Laser Light Section – a Key Feature in 3D Laser Measurement Technique

No-contact geometry and contour control

Light section methods are utilized as a 3D measurement technique for more than 70 years as a no-contact geometry and contour control, e.g. with the thread profile measurement using the light section microscope by Carl Zeiss developed in 1934. With the invention of the HeNe-laser more than 40 years ago, light section methods were taken from infancy.

The HeNe-laser generates a collimated beam. Introducing a round glass rod into the laser radiation, the collimated beam is in one axis fanned out into a line with gaussian intensity distribution. Meanwhile, in the industrial measurement technique diode laser based on semi conductors have replaced the HeNe-laser due to their small installation size and favorable cost-benefit ratio. Laser beam forming reshaping the collimated laser diode emission into a fanned out laser line is established in standard systems using the same principle as described above. Today, only the round glass rod was substituted by a glass- or polymeric pellet. The laser line is, using this beam shaping method, in wider the center than at the line ends. The intensity distribution is Gaussian. Aspiring a speed optimized measurement method with high resolution, this laser line characteristic is disadvantageous. Laser line generators with constant linewidth and homogenous intensity distribution increase the resolution and the capability of a laser light section sensor.

Laser line generators with these beneficial beam characteristics are developed and manufactured by Schäfter + Kirchhoff as microline or macroline generators. Accomodating to various different measurement requirements, a wide choice of products are available. 30 years of experience in laser beam shaping provide the backbone of numerous innovative laser measurement techniques for industrial, scientific and space-related deployment.

Laser Light Sectioning

The laser light section method is a 3D-procedure to measure object profiles in one sectional plane. The principle of the laser triangulation (see Fig. 1) requires an orthogonal to the objects surface positioned area camera (CCD- or CMOS-matrix) to measure the lateral displacement or the deformation of a laser line projected in an angle ALPHA onto the objects surface (see Fig. 2 and Fig. 3).

The elevation profile of interest is calculated from the deviation of the laser line from the zero position. Measuring range and resolution are determined by the triangulation angle alpha between the plane of the laserline and the optical axis of the camera (see Fig. 1). The more grazing this angle, the larger is the observed lateral displacement of the line. The measured resolution is increased, but the measured elevation range is reduced. Criteria related to objects surface characteristics, camera aperture or depth of focus and width of the laser line may reduce the achievable resolution.

Object Surface Characteristics

One requirement for the utilization of the laser light section method is an at least partial diffuse reflecting surface. An ideal mirror would not reflect any laser radiation into the camera lens and the actual reflecting position of the laser light on the object surface can not be viewed by the camera. With a complete diffuse reflecting surface the angular distribution of the reflected radiation is independent of the angle of incidence the incoming radiation hits the object under test. Real technical surfaces usually provide a mixture of diffuse and reflecting behavior. The diffuse reflected radiation is not distributed isotropical, i.e. the more grazing the incoming light arrives, the less radiation is reflected in orthogonal direction to the objects surface. Using the laser light section method, the reflection characteristics of the objects surface (depending on the submitted laser power and sensitivity of the camera) limits the achievable angle of triangulation alpha.

Fig. 1: Laser triangulation (optical scheme)
From the deviation of the laser line propagating in the angle alpha onto the objects surface the elevation of the object is determined by the point of incidence (see Fig. 2 and 3).

Fig. 2: System components for laser light section measurements
1 Object of interest (safety key)
2 and 3 Laser line generators 13LTM...
4 Additional diffuse illumination (optional)
5 Macro lens, area camera.
With the line generators 2 and 3 the different measurement ranges and resolutions are realized (21 and 31 refer to the different laser lines).

Fig. 3: Laser light sectioning
Laser light sectioning is the two-dimensional extension of the laser triangulation. With projecting the expanded laser line an elevation profile of the object under test is obtained. Insert A:
Image recorded by the area camera. The displacement of the laser line indicates the object elevation at the point of incidence.
Lens and Laser Line Requirements

To ensure a widely constant signal amplitude on the sensor, the depth of focus of the camera lens as well as the depth of focus of the laser line generator has to cover the complete measurement elevation range.

