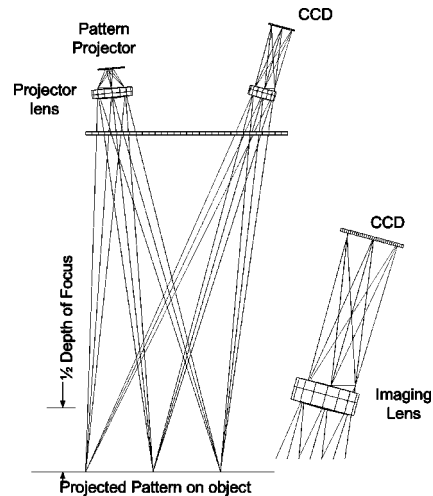
A in Sec. 5). These physical limits are today the main limitations, and major new innovations must be researched.

Manufacturers must often sacrifice many of these ideal considerations for cost reasons. For example, the Schleimpflug condition is rarely used with slit scanners, and although this dramatically reduces the depth of focus, applications such as inspection of surface defects that do not require large depth will not suffer. However, because it does not show in the manufacturer specifications, many users are often surprised when testing their large volume system, wondering why the system did not performed as expected.

2.3 Pattern Projection and Moiré

Pattern techniques use multiple stripes or patterns projected simultaneously on the object, as seen in Fig. 6, rather than mechanically scanning a single laser line of point on the scene and processing independent range profiles.[25–27]

The basic moiré principle uses two precisely matched pairs of gratings, the projected light is spatially amplitude modulated by the grating, and the camera grating demodulates the viewed pattern and creates interference fringes whose phases are proportional to range.[28] Projective moiré is considered a triangulation-based method and follows the mathematics presented in Appendix A in Sec. 5. Other methods use only the projective moiré pattern and software to demodulate the signal.[29] Moiré patterns are most useful with objects having relatively large flat surfaces and small depth variations. To avoid the problem of phase discrimination of moiré patterns (phase measurement multiples of π), different methods have been proposed, the most common being surface continuity algorithms.

Other methods propose the use of a projective pattern and the detection of the same pattern from multiple views using stereoscopic systems.[30] To use redundancy in the range measurement created by a double-aperture mask to validate detection when multiple laser line profiles are projected,[31,32] the use of a circular mask and projection of a pattern of dots[31,33] are other elegant solutions. These ap-
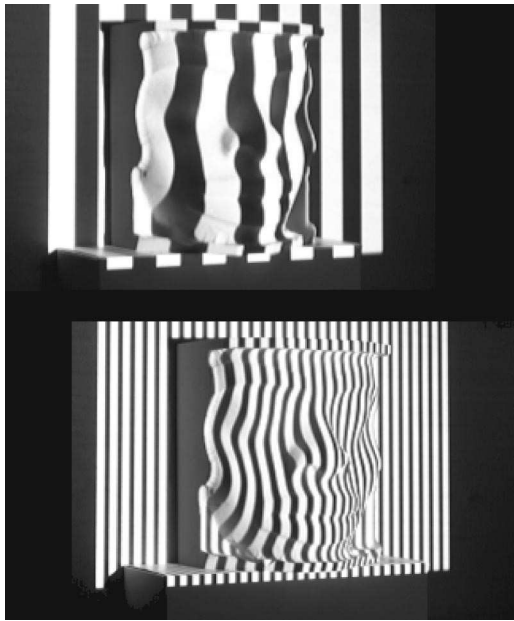
Fig. 7 Binary coded pattern projection; a 3-D image can be acquired in a few frames.

proaches are commercially available from ShapeGrabber and Wolfbeck (Sec. 3.2). The Virtual 3D Tech system uses a multiple-view camera system and algorithms to detect the correlation between speckle-generated images.[34]

The sequential projection of encoded patterns is another elegant way of dealing with range (or phase shift) ambiguities.[35] The most popular methods for pattern projection use binary coded or phases shift fringe patterns.[36–40] Gray-code binary images use multiple frames with increased resolution (bits) to encode a pixel on the CCD with its corresponding range, as shown in Fig. 7. Subpixel resolution is obtained by detecting the edge transitions in the highest resolution image. Steinbichler[41] commercializes sensors based on this technique. Other methods use sinusoidal phase encoding to measure range.[42,43] Using this method, it can be demonstrated that three video frames are sufficient to calculate the relative phase of the sinusoidal pattern, although in practice more frames are used to increase accuracy. Coded pattern methods are also very popular because of the availability of low-cost projectors and a

full 3-D volume can be acquired quickly in just a few video frames.

