

3D sensor zoo

Species and natural habitats

▶ **Optical 3D Sensors provide a fast non-destructive possibility to obtain the three-dimensional shape of a huge variety of objects. In this paper we will give an overview of some important sensor principles and their limits as well as some critical points to pay attention to when choosing a sensor.**

Optical sensors can be used for quality control, reverse engineering, or virtual reality. Objects of art and machined objects made of metal, plastic, silicon, ceramics, or glass can be measured as well as human skin. The size of the objects can vary from microns to several meters. Depending on the size of the object, the lateral resolution can go down to the sub-micron regime. The longitudinal resolution can be in the sub-nanometer regime.

Because of the great variety of different available sensor principles, it is not easy to find the right sensor for a specific application and to use it wisely. An overview of most commonly used systems can be found in [1].

Our group at the University of Erlangen has been doing research in the field of optical 3D sensors for more than 20 years. We are not only interested in finding new principles or in optimizing existing principles but also in finding the physical and information theoretical limits for optical sensors and to make sensors that work as close as possible at those limits. This article gives an overview of sensor principles, their limits, and their possible applications. Additional information can be found in [2].

Application specifies the sensor

The sensors we present in this paper can be divided into distance measuring sensors and slope measuring sensors.

Looking closer at the working principles of the distance measuring sensors, they can all be classified into three groups: triangulation, white light interferometry on optically rough

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surfaces, and classical interferometry. The classification is based on the measurement uncertainty's dependency on the working distance.

The slope measuring sensors subdivide into two groups depending on what you measure: matt or specular surfaces.

To find the right sensor for a specific application it is not sufficient to look at the measuring uncertainty. The sensor has to work properly with the given boundary conditions. These can be the measuring time or environmental conditions.

One of the key conditions is the type of the surface. The surface can be optically smooth (e.g. mirrors, lenses or silicon wafers) with specular reflection, optically rough with diffuse reflection, or something in between. Therefore, turned or milled surfaces can be very difficult for optical sensors because they are neither optically smooth nor rough. Furthermore, we have to distinguish surface scattering (e.g. metal) or volume scattering materials, which also reflect light at layers inside the object (e.g. plastics, teeth, skin, rubber ...). In Fig. 1, you can see the com-

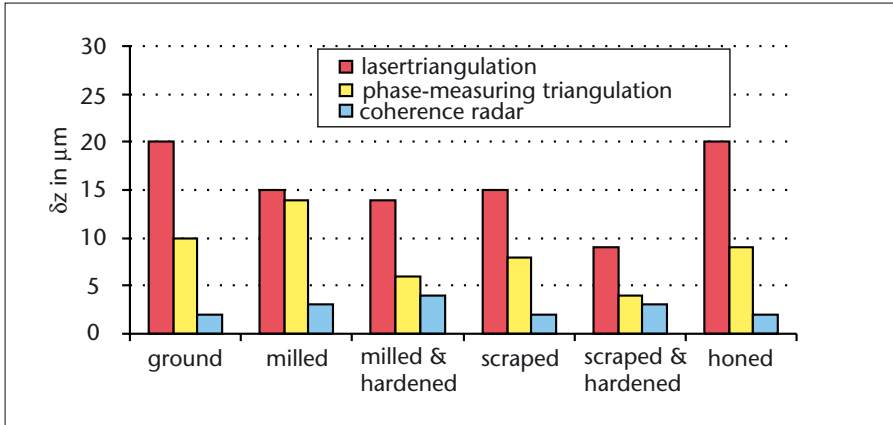


FIGURE 1: Measuring uncertainty for different sensors und surfaces.

parison of different sensor principles. Here the measurement uncertainty is plotted for three sensors and six different surfaces. When performing these tests we assured that the aperture and the working distance were comparable.

Another important criterion is the local slope of the object. Highly tilted surfaces are a problem for most optical sensors. Especially on optically smooth surfaces (but also on optically rough surfaces) the amount of light which is reflected or scattered into the pupil of the sensing system may not suffice to produce reliable measurements. Deflectometric sensors can solve this problem for optically smooth objects.

Every triangulation sensor will fail when it comes to measuring the bottom of deep

boreholes. A measurement becomes feasible with white-light interferometry because there is no angle required between illumination and observation.