Depth of Focus of the Camera and Lens

By imaging the object under test onto the camera sensor the depth of focus of the imaging lens increases proportional to the aperture number k, the pixel distance \( \Delta y \) and quadratic to the imaging factor \( \beta \) (=field of view / sensor size).

The depth of focus 2z is calculated by:

\[
2z = 2 \Delta y k (1 + \beta)\]

In the range of \( \pm z \) around the optimum object distance no reduction in sharpness of the image is evident.

**Example:**

- Pixel distance \( \Delta y = 0.010 \text{ mm} \)
- Aperture number \( k = 8 \)
- Imaging factor \( \beta = 3 \)

\[
2z = 2 \times 0.010 \times 8 \times 3 \times (1+3) = 1.92 \text{ mm}
\]

With fixed imaging geometry a fading aperture of the lens increases its depth of focus.

A larger aperture number k cuts the signal amplitude by a factor of 2 with each aperture step, it decreases the optical resolution of the lens, and increases the negative influence of the speckle effect (see Tab. 1 or section 'laser speckle', resp.).

Camera sensors and lenses in applications with large elevation ranges are therefore usually arranged in the Scheimpflug-configuration relative to the direction of laser line propagation (details see page 4).

Even with small aperture numbers a constant signal amplitude throughout the whole measuring range can thus be ensured.

Admittedly, it has to be dispensed with a sharp image all through the objects surface.

<table>
<thead>
<tr>
<th>Aperture Number k</th>
<th>Depth of Focus (mm)</th>
<th>Optical Resolution (µm)</th>
<th>Relative Signal Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,8</td>
<td>0.7</td>
<td>31</td>
<td>100 %</td>
</tr>
<tr>
<td>4</td>
<td>1.0</td>
<td>32</td>
<td>50 %</td>
</tr>
<tr>
<td>5.6</td>
<td>1.3</td>
<td>33</td>
<td>25 %</td>
</tr>
<tr>
<td>8</td>
<td>1.9</td>
<td>36</td>
<td>12.5 %</td>
</tr>
<tr>
<td>11</td>
<td>2.6</td>
<td>40</td>
<td>6.3 %</td>
</tr>
<tr>
<td>16</td>
<td>3.8</td>
<td>49</td>
<td>3.1 %</td>
</tr>
<tr>
<td>22</td>
<td>5.3</td>
<td>62</td>
<td>1.6 %</td>
</tr>
</tbody>
</table>

Table 1: Depth of focus and resolution – The aperture number of the lens determines the depth of focus, the optical resolution, and the relative signal amplitude of the image. The listed values apply for the magnification of 1:3 and a pixel distance of 10 µm.

Depth of Focus of a Laser Line

The laser line is focussed to a fixed working distance. With actual working distances diverging from the setting the laser line widens and the power density of the radiation decreases.

The region around the nominal working distance, where linewidth does not increase by more than a factor of 1.41, is according to agreement characterized as the depth of focus of a laser line. There are two types of laser line generators (see Fig. 4).

Laser micro line generators create thin laser lines with gaussian intensity profile orthogonal to the laser line. The depth of focus of a laser line at wavelength \( \lambda \) and of width B (at 13.5%-level) is given by the so called Rayleigh Range 2z:

\[
2z_R = \frac{\pi B^2}{2 \lambda}
\]

Laser macro line generators create laser lines with increased depth of focus. At the same working distance macro laser lines are wider than micro laser lines (factor 2-5). At the same working distance, their depth of focus is enlarged by a factor of 7 to 35.

**Line Width**

Within the two design types, macro resp. micro line generator, the line width is proportional to the working distance. Due to the theoretical connection between line width and the depth of focus, the minimum line width of the laser line is limited by the application due to the required depth of focus.

- **Fig. 4:** Comparison of laser micro line and laser macro line generators.

Basic Setback: Laser Speckle

Laser speckling is an interference phenomenon, originating from the coherence of the laser radiation e.g. reflected by a rough-textured surface. Laser speckle disturbs the edge sharpness and the homogeneity of the laser lines. Orthogonal to the laser line the center of intensity is displaced stochastically.

The granularity of the speckle depends on the setting of the lens aperture viewing the object.