The use of incoherent light reduces speckle noise associated with lasers and consequently provides better surface smoothness. However, the depth of view is smaller when compared to laser strip scanners, as shown in Fig. 7. Absolute accuracy for an equivalent 3-D volume (and not only for a surface) will be relatively smaller than its laser counterparts. As illustrated in Fig. 7, important technical issues have to be addressed, especially the defocus of the projected pattern due to the fact that a larger projector lens is needed to collect as much light as possible from the light source, the spatial resolution of the pattern, smaller depth of focus of the imaging lens, and reduced dynamic range in intensity.

2.4 Time-of-Flight Systems

For large structures, time-of-flight (TOF) 3-D scanners are by far the preferred choice for measurements at longer ranges. Range accuracy is relatively constant for the whole volume of measurement. Because these systems require detection of the time light propagates through air, measurements will be affected mostly by drifts and jitter in the electronics (see Appendix B in Sec. 6). Different methods have been proposed in the research community: pulse, amplitude modulation, frequency modulation, hybrid detection, and self-mixing diodes.[44] We describe only the most popular methods.

A pulse TOF detects the time a laser pulse is reflected back to the receiving detector, usually an avalanche photodiode. Picosecond resolution implies very sensitive electronics with high bandwidth, constant group delays, and excellent thermal stability. To reduce noise, multiple pulses are averaged, and resolution in the order of 0.5 to 1 cm is now standard. Different methods have also been proposed to create a reference signal used to autocalibrate the system.

High-frequency bandwidth in the electronics is needed to amplify the large-frequency spectrum associated with pulses. Amplitude modulation of the optical carrier has been proposed, where range is measured from the phase variation between the transmitted and received signal. The electronics are a little more complex than pulse TOF, but the reduced bandwidth provides better range resolution in the order of 3 to 5 mm. Other frequency modulation techniques (e.g., FM) are also used, and as expected, excellent

Table 1 Interferometry. Legend for all tables is as follows: T=Triangulation, TOF=Time of flight, M =moiré, St=stereo, Sil=shape from silhouette, Int=interferometry, P=pattern projection, Ph =photogrammetry, and A=aperture/mask.

Company	Type	Description	Range	Accuracy
Atos (www.atos-online.de)	Int	White light interferometer and confocal systems		0.02 nm
Optimet-Conoscan (www.optimet.com)	Int	Conoscopic holography	0.6–180 mm	2–50 μm
Optonor (www.optonor.com)	Int	Projective microscopy moiré and interferometry		
MiiC-Opton Co. Ltd. (www.opton.co.jp)	Int	Moiré projection	10–20 mm	10–25 μm
Zygo (www.zygo.com)	Int	White light interferometer	150 μm	0.1 nm

Table 2 Others.

Company	Type	Description	Range	Accuracy
Nanofocus/UBM Corporation (www.nanofocus-inc.com)	Misc	Confocal laser		0.1 μm
Northern Digital Inc.-Optotrack (www.ndigital.com)	St+Ph	Optical stereo/photogrammetric tracking system	2.25 m	0.15 mm
Imagine Optics (www.imagine-optic.com)	Misc	Optical wavefront curvature measurement		
3DV Systems-Zcam (www.3dvsystems.com)	Zbuf.	Color and Z buffer, depth keying at video rate	0.5–7 m	1 cm
Metric Vision-SMX Tracker (www.smxcorp.com)	Int	Very high accuracy laser tracking system	35 m	1 cm

range accuracy have been measured; submillimeter range resolutions are reported (see Table 5).

Other techniques have been proposed that fall in the gray region between TOF and interferometry.[45,46] Tables 1 and 2 show examples of commercial systems that use modulation of the light wavelength itself rather than a carrier. Other interferometrics methods have also been developed, such as optical wavefront propagation,[47,48] light-in-flight interferometry,[49,50] holography,[51] and single photon counting.[52,53]

3 Commercial Systems

Cost is the major concern for the widespread use of 3-D technology. Powerful ranging techniques and many companies failed commercially simply because they were unable to compete or to market their products, even if, in many cases, their products were technically far superior. 3-D technology is still in the early innovators stage of the technology adoption life cycle.[54] Sarcastically, the increasing number of patent infringement lawsuits is another indirect indicator of a growing sector of our economy. The tables list companies that, at the time of writing, were still active in 3-D. These companies are offering products based on the principles described in this work.