In production control often the measuring time is the crucial criterion – sensors are never fast enough! There is significant room for improvement by using information theory. Most sensors acquire more raw data than necessary to solve the measuring task. This redundancy requires a big channel capacity, which is expensive and blows up the measuring time. For very fast applications, sensors with high information efficiency are required. The information efficiency can be defined as the ratio of output information to raw-data information. The efficiency is very low for the triangulation sensors and for the white-light interferometry. It is better for the fringe-projection triangulation, but it is nearly optimal for the photometric stereo sensor and deflectometry which are described below. In Fig. 2,

FIGURE 2: Summary of several criteria for different sensors

	Lasertriangulation & Autofocus	Fringe Projection	Coherence Radar	Classical Interferometry	Photogrammetric Stereo	Deflectometry
result	z(x,y) point/line	z(x,y) surface	z(x,y) surface	z(x,y) surface	grad z(x,y) surface	grad z(x,y) surface
scaling of measuring uncertainty	Cz^2 $C=1$	Cz^2 $C \sim 0.3$	independent of z	1/z	Cz^2 $C \sim 0.1$	independent of z
information efficiency	-	0	--	+	++	++
surface						
specular, flat	--	--	++	++	--	++
specular, curved	--	--	--	--	--	++
matt, lambertian	+	++	++	--	++	--
machined surfaces	0	+	++	--	+	-
tilted machined surfaces	0	0	+	--	0	-
deep boreholes	--	--	++	--	--	--
volume scatterer	-	0	0	--	0	--
measuring time	0	++	0	+	++	++

criteria for the right sensor choice are summarized. The reader will understand most of the entries by further reading the description of the different sensor principles.

Triangulation

In this group we find laser scanners, fringe projection sensors, and photogrammetric sensors, as well as auto-focus-sensors, sensors using chromatic aberration, and confocal microscopes. The measuring uncertainty δz of all these triangulation sensors scales with the quadratic working distance z from the object:

$$\delta z \sim Cz^2. \tag{1}$$

This dependency is based on coherent noise which is not limited to laser illumination. Every illumination has inevitable spatial coherence [3]. Using laser illumination the coherent noise is maximal (speckle contrast $C=1$). We can calculate the measuring uncertainty for the different triangulation sensors. Using a sensor where the object is illuminated from one direction and observed from another direction (active triangulation) or a sensor where the object is observed from different directions (passive triangulation), the measuring uncertainty depends on the triangulation angle θ between illumination and observation and on the observation aperture $\sin u_{obs}$ [4].

The measuring uncertainty for this type of sensors is

$$\delta z = C\lambda / (2\pi \sin u_{obs} \sin \theta) . \tag{2}$$

++: measurement has no restrictions
 0: suited in some cases
 --: measurement is impossible

For the autofocus sensors the triangulation angle is the aperture of the illumination and the observation. Hence, the physically limited measuring uncertainty is

$$\delta z = C\lambda / (2\pi \sin^2 u_{obs}) . \quad (3)$$

Equations (2) and (3) give the physical limit of triangulation sensors. Depending on the type of the surface the real measuring uncertainty can be higher – on milled or turned surfaces up to ten times.

Fringe projection is working with less spatial coherence than laser scanning and, hence, displays (up to five times) less measuring uncertainty under equal conditions. Therefore, the development of laser triangulation was stopped in our institute and we changed to fringe projection sensors instead which we call “phase measuring triangulation” (PMT) [5]. The sensor principle is scaleable and can be used for large objects such as car bodies and for small objects like human faces or even teeth and small mechanical parts. In Fig. 3, you can see a complete measurement of a small thread which was performed automatically.

White-light interferometry on optically rough surfaces

Classical interferometry on optically smooth surfaces has been well known for decades. It took until 1990 that interferometry on optically rough surfaces was invented. Doing interferometry on such surfaces is much more complicated: When waves are scattered on optically rough surfaces they get a random phase and intensity. We cannot observe interference fringes any more but a speckle pattern instead. Nevertheless, it is possible to create interferences in the speckles, if we satisfy special conditions, regarding the illumination and observing aperture, and the coherence length of the light source [6]. The phase in each speckle is random and contains no useful information about the object surface but we can measure the contrast of the interferences. The height of the object can be obtained with a broadband light source and a longitudinal scan. Because of the short coherence length of the light source, interferences only occur if the surface is close to the reference plane. The physical mechanism of the signal generation is completely different compared to triangulation and to classical interferometry. Following the electrical radar we called this method ‘coherence radar’ [6]. The coher-

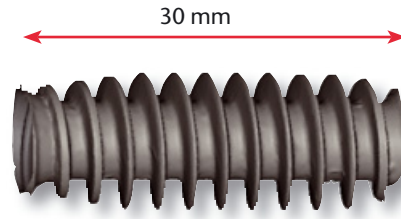


FIGURE 3: Measurement result of a thread. The measurement was performed with a sensor commercialized by 3D-Shape GmbH (www.3d-shape.com).

ence radar has a very remarkable property: The measuring uncertainty is independent of the working distance z and only depends on the roughness R_q of the object. For that reason it is possible to measure in deep boreholes without any loss of longitudinal accuracy. A major problem for white-light interferometry on optically rough surfaces is the intensity distribution of the generated speckle pattern. There are a lot of dark areas where the signal evaluation gets less precise and the measuring uncertainty increases. In the worst case it will yield outliers. Outliers will also occur on highly tilted surfaces. Figure 4 depicts the 3D view and cross section of a measured mold.