With a small aperture number the arising speckles have a high spatial frequency, with a large k-number the speckles are rather rough and particularly disturbing (see Fig. 5). Because a diffuse reflective and thus an optically rough-textured surface is essential for the utilization of the laser light section method (s. a.), laser speckling is not to be avoided in principle.

A reduction of the disturbing effect is possible by:

- utilizing laser beam sources with decreased coherence length (i.e. superluminescence diodes),
- a relative movement between object and sensor, possibly using an anyway necessary or existent movement of the sensor or the object (i.e. profile measurement of railroad tracks while the train is running),
- diminishing the speckle pattern by choosing large lens apertures (small aperture numbers), as long as the requirements of depth of focus is tolerating this.

**Fig. 5:** Laser light sectioning of a safety key profile – lens aperture and laser speckling

- A: imaged with small aperture number k=2.8
- B: imaged with large aperture number k=22

The aperture of the imaging lens acts as a spatial frequency filter. With small aperture numbers the speckle pattern appears to be less disturbing due to a high spatial frequency. With a large aperture number speckling introduces cuts and gabs in the contour of the line.
Dome Illuminator for Diffuse Illumination

The introduced application requires a simultaneously to the 3D profile measurement performed control of the object outline and surface. For this purpose, the object under test is illuminated homogeneously and diffuse by a dome illuminator. A LED ring lamp generates the illumination, that propagates, scattered by a diffuse reflecting cupola, to the object of interest. In the center of the dome an opening for the camera is located. There is no radiation falling onto the object from this direction. Shadow and glint is widely avoided. Because the circumstances correspond approximately to the illumination on a cloudy day, this kind of illumination is also called ‘Cloudy Day Illumination’.

Optical Engineering

Using a laser light section application with high requirements, the design of the system configuration is of great importance. This ‘optical engineering’ implies the choice and the constructive design of the utilized components like camera, lens, and laser line generator from the optical point of view. Considering the optical laws and their interactions, an optimum picture recording within the given physical boundary conditions are accomplished. Elaborate picture preprocessing algorithms are avoided.

Arranging first steps to measure objects with largely diffuse reflecting surfaces or with reduced requirements in resolution, cameras and laser line generators from the electronic mail-order catalog may be used for the first system testing (i.e. school practicum, etc.). These simple laser line generators utilize mostly a glas rod lens to produce a gaussian intensity profile along the laser line (as mentioned in the beginning).

With increased requirements, laser lines with largely constant intensity distribution and line width have to be utilized.

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Laser Line Generator 13LT...

for the 3D control of objects with small elevation profile (e.g.: safety key)

Fig. 7: The diffuse illumination enhances the contour of the safety key. X1: Contour of the laser line

Laser micro line generator 13LT...

Order-Code
13LT-165-S-1+90CM-M60-660-55-M25-P-6 for a micro line generator, wavelength 660 nm, working distance 160 mm and laser power 55 mW.

Specifications:
- Line width: ≥ 11 µm (1/e²)
- Line length: 15 mm
- Spectral range: typ. 660 nm, optional 390-1600 nm
- Laser power: up to 55 mW (660 nm)
- Integrated electronics for the laser power control
- Laser output power adjustable with potentiometer

Housing complete metal, diameter 25/28 mm

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Laser Line Generator 13LR...

for the 3D control of objects with large elevation profile (e.g.: rails)

Fig. 10: Laser line with homogeneous intensity distribution and constant line width

Specifications:
- Line width: ≥ 26 µm (1/e²)
- Line length: 26 - 3000 mm (dep. on working distance)
- Spectral range: typ. 660 nm, optional 390-1600 nm
- Laser power: up to 100 mW (660 nm)
- Integrated electronics for the laser power control
- Laser output power adjustable with potentiometer

Housing complete metal, diameter 25/28 mm

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Further information and dimensional drawings: http://www.SuKHamburg.de
Laser Light Sectioning in Scheimpflug-Configuration

With the standard imaging technique object-, lens-, and image-plane (sensor or film) are parallel. Using laser light sectioning the object-plane marked by the laser is by principle not parallel to the plane of the imaging lens. The precondition posted by Theodor Scheimpflug 1904 specifies the inclination of the image-plane (i.e. the sensor) to produce a sharp image of an inclined object-plane.

