Applications: Measuring and Process Control in 3D using Laser Lines, Laser Spots and Laser Patterns

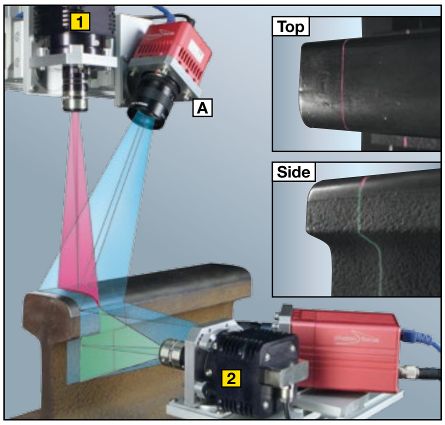

Fig. 1: 3D profiling of a railway track using laser macro line generators 13LRM-... 1 and 2

A and B CMOS matrix detection cameras

Top image of laser line 1 recorded by camera A

Side image of laser line 2 recorded by camera B

1. Using laser lines in 3D measuring applications of profile assessment

Laser light sectioning is a 3D method for determining a profile at a predefined incident section using laser triangulation (Figure 2). The imaging camera is mounted directly perpendicular to the scanned object and it measures the lateral displacement and distortion of the incident laser line projected at an angle a onto the object. The recorded camera image contains all of the height information obtained from the section defined by the incident laser beam, which is then decoded to provide the 3D height profile as the object passes through the laser line camera detection system.

The depth of the measuring area and its resolution are determined by the triangulation angle α between the planes of the dissecting laser line and the optical axis of the camera lens, with deeper angles of the dissecting incident laser line producing the greatest range in recordable height variations (Figure 3). Conversely, the resolution of that detection is increased by higher angles of incidence for the

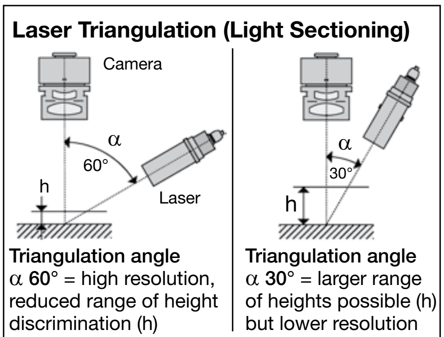

Figure 2: Laser triangulation principle
The incident angle αof the laser beam on the object to be measured determines the resolution and, conversely, the height discriminating range of the laser

dissecting laser line, as would be expected for conventional optical systems where depth of focus varies inversely with area of field or aperture size. In practice, the width and focussed depth of the laser line itself also plays a critical role. An appropriate tuning of these characteristics with the requirements of height discrimination and resolution allow a practical solution to be found for each desired application.

1.1 Surface characteristics of the object to be scanned

The surface of the object to be measured must be capable of reflecting some light for laser light sectioning to be successful [1], since a perfect mirror cannot reflect any incident light from an angled laser beam into a detecting camera.
In practice, most objects are composed of a mixture of surfaces with variably diffuse and reflective characteristics. A diffusely reflecting object produces a detectable signal essentially independent of the incident angle but generally in an anisotropic manner, with lower incident laser lines producing a lower signal for the perpendicular detector to capture. Laser output power and camera sensitivity also have an influence on the range of attainable triangulation angles a for a particular reflecting surface.

1.2 Laser line depth of focus

In order to obtain a constant signal amplitude at the sensor, the depths of focus of both the dissecting laser line and the detecting camera system must be large enough to encompass the predefined height discrimination require-ments.

A laser line is focussed at a predefined working distance from the beam source. At distances outside of this point, the laser line becomes wider and its intensity declines. The depth of focus of a particular laser line is defined as that depth in which the line width does not increase by more than a factor of 1.4. Laser line generators can be divided into two types, micro or macro, according to their line widths and applicability (Figure 4).

1.3 Laser micro line generators

Laser micro line generators produce narrow laser lines with a Gaussian intensity profile in the perpendicular direction. The depth of focus of a particular laser line with a width B (at the 13.5% level) and wavelength λ is determined as the Rayleigh area $2z_R$ where:

$$2z_R = \frac{\pi B^2}{2\lambda}.$$

1.4 Laser macro line generators

Laser macro line generators produce laser lines with an extended depth of focus $2z_M$ where:

$$2z_M = \frac{4\pi B^2}{6\lambda}.$$

For a particular line width, the depth of focus of a macro line is almost twice that of a micro line. At the same working distance, macro lines are 2 to 5-times wider and have a depth of focus 7 to 35-times larger than the equivalent micro line.