3.1 Single-Point Probes and Laser Scanners

Specialized applications that require speed, high immunity to ambient light, or increased depth will benefit from single-point triangulation-based laser scanners. For example, rather than developing a unique general-purpose scanner solution, LMI offers a very large inventory of single-point probes and slit scanners that can be integrated into dedicated inspection systems. A wide range of industrial 3-D machine vision solutions under several brand names is offered to industrial sectors such as forestry, metallurgy, automotive, electronics, robot guidance, road, and manufacturing. LMI is the merging of four industrial players in the 3-D machine vision industry: Selcom (Sweden), Dynamic Control Systems (Canada), Sensors-95 (Holland), and Diffracto (Canada).

RVSI Electronics is an example of a market strategy to provide a vertically integrated line of products for a key industrial sector. They offer 2-D and 3-D vision systems with a focus toward the inspection of semiconductor packages and the semiconductor industry. The major distinctive characteristic of their systems is speed, approximately 5 million 3-D points per second with resolution to 2.25 μm.

Servo-Robot is specialized in automatic welding systems and uses the autosynchronized laser scanner principle to obtain high-accuracy range images. Figure 8 shows an example of a 3-D color object acquired with the NRC system. The autosynchronized scanner is coupled to an RGB laser to create high-resolution color textured 3-D objects. Because color is perfectly registered with shape, high-resolution color textured objects are measured without the ambiguity and problems of registration created by projecting the color texture acquired from a separate camera. Arius 3-D commercializes its own proprietary implementation based on a variation of this principle.

Neptec has recently developed, in collaboration with NRC, an eye-safe scanning laser range camera, based on the autosynchronized principle, to the stringent requirements set by NASA for use aboard the space shuttle. The system was tested on-board the space shuttle Discovery in August 2001, and more recently, during the investigation of Columbia's disaster. The system can acquire volumes of up to 10 m in triangulation mode, as shown in Fig. 8. High immunity to ambient light and increase depth is obtained.

The Digibotic system integrates both rotation and translation with a high-accuracy, single-point 3-D laser probe to automatically scan an object. Two triangulation detectors, located on either side of the laser projector, are mechanically moved until the laser point on the object is aligned with the two optical heads. Scanning is implemented using mechanical translation (two-axis) of the optical probe and rotation of the object. Accuracy is mostly limited by mechanical constraints; long focal length lenses are used to increase accuracy.

For very high accuracies using triangulation, Atos offers a white light confocal profiler that consists of a confocal microscopy setup and a noncontact probe. The probe is located on a computer-driven precision table and the confocal unit is mechanically moved in z. Because of the very narrow depth of focus of a confocal microscope, high range resolution (0.1 μm) is obtained. Nanofocus is another example of a confocal microscopic-based laser system.

3.2 Slit Scanners

Slit scanners are by far the most popular triangulation-based systems because of their low cost. Quoted precisions are relatively similar between manufacturers, because slit

Table 3 Triangulation with lasers.

Company	Type	Description	Range	Accuracy
Steintek (www.steintek.de)	T	Probe on multiaxis mechanical structure	10–60 cm	20–300 μm
ShapeGrabber (www.shapegrabber.com)	T+A	Plane of light on translation or rotation stage	40–650 mm	25–200 μm
Cyberware (www.cyberware.com)	Tri	Several products; body scanner, color, simple scanning unit		50–300 μm
3Dscanners-Model Maker (www.3dscanners.com)	Tri	Hand-held laser stripe camera mounted on mechanical probe		
RVSI/Abante Automation (www.rvsi.com)	T	Semiconductors/elect. inspection systems, ultra fast (MHz)		2.25 μm
Minolta-Vivid Systems (www.minolta-3d.com)	T	General purpose-galvanometer/mirror scanner	70–1.1 m	100 μm −7 mm
Kreon (www.kreon3d.com)	T	Probe for CMM/CNC machine-laser slit	50–100 mm	10–25 μm
Cyberoptics (www.cyberoptics.com)	P	PCB/solder paste/semiconductor inspection		
Integrated Vision-Ranger (www.ivp.se)	T	Very high speed profiler camera-10000 profiles/s		
Virtek Vision International (www.virtekvision.com)	T	Multiple lines of industrial products	25 mm	100 μm
Hamamatsu-Body Scanner (Usa.hamamatsu.com)	P	Full body scan (10 s)	0.5 m	−0.005
Virtual 3D Tech (3d.itri.org.tw)	T	Slit		0.1–0.2 mm
Metris (www.metris.be)	T	CMM/CNC slit scanner probe	100 mm	5–12 μm
Nagoya Inst. Tech.-Cubicscope (hilbert.elcom.nitech.ac.jp)	T+P	Laser slit scanning with space encoding	300 mm	1–2 mm
DLR (www.robotic.dlr.de)	T	Single point rotating head; robotics applications		
GIE Tech.-LaserVISION (www.gietech.com)	T+A	Multiple head; multiple lines projection; road inspection		
Servo Robot Inc. (www.servorobot.com)	T/L	Robotic control; automatic welding; industrial inspection		
Arius3D (www.arius3d.com)	L	High accuracy and resolution color		
Digibotics-Digibot (www.digibotics.com)	T	Four-axis automatic placement probe with rotating table		
Laser Design Inc.-Surveyor (www.laserdesign.com)	T	Line of products, from portable to CMM mounted, reverse eng.		
Mensi-SOISIC (www.mensi.com)	T	Large triangulation base; slow 100 voxel/s	to 25 m	0.2–0.6 mm
Virtual 3D (www.virtual3dtech.com)	T	Several products		
Table 3. (cont.)				
Vitronic (www.vitronic.com)	T	Industrial inspection to body scan		
Polhemus-FastSCAN-3Draw (www.polhemus.com)	T	Hand-held slit scanner with magnetic trackers		
Nextec (www.nextec-wiz.com)	T	CMM-based optical probe		
3D Digital Corp. (www.3ddigitalcorp.com)	T	Laser strip with optional color texture, inspection		
Perceptron (www.perceptron.com)	T	CMM or portable arm hand-held, high accuracy inspection		
Scantech (www.scantech.net)	T	Dual view triangulation, laser slit	40–400 mm	20–200 μm
Micromeasure (www.micromeasure.de)	T	Laser slit		
Roland-Picza (www.rolanddg.com)	T	Triangulation with piezo displacement		