But the coherence radar is not only limited to surfaces. It is also possible to measure the optical thickness of glass, paint or other transparent layers. The micro topology of surfaces can be measured with a microscopic high-aperture setup of the system.

Deflectometry

Measuring specular free-form surfaces is a challenging task for optical metrology. Looking at a mirror, for example, you will not see the mirror itself but the mirrored image of your face. You only can see the effect a surface has on the reflected light. A tilt of the surface yields a movement of the mirrored image. To measure specular free-form surfaces we developed Phase-Measuring Deflectometry (PMD) [7]: Sinusoidal fringes are projected on a screen and observed by a camera using the specular surface under test as a mirror. As we cannot focus onto the surface and the reflected pattern at the same time, sinusoidal fringes are optimal for deflectometry – the phase does not change even if the fringes are blurred. Local variations of the surface’s gradient cause deformations of the reflected fringe pattern. Thus, compared to other optical 3D sensors, deflectometry does not measure the local height of a surface but the

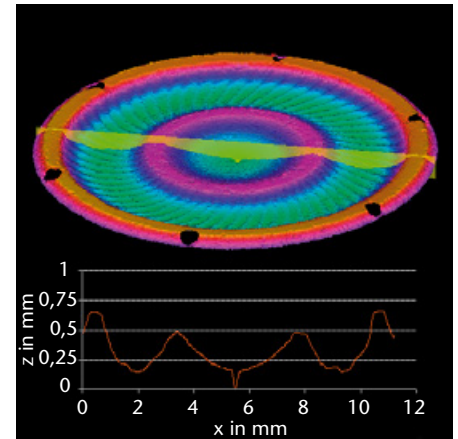


FIGURE 4: Color-coded height measurement of a mold. The measurement was performed with the coherence radar and has a longitudinal measuring uncertainty of $5 \mu\text{m}$.

local gradient.

The measuring uncertainty of the local slope $\delta\alpha$ and the lateral uncertainty δx are linked by an uncertainty relation:

$$\delta x \delta\alpha \geq \pi\lambda/Q . \quad (4)$$

The quality factor Q denotes the number of distinguishable phase steps. It can be increased by using longer exposure times and taking more images.

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The Institute is part of the University of Erlangen-Nuremberg. The University runs the Institute together with the Max Planck Society as Max Planck Research Group. Optics research has a tradition at the University of Erlangen-Nuremberg since 1974. The Center for Modern Optics, established in 2000, consolidates existing research projects and links the faculties of the natural sciences, medicine, and technology, and particularly the areas of materials science and communications engineering. As a result many synergies arise, which also benefit the Research Group which investigates basic research problems in the areas of optical metrology, light wave communications, optical materials, and optics in biology and medicine. Further information: www.optik.uni-erlangen.de

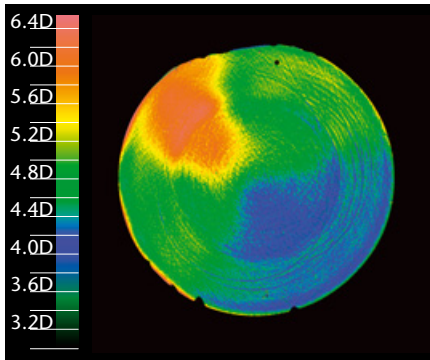


FIGURE 5: Refraction power of a progressive eye glass lens. The complete measurement just takes several seconds.

The shape of the surface can be calculated by integration of the measured slope data. From one pixel to the next the height difference is $z = \delta x \cdot \alpha$, with the pixel pitch δx . The uncertainty δz then is

$$\delta z = \delta x \delta \alpha = \text{const.} \quad (5)$$

and, thus, independent of the working distance. The reconstruction of the complete shape from gradient data in two dimensions is difficult and current research work of our group [8].

Measuring the local gradient instead of the height is very advantageous regarding information theory because the information about the working distance has not to be transferred through the channel [9]. This sensor principle has very high information efficiency and therefore needs less expensive channel capacity.

