Learned in School –
Learned for Life

Optical Metrology Basics: Triangulation

Triangulation is a trigonometric method to determine the distance between a reference point and a point of interest by aiming at the target from two different positions. In a so-called triangulation sensor this principle is put into practice and utilized for optical metrology: a laser beam is directed onto a surface at a well-defined angle of incidence, and the spot is picked up at a different angle and imaged onto a detector array [1]. Combined with a scanner or a linear drive, the complete surface of the object may be probed and can be depicted as a point cloud in three-dimensional space. This article describes the basic features of triangulation sensors.

The idea behind triangulation is quite basic, carefully planted into children at school during trigonometry lessons with more or less success, and may later on be revisited at numerous occasions if you care to watch out. With a glimpse at figure 1 you will instantly get the point. Just assume that the distance between point B and object C for some reason can not be measured directly. Instead, C is viewed from points A and B, and the angles of view with reference to a standard direction are measured. Finally, the length of the base line b must be determined, and with some trigonometry, all the angles and side-lengths of the triangle may be calculated, including the distance between B and C. This geometry is similar to the standard-stereo-configuration of

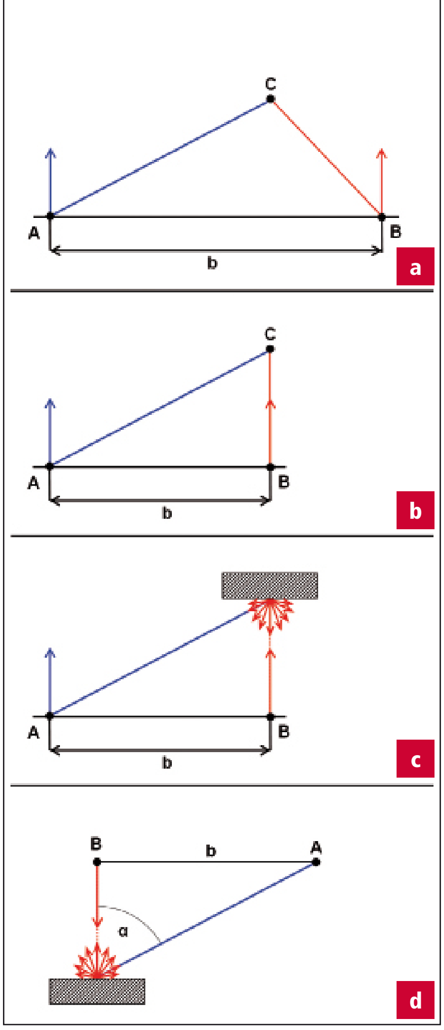

Fig. 1: The principle of triangulation

two cameras with their optical axes running parallel [2]. Figure 1b shows a special case where one line of view is along the reference direction. In a triangulation sensor, this special perspective is replaced by a laser beam shining along this line of view onto a surface. The resulting laser spot serves as the point of interest C, which is viewed from position B and appears under a certain angle. The geometry of this configuration is completely equivalent to the situation in figure 1b. Rotation by 180° results in the set-up shown in figure 1d, traditionally depicted in textbooks and articles to back up the standard-description of a triangulation sensor: a laser beam is directed onto a surface at normal incidence, and the laser spot is imaged onto the detector at the triangulation angle α.

Imaging

Figure 2 explains the optical set-up with the pick-up lens producing an image of the laser spot in the detector plane. The optical axis of the lens is aligned to intersect the surface under examination at the working distance z of the sensor. When the surface is moved along the direction of propagation of the laser beam, the distance z becoming larger or smaller, the position of the image spot in the image plane will move along the detector surface. An image-shift Δx in the detector plane is proportional to a distance-shift Δz, at least in first-order approximation:

$$\Delta x = \beta' \sin\alpha \, \Delta z$$

The magnification β' is determined by the focal length f' of the lens and by the object distance a or the image distance a', respectively:

$$\beta' = (a'/a) = f'/(a+f')$$

The main task within a triangulation sensor thus is to measure the shift Δx of the image of the laser spot in the detector plane with reference to the optical axis. A linear detector array with discrete pixels is well suited and widely used, but a position sensitive device with analog output is a reasonable alternative. The factor β' sinα is constant within a first-order approximation. Deviations from the linear relation between Δx and Δz may be determined by calibration and can be compensated during signal processing. The working range of the sensor, in other words the maximum distance-shift Δz, is limited by the maximum shift Δx of the image spot in the detector plane, which is limited by the length