Table 3 Continued.

Company	Type	Description	Range	Accuracy
Neptec (www.neptec.com)	T/L	Space, industrial, mining, autosynchronized laser scanning		
Steinbichler Optotechnik-Comet (www.steinbichler.de)	T	Optical tracking hand-held slit scanner	83 mm	30 μm
Wolfbeck (www.wolfbeck.com)	A	Circular aperture triangulation probe		
Dipix (www.dipix.com)	T	Online inspection food industry		
LMI Technologies (www.lmint.com)	T	Over 40 products: elect., inspection, manufacturing, forest		
Acuity Research-AR600 (www.acuityresearch.com)	T	Probe	up to 0.5 m	0.10%
Taicaan (www.taicaan.com)	T	Single probe with translation	10 mm	2 μm
Steintek-3D-SCAN (www.steintek.de)	T	Triangulation based, laser slit	100–600 mm	20–300 μm

scanners share the same optical principle and similar components (e.g., 1/2-in. CMOS detector and laser diodes). Image resolution is also relatively equivalent between two-competing systems. Accuracy and stability of a well-engineered mechanical head that uses composite material and good quality lenses rather than some inexpensive thermally unstable plastic material of a poor design is more difficult to assess. Comparing systems based solely on their

Table 4 Triangulation with pattern projection.

Company	Type	Description	Range	Accuracy
InSpeck Inc (www.inspeck.com)	P	Sinusoidal fringe pattern, head to full body scanner, color		
[TC]^2's Body Measurement Sys. (www.tc2.com)	P	White light phase measurement body scanner		2 mm
Symcad (www.symcad.com)	P	Full body scanner		
Wicks and Wilson Limited (www.wwl.co.uk)	P	White light pattern encoding, body scanner		
Virtual 3D Tech (3d.itri.org.tw)	P	Random pattern		2–20 μm
Gom (USA) (www.gom.com)	P	See capture 3-D		
Capture 3D (www.capture3d.com)	P	Fringe multiple projection system, large triangulation base	0.6–1.6 m	20–100 μm
Steinbichler Optotechnik-Comet (www.steinbichler.de)	P	Fringe projection system	35–800 mm	
Optonet (www.optonet.it)	P	Fringe pattern encoding system, configurable projection		
Eyetronics-ShapeSnatcher (www.eyetronics.com)	P	Fine grid pattern projection, handheld system for face capture		
Voxelan (www.voxelan.co.jp)	P	Multiple patterns/views		
3DMD-3Q (www.3dmd.com)	P	Random light patterns, photogrammetry, up to 144 camera		20–250 μm
Genex (www.genextech.com)	P	Structured light with random colors	35–300 mm	
EOIS (www.eois.com)	M	Now Opton Japan		10–20 μm
MiiC Opton (www.opton.co.jp)	M	Moiré projection based systems, handheld to CMM	130 mm	
3Dmetrics (www.3dmetrics.com)	P	Coded pattern, color, model creation for the Web		
ABW GmbH (www.abw-3d.de)	P	coded projection systems		
RVSI/Abante Automation (www.rvsi.com)	P	Semiconductors/elec. inspection, ultra-fast 3-D systems (MHz)		2.25 μm

Table 5 Time of flight.

