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 measures the lateral displacement and distortion of the incident laser line projected at an angle α 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 angles α and ξ 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 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 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 requirements. 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 2.4. 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 2zR 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 2zM 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.
1.6 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 distribution 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 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 on 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:

\[ h = \frac{A \cos \gamma}{A' \sin \alpha - \cos(\alpha - \gamma)} \]

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

The precision of the measurement is given by:

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

The change in height of \( \Delta h \) in the measured object results in a line image displacement with a pixel shift of \( \Delta x \).

The relationship between h and \( \Delta h \) also pertains even when the Scheimpflug principle does not apply, so that \( \gamma \) is set at zero.