1.5 Line width

The width of the laser line does not restrict the height discriminating ability of the laser light sectioning technique. Height information is obtained from the extent of the laser line displacement using an apppropriate algorithm that is even more accurate for wider lines than thin lines. Line width is particularly important for height differences in the direction of the scanning movement, as they go undetected when they are smaller than the width of the laser line. The lowest limit of detection for a particular width B of focussed micro line at a working distance A is physically restricted according to:

$$B = \frac{4\lambda A}{\O_S \pi},$$

for a particular wavelength λ and position $\O_S$ for the line sensor optics perpendicular to the incident beam diameter.

Since there is no limiting focus threshold for a beam with a Gaussian intensity distribution, it is customary to define the line width and beam diameter at the $1/e^2$-level, at about 13.5% of the maximum intensity.

Line width increases at greater working distances and wavelengths and inversely with the beam diameter at the line sensor lens. The consequences of this inverse relationship between line width and beam diameter are often overlooked. For example, to produce a 15 µm wide laser line at a working distance of 250 mm using a 660 nm laser requires a laser beam diameter of 14 mm. Clearly, this is impossible to achieve when the original plans predetermined that the available laser mounting space could only be 12 mm.

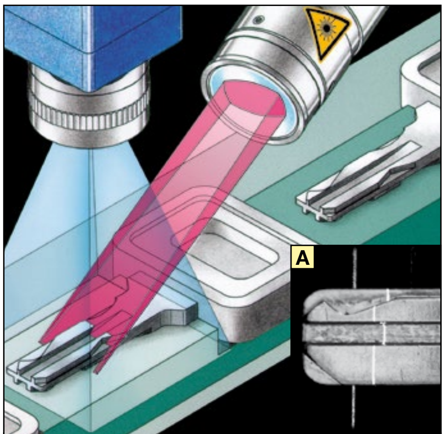

Figure 3: Laser light sectioning

is a 2D refinement of laser triangulation. The contouring or height profile of an object is provided by the degree and extent of distortion of a projected laser line.

Insert A: the image obtained from the camera. The relative displacement of the laser line provides information about the object height at that point.

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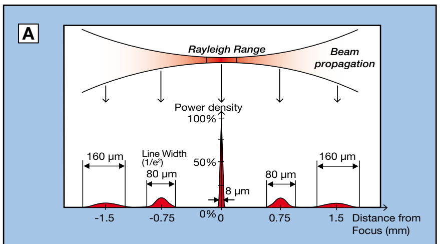
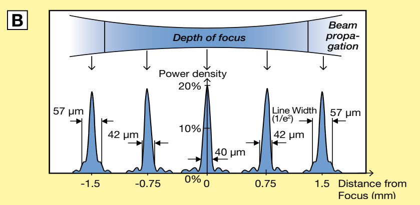


Micro line: intensity profiles and line widths for a **micro line generator:**

Higher power density and narrower lines when in focus. Line width spreading and greatly reduced power density when distance to object changes.



Macro line: intensity profiles and line widths for a **macro line generator:**

Power densities and line widths remain almost constant for a depth of focus up to 35-times greater (in comparison with micro lines, as in A).

Figure 4:
Feature comparison for micro and macro laser line generators

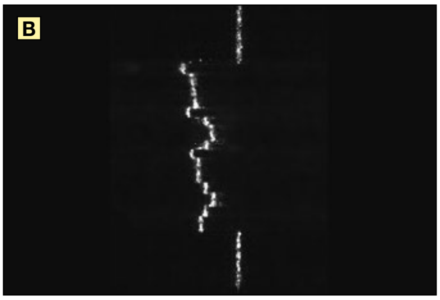


Fig. 5: Laser light sectioning of a safety key profile – lens aperture and laser speckling

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 apears 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.

1.6 Laser intensity distribution at the line detector

A laser beam impinging onto a spherical cylinder lens is perfectly transformed according to the original elliptical form produced by the laser diode. A laser line is simply a highly extended ellipse that maintains its Gaussian intensity distributiion in the direction of the beam. A camera acquisition of such a laser line reveals its elliptical heritage, with heightened brightness and greater width at the center, restricting the useful measuring region and resolution substantially.