Company	Type	Description	Range	Accuracy
Optech (www.optech.on.ca)	TOF	Long range laser radar	800 m	1 cm
Cyra-The Cyrax System (www.cyra.com)	TOF	High accuracy laser radar system, model and airborne	100 m	4 mm
Riegl-LMS-Z210 (www.riegl.co.at)	TOF	Time of flight system, long range	450 m	
Noptel (www.noptel.fi)	TOF	Range finders		2.5 mm
3rdTech (www.3rdtech.com)	TOF +	TOF and color texture projection	12 m	
I-Site 3D Laser Imaging (www.isite3d.com)	TOF	Riegl system		
Acuity Research-AR4000 (www.acuityresearch.com)	TOF	Optical range finder units	50 m	2.5 mm
Zoller+Froehlich GmbH (www.zofre.de)	TOF	Phase radar scanner (resolution 0.4–0.8 mm)	25–55 mm	3–5 mm
Trimble-Callidus (www.trimble.com)	TOF	Large FOV surveying system		6 mm
Mensi (www.mensi.com)	TOF	Time of flight system		
Metric Vision (www.metricvision.com)	TOF	Frequency modulated laser radar	2–24 m	50–300 μm
IQSun Gmbh, (www.iqsun.com)	TOF	Radar scanner with internal temperature drift compensation	80 m	2 mm
Bushnell (www.bushnell.com)	TOF	Point range finder for sport	3–700 m	
Basis Software Inc.-SurPhaser (www.surphaser.com)	TOF +	Phase shift detection ranging	5 m	25 μm

accuracies is also difficult, because the manufacturers will often quote partial performances of the optical head only, not the whole system (see also Sec. 2.2).

The volume of measurement of a slit scanner is relatively small compared to a single-point laser scanner (Appendix A in Sec. 5). Because of their single profile, they are usually mounted on a mechanical motion stage to scan the object and create a complete 3-D model. Different alternatives are proposed:

- CMM or portable CMM (telescopic arms) probes
- linear or rotation stages
- optical or magnetic trackers.

Cyberware was one of the first companies to offer general-purpose 3-D range sensors. Today, they are mainly recognized for their full-body scanner for anthropometric measurements. This system includes four optical heads mounted on a long vertical translation stage to scan a complete human body in less than 17 s. A separate video sensor in each scanner head acquires color. Although color registration and resolution is not as refined when compared to the color autosynchronized scanner, it is sufficient for the application. Body measurements are very popular today, as shown in the tables. Hamamatsu, for example, offers a body scanner system very similar to Cyberware.

ShapeGrabber has selected a combination of optical heads and mechanical scanning translation and rotation stages to create complete stand-alone, portable, general-purpose turnkey 3-D systems. They use different interchangeable optical heads to cover different volume configurations, each head with a built-in intrinsic calibration.

The user only needs to scan a reference calibration target array to recalibrate the system when interchanging optical heads on either linear translation stages or tripod-mounted rotation stages. This approach offers a cost-effective solution while preserving high accuracy and reliable measurements. The slit scanners are based on a combination of standard triangulation and the more robust Biris principle to provide high immunity to ambient light (see Fig. 4 and Appendix A in Sec. 5). Range accuracy between 25 μm for small volumes to 200 μm at 0.6 m are quoted.

ModelMaker from 3-D scanners also works on the principle of laser stripe triangulation. A lightweight noncontact scanning head is mounted on a portable CMM. Accuracy is not specified. Kreon manufactures similar compact triangulation heads that can be mounted on a robotic arm or CMM. A dual-view triangulation approach is used for reducing the problems associated with shadows (Fig. 3). As expected, accuracy of the probe is slightly better than single-view probes because of redundancy in the measurement. Specified accuracies for the sensor head vary between 10 and 25 μm. Many other industrial companies are offering CMM-based sensors, mostly for the automotive industry: Metris, 3D Laser Scanning, Scantech, and Perceptron, to name a few. It is important to note that the inaccuracy of the CMM is not specified and must be added to these figures.

The Comet/T-Scan system from Steinbichler is a single, relatively compact hand-held laser slit scanner. The T-Scan uses a photogrammetry-based optical tracker to compute the exact global position of the sensor head in all 6-deg of freedom.