One major application is the measurement of eye glass lenses. Here, the refractive power of the surface is the main property of interest. Thus, measuring the gradient has an additional advantage compared to measuring the height: Every differentiation increases the high frequent noise. Starting with slope data, only one numerical differentiation is necessary, instead of two, to calculate the curvature.

The achieved uncertainty of the local refractive power is about 1/100 D calculated on a field of only $3 \times 3 \text{ mm}^2$. This uncertainty is equal to a height variation of 20 nm on 1.5 mm. The complete measurement of an eye-glass lens with 1000×1000 data points just takes several seconds. In Fig. 5, you can see the result of such a measurement. Note the clearly visible milling grooves.

Deflectometry is suitable for eye glass lenses and many other objects such as wafers, painted car bodies, micro lenses, wind shields, mirrors,...

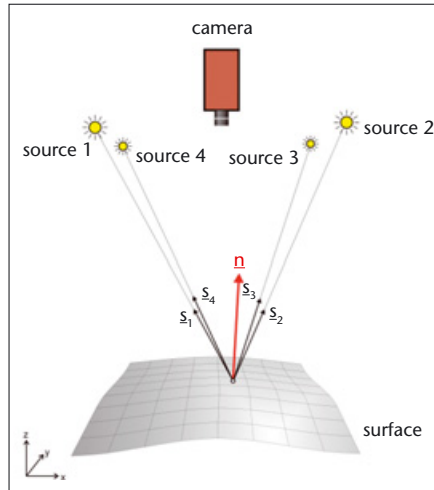


FIGURE 6: Scheme of photometric stereo. The object under test has to be illuminated from at least three directions.



FIGURE 7: Intensity-encoded slope of a flake board. The small dents are about 3 microns high.

Photometric stereo

Photometric stereo is an easy-to-use and information efficient sensor for measuring the slope of non-specular surfaces [10]. The sensor takes several images illuminated from different directions. The minimal number of different illumination directions for calculating the slope of the surface is three. With more light sources the results get more robust. A scheme of the sensor with four light sources is depicted in Fig. 6.

The angular measurement uncertainty is

$$\delta \alpha = \cotan \theta \cdot 2\pi/Q \quad (6)$$

According to triangulation, θ is the angle between illumination and observation. Q is the quality factor. According to [11], the corresponding measurement uncertainty of the integrated height then calculates to

$$\delta z = C\lambda / (2\pi \sin u_{obs} \tan \theta) \quad (7)$$

Therefore, the uncertainty also scales with the quadratic working distance:

$$\delta z \sim Cz^2 \quad (8)$$

The method is very sensitive to local slope variations. Thus, the detection of surface imperfections is a key application. In Fig. 7 you can see the slope data of a flake board. You can clearly see the small dents with a height of about 3 microns.

To get the global shape of the object the slope data have to be integrated as in deflectometry.

Testing a sensor

When testing the measuring uncertainty of a sensor we have to distinguish repeatability and reliability. A good repeatability is necessary to achieve a low measuring uncertainty but it is not sufficient. For example, a triangulation sensor can have a very high repeatability but the measured values might be equally wrong for all measurements. In this case, the measurement error is caused by the coherent noise – the reliability depends on the structure of the surface.

A simple test of the specified measuring uncertainty would be the measurement of a flat ground glass with a roughness below one micron and the measurement of a milled surface with milling grooves in the one micron range. With a good sensor the standard deviation of the results will be the same as the specified uncertainty. For this test it is important, that the data was not low pass filtered. The accuracy of the measured shape additionally depends on the calibration of the sensor and has to be tested separately.

Conclusions

Triangulation sensors have a simple technology, are easy to handle, are fast, and are cheap. Thus, they are well established in optical metrology. The measurement uncertainty strongly depends on the micro topology of the surface under test and on the observation aperture. Laser sensors display significant coherent noise.

For high accuracy in the micrometer regime, white-light interferometry is the first choice. It works as well on optically rough surfaces as on optically smooth surfaces. The measuring uncertainty depends on the roughness of the object. Though these sensors are very accurate, they often need long scanning times.

Phase-Measuring Deflectometry is the method of choice for free-form specular surfaces. It is a robust and fast principle which even can replace the more sophisticated interferometry for some applications.

For the detection of imperfections on optically rough surfaces photometric stereo should be used. Sensors based on photometric stereo can be set up cheap and, however, detect small details very fast.

To return to our title: Every species in the 3D sensor zoo has its natural habitat which means: We have to carefully select and apply the sensor, depending on the application and on the boundary conditions. This article, hopefully, helps the hunter to find the right sensor for his appetite.



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