Obviously, laser lines that have been carefully controlled to produce a constant width and a homogeneous intensity distribution improve the performance capabilities of laser light sectioning considerably.

1.7 Interference from laser speckle

Laser speckle is interference in the laser beam coherence as a result of reflection from a non-smooth object. The laser line homogeneity is disrupted because the laser beam intensity peaks are displaced laterally to the beam in a stochastic manner. Since a non-smooth surface is required for the successful application of the laser light sectioning/triangulation method (see 1.1), laser speckle cannot be avoided.

The relative contrast of the speckle patterning is a function of the coherence length of the laser source used, with more homogeneous lines achieved by using low coherence sources of the LNC-Series.

The granularity of the observed speckle is also a function of the aperture setting of the objective, with smaller coincident speckles produced at wider apertures (Figure 5a) and larger disruptive patterns at narrower apertures (Figure 5b). Ideally, using the widest objective aperture reduces interference from laser speckle to the most acceptable level.

1.8 Image acquisition techniques

The successful illumination of the whole object to be measured by a focussed laser line is only one requirement for the determination of its height profile. Of equal importance is the sharp imaging of the contoured line on the camera sensor.

The depth of sharpness of the acquired image of the measured object increases linearly with the aperture number k and the interpixel distance Δx but falls, almost quadratically, with the scale of the image β (= sensor size/image area).

For a sharpness depth of $2z_K$ then:

$$2\,z_K = 2\,\Delta x\,k\,\frac{1+\beta}{\beta^2}.$$

For working distance changes of up to $\pm\, z_K$ from the ideal position, there is no influence on the sharpness of the acquired image. As in optical systems, generally, the conventional manner of increasing the depth of height perception or range in focus is to reduce the aperture size of the objective from low to high stop sizes.

Unfortunately, for smaller apertures with an increased stop size k, the signal amplitude is reduced by a factor of 2 for each increase in stop size, with concomitant detrimental effects on the optical resolution and interference from speckle. Thus, it is recommended that applications requiring a greater range of height discrimination are better served by using a Scheimpflug configuration for the incident laser beam in relation to the camera sensor and objective.

1.9 Scheimpflug configuration

Conventional imaging assumes the parallel alignment of objective and imaging planes (sensor or film) with the object to be scanned. For laser light sectioning, the objective and scanned object are deliberately non-parallel with each other. In 1904, Theodor Scheimpflug formulated the degree to which the imaging field (e.g. the sensor) must be bent or transformed, in order to compensate for an obliquely placed object, so that a fully focussed image of the object can be produced.

The object plane is reproduced correctly in the image plane when both they and the objective all occupy the same sectional plane orientation.

Figure 6 depicts the configuration used for laser light sectioning. There is a non-linear perspective relationship between the height difference h and the peak position on the camera sensor x (when measured from the optical axis of the objective):

$$h = \frac{Ax\cos\gamma}{A'\sin\alpha - x\cos(\alpha-\gamma)}$$

A and A' are the distances of the major planes of the object and the image, relative to the objective, about the Scheimpflug angle g. The Scheimpflug configuration provides an essentially constant signal amplitude even at larger apertures (lower stop size).

The precision of the measurement is given by:

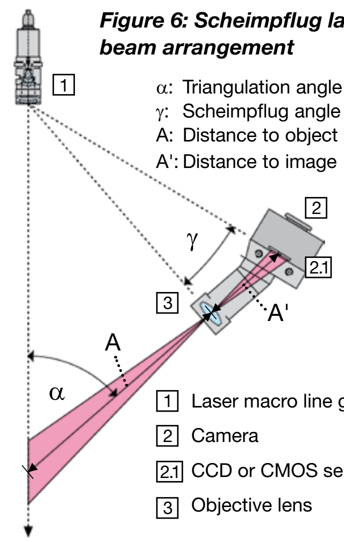
$$\Delta h = \frac{AA'x\cos\gamma\sin\alpha}{\left(A'\sin\alpha - x\cos(\alpha-\gamma)\right)^2}\Delta x$$

The change in height of Δh in the measured object results in a line image displacement with a pixel shift of Δx.

The relationship between h and Δh also pertains even when the Scheimpflug principle does not apply, so that γ is set at zero.

Figure 6: Scheimpflug laser beam arrangement

α: Triangulation angle
γ: Scheimpflug angle
A: Distance to object
A': Distance to image



1 Laser macro line generator
2 Camera
2.1 CCD or CMOS sensor
3 Objective lens

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