Neptec and Mensi are the only manufacturers we are aware that offer triangulation-based systems for larger vol-
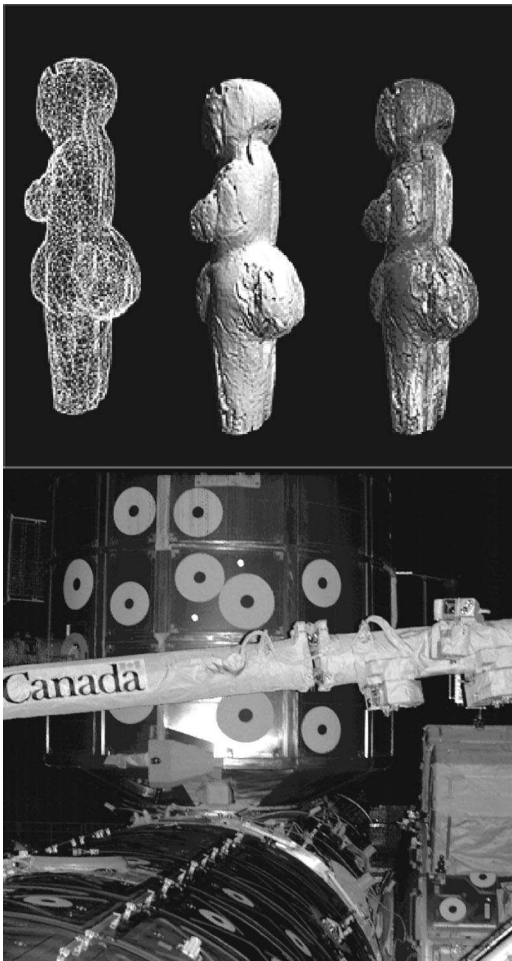
Fig. 8 Applications of 3-D sensor range from high-accuracy 3-D color imaging of inestimable historical objects to inspection of large structures in the harsh environment of space.

umes. Mensi developed a camera head that relies on a very large triangulation based d (see Appendix A in Sec. 5). The system mechanically adjusts the imaging parameters (e.g., focus) resulting in a very slow acquisition rate (100 Hz). Neptec uses the synchronized principle (Fig. 1) that allows long focal length f while preserving a large field of view and acquisition speed in the 10-kHz range. The mechanical head is much smaller, providing better mechanical stability. A lower cost commercial version of their space-qualified system is under development.

Recently, Minolta's marketing plans and aggressive prices make them an important player in the general-purpose 3-D market. Their laser scanner is also based on laser scanning. Galvanometers are used to scan a laser line over the object, removing the need for external mechanical rotation or translation stages. The optical system does not use an autosynchronized principle, and as such requires refocusing for a specific volume. A collinear color camera maps the color texture information on the geometry of the object. Only sensor resolution is quoted.

Finally, several examples of vertically integrated industrial 3-D solutions using slit scanners are commercially available. LMI also offers a wide variety of slit scanners for industrial applications. Other examples of vertically inte-

grated solutions are Dipix with products for on-line food inspection, and Servo-Robot for automatic industrial welding. In the case of GIE, a six-head 3-D system, each with a 60-deg field of view and three laser lines simultaneously produces 18 3-D profiles on the surface of a road, producing more than 23 million 3-D points per s. Real-time onboard 3-D data analysis provides dense inspection of road surfaces for vehicles traveling at speeds of 90 km/h.

3.3 Pattern Projection

Pattern projection systems offer the possibility of acquiring a full 3-D image without the need for a complex mechanical scanning apparatus (Figs. 6 and 7). Although the accuracy for an equivalent depth of view will be comparatively smaller than a slit or laser point scanner, the use of incoherent light removes the speckle noise associated with lasers, resulting in smooth data and the possibility of acquiring color texture. This method is therefore ideal for human body measurements where absolute accuracy is not as important as rapidly obtaining smooth surfaces (e.g., Inspeck, TC2, Symca, Wicks and Wilson, and 3Dmd).

For industrial inspection applications, Steinbichler Optotechnik offers the Comet/Vario Zoom that uses white light binary fringe projection added to the possibility of using accurate photogrammetric reference measurements. The fringe projection system provides data accuracy to 20 μm over a surface of approximately 45×35 mm. Range depth is not specified (see also Sec. 2.3). Optonet offers a similar single camera-projector system.