The object-plane is imaged sharply in the image-plane, if object-, image- and lens-plane intersect in the same line.

Fig. 12 shows the related constellation utilized by the laser light section method. Due to perspective distortion, a non-linear implication between elevation difference h and the peak position on the camera sensor x arises (measured each at the optical axis of the imaging lens).

It is:

\[ x = A \cdot \cos(\beta) \]
\[ \sin(\alpha) = A \cdot \cos(\beta) \cdot \cos(\alpha - \beta) \]

with:
- A: Object distance, i.e. distance between laser line and lens principal plane H
- \( \alpha \): Image distance, i.e. distance of the sensor from the lens principal plane H (each on the optical axis of the lens)
- \( \beta \): Angle between the plane of the laser line propagation and the optical axis of the imaging lens
- \( \Delta x \): Distance between the lens-plane and the sensor plane

The pixel distance \( x \) representing the elevation difference \( \Delta x \) is calculated by:

\[ x = A \cdot \cos(\beta) \sin(\alpha) \]

Optical, Optoelectronic, and Mechanical Engineering

Application: 3D measurement manipulator for the inspection and Geometry control of header in pressurized and boiling water reactors.

With the manipulator ITDM 190/33 developed by Schäfter + Kirchhoff the fully automated inspection and geometry control in contaminated areas is realized.

Measurement method: Laser light sectioning

For the upgrading of the measurement range and a high spatial resolution 2 cameras in Scheimpflug-configuration are recommended in the measuring head. Additional sensors detect the azimuth and the z-coordinate.

Fig. 13:
- Measurement head for laser light sectioning, cameras and laser line generators in Scheimpflug-configuration
- Optical section with beam redirection. The Scheimpflug-condition is realized with the arrangement of the mirror
- High spatial resolution due to the utilization of two camera systems superimposing the measuring fields.

Optical Line, Micro Focus Generators and Fiber Optic Beam Sources for Optical Measurement Techniques

For the 3D laser measuring techniques like laser light sectioning and other applications Schäfter+Kirchhoff offers a product range of laser line generators well accommodated to the requirements of the designated measurement application.

The type series of laser line identification 13LR-, 13LT- and 13LN.. feature laser lines with homogeneous intensity distribution, constant line width and nearly rectangular intensity distribution along the line. For the pointformula illumination with laser spots ≤0.001 mm laser micro focus generators are utilized. Laser beam sources with fiber connection offer all advantages of the fiber optic techniques. The emitted beam profile is rotationally symmetric with gaussian intensity distribution. Accessories like reflective and diffractive beam shaping optics for generating laser lines and grading structures are offered. Detailed informations are supplied in the .PDF data sheets on our website:

http://www.SuK Hamburg.de

Components for the 3D measuring technique following the laser light section method

Applicaton: Safety key, Fig. 2, page 1

Laser macro line generator 13LM...


CMOS camera

- Magapixel-camera with Camera-Link interface
- Photonfocus AG
- www.photonfocus.com

Dome Illuminator

- Nerlite™
- www.nerlite.com
- Distributor: Fa. SVS-Vistek
- www.svs-vistek.com

Optical Engineering

Optics for the 3D light recording and illumination techniques as well as optical instruments are developed and produced by Schäfter + Kirchhoff since more than 40 years. For external image processing we calculate and optimize the system configuration and supply components and devices like laser beam sources and CCD line scan cameras or complete system solutions.

The image of a CCD line camera is an illumination slit across the object under test. The line frequency can amount to 120 kHz.

This line scan sensor, imaging by a factor of 100 faster compared to a CCD area sensor, is thus favored for the design of fast measurement devices utilizing the laser triangulation method and numerous innovative opto-electronical measurement and sensor configurations for production and quality control.

The CCD line scan cameras by Schäfter + Kirchhoff provide a modular interface concept. They are available with the interfaces LVDS, CameraLink, and USB 2.0. Conventionally, the LVDS option is provided with the PC interface SK9192D, consisting of PCI-bus and software package SK911PC-WIN–LX including drivers for the operating systems Windows®98/2000/XP and Linux, as well as a SDK for custom development.

Further informations at our website

www.SuK Hamburg.de