For body measurements, 3Dmetrics and Inspec use white light 3-D projection systems. 3Dmetrics uses a color-coded grid pattern, while Inspec selected a sinusoidal fringe pattern projection method. Genex uses a dual camera with a white light projector to obtain both range and color texture information at the same time. Several multihead configurations are available, from small to large volumes, that can cover the full human body. The 3D Tech system includes a stereoscopic dual-camera setup and a speckle generator. The speckle generator projects spots onto the surface of the target object, and two cameras take snapshots from their respective viewpoints. Algorithms establish the correlation of corresponding partitions on the two speckled images to compute the 3-D coordinates. The Atos system from GOM is another stereoscopic system, but fringes are projected onto the object surface, recorded by two CCD cameras.

The Cubicscope from Nagoya Institute of Technology is based on binary space encoding methods, but contrary to other systems, they use a modulated laser slit that is scanned over the surface of the object. The polygonal mirror has 12 faces and a servomotor at 1800 rpm drives it. Very fast modulation of the laser beam generates the binary pattern. Larger depth of field is possible because of the use of a laser beam at the compromise of some jitter and wobble associated with rotating mirrors.

Finally, EOIS specializes in geometrical projection moiré-type 3-D sensors with resolution typical of triangulation systems (25 μm). Because a moiré projector does not need the complexity of pattern projectors, a more compact CMM-based scanner head can be built. Range ambiguity, object surface discontinuities, and fringe counts are compensated by software.

3.4 Time-of-Flight Systems

For large structures, time-of-flight 3-D scanners are by far the preferred choice for accurate measurements at long range. Range accuracy is relatively constant for the whole volume of measurements. Many companies are offering lidar products and services for topographic surveys, for example, and they are not listed here. We have limited the list to ladar, with accuracies better than 2 cm.

Optech has been specializing in aerial topography measurements for years and have developed accurate TOF scanning systems. It was therefore a natural extension to introduce a TOF product for more general use. This system, along with the Cyra and Riegl laser scanners, are based on pulse-modulated TOF. Range resolution varies between 5 mm to 2 cm and acquisition speed from 2 to 20 kHz. Accuracy is improved by programming the scanner to average multiple measurements, or from the 3-D images. 3rd Tech couples a TOF system and a high-resolution color camera to produces textured 3-D maps of the structures. This option is also offered by I-Site. Mensi has also recently introduced a new TOF line of products. Because of the shared principle, accuracy performances between these systems are relatively similar, and differences are mostly related to engineering implementations.

Zoller's laser sensor is based on a phase difference amplitude modulation of the laser beam. The system also measures the amplitude of the received signal to create surface reflectivity maps of the object. The advantage of AM modulation is usually better range resolution (0.3 mm) and linearity (3 mm); the phase can be measured during the whole wave modulation rather than only during the edges of the pulse; and reduced requirements for the electronics (bandwidth) is obtained. Modulation, however, generates ambiguity interval problems (phase multiple of π). Multiple frequencies modulation of the light beam is used to minimize this ambiguity, but absolute maximum range is still limited when compared to pulse systems. Metric Vision with their FM modulation range finder pushes the accuracy even further with range accuracy varying from 50 to 300 μm at ranges to 25 m. The cost of the sensor is justified by the need for expensive and extremely stable mechanical components (e.g., the use of rotating motion stages with ceramic ball bearings). The bulky mechanical system is needed to provide enough thermal mass for accurate temperature control.

Surphaser proposes a principle where measurements are based on phase-shift detection ranging. The distance to a point on the object is related to the difference in phase between the laser light reflected from the target and a reference signal. Multiple frequencies are used to achieve high accuracy and to reduce interval ambiguities. Accuracy of 20 μm and volumes up to 5 m are reported.

3.5 Interferometry

The list of companies offering interferometry-based systems is obviously larger than those listed in Table 1. The ones selected here are representative of important physical principles, demonstrating that shape measurement is not limited to triangulation or TOF methods.

- Coherent holographic interferometers use light from laser sources to produce interference patterns that are due to the optical frequency phase difference in the optical paths. These interference patterns are analyzed to reconstruct the shape of the object.

- In classical holography, an interference light pattern is formed between an object beam and a reference beam using a coherent light source (laser). The two beams propagate with the same velocity, but follow different geometrical paths.

- With conoscopic holography, two beams that traverse a crystal individually but along the same path replace the two separate beams. This produces holograms with fringe periods that can be measured precisely to determine the exact distance to the point measured on the object.

Holographic interferometry is often use to visualize stress or to detect object deformations in real time. Optonor offers microscopic vibration measurement systems based on the technique of TV holography [or electronic speckle pattern interferometry (ESPI)]. Object size varies from submillimeter (microscopic system) up to several meters. Height variations down to a nanometer can be detected. Optimet and Zygo offer white light interferometers and conoscopic systems with depth resolutions in the nanometer range.

4 Conclusion

This work reviews some of the most important methods that have been developed during the past 20 years to acquire 3-D shape information. The evolution of some key technologies used to build range sensors is quickly presented, showing the trends and progress accomplished during the past two decades. Because prototype development usually takes five to ten years from the initial research laboratory to commercialization, and incremental innovations are implemented more quickly, industrial systems are a good indicative of past and current trends in the field. The work describes the most important ranging principles that are now commercially available.

Current industrial trends and research applications show that 3-D shape alone is not sufficient for a large variety of applications, and shape must be complemented with 2-D texture maps as well as with other types of sensory data. Many examples have already been demonstrated for several industrial applications (e.g., electronics, roads, forestry, and food inspection) and for the creation of 3-D models (e.g., web, museum, heritage, and architecture). The fusion of data from different sensors is today an important research topic.

5 Appendix A: Range Accuracy of Triangulation-Based System

Range sensors are optical systems and as such are limited by the laws of physics that include geometrical and diffraction optics. Assuming perfect optics, aberrations are negligible and only distortion and diffraction-limited optics remain. From Ref. 18 and from the sine law, range can be approximated using:

$$z = \frac{d \cdot f}{p + f \cdot \tan(\theta)}. \tag{1}$$

The gain of triangulation-based 3-D systems is simply

$$M_{3D} = \frac{\delta p}{\delta z} = \frac{f \cdot d}{z^2}, \tag{2}$$

where δp is the peak/pixel position accuracy that is limited by subpixel speckle noise[17] when lasers are used, or by the Rayleigh criteria[18] q in the case of pattern projection systems:

$$\delta p = \frac{1}{\sqrt{2\pi}} \cdot \lambda \cdot fn, \tag{3}$$

$$q = 1.22 \cdot \lambda \cdot fn. \tag{4}$$

Assuming a perfect lens, the Raleigh criterion indicates how well an image can be resolved. For example, with a wavelength of $\lambda = 680$ nm, a typical lens f-number of $fn = 4$, the image resolution will be $q = 4$ μm and the laser subpixel will be $\delta p = 1.4$ μm, showing that lasers are usually more accurate given the same optomechanical configuration. Using conventional geometry, the field of view of the sensor is

$$\Phi = 2 \cdot \tan^{-1}\left(\frac{P}{2 \cdot f}\right), \tag{5}$$

where f is the focal length of the lens, d is the triangulation base, and P is the dimension of the CCD. This yields to the compromise

$$M_{3D} = \frac{d \cdot P}{z^2 \cdot 2 \cdot \tan(\Phi/2)}. \tag{6}$$

To increase the accuracy of the sensor while preserving the field of view of the scanner Φ, we must either increase the triangulation base d, the dimensions of the detector P (e.g., using a linear detector), or reduce range z. From Eq. (1), the maximum and minimum range relationship is

$$\frac{1}{z_{min}} = \frac{1}{z_{max}} + \frac{P}{f \cdot d}. \tag{7}$$

Synchronization (either lateral or longitudinal) offers the advantage of simultaneously having long detectors (P) and reduced field of view (Φ), while having a small triangulation base (d).

These triangulation principles also apply to pattern projection methods with some important differences. The total depth of field of the sensor is comparatively smaller than a slit scanner; the detector is split between the simultaneous measurements. Furthermore, assuming a perfect projection system, image resolution is also limited by the Rayleigh criteria [Eq. (3)] and by poor image focus.

A confocal microscopy system provides very high magnifications M_{3D} because of very small range z (mm). The object is mechanically moved to the focus of a microscope objective. Confocal microscopes are also fast optical systems ($fn = 0.8$) and consequently low noise δp is obtained.

6 Appendix B: Accuracy of Time-of-Flight Systems

The accuracy of a time-of-flight (TOF) laser scanner is basically limited by how well the electronics can resolve time. Range is given by the roundtrip delay of light:

$$R = 0.5 \cdot c \cdot T, \tag{8}$$

$$\partial R = 0.5 \cdot c \cdot \partial T, \tag{9}$$

where c is the speed of light (3×10^8 m/s). For example, an accuracy of 1 cm requires a time resolution of 66 ps in the electronics or an equivalent bandwidth of at least 15 GHz. To reduce noise, time averaging is used, but stability, especially thermal, and nonconstant group delays are major concerns that must be automatically calibrated. Accuracy in the measurement is directly related to the amplitude of the returned signal (signal-to-noise ratio). AM modulation measures the relative phase information from the returned signal. FM modulation measures the beat frequency between the returned signal and its reference; frequency is related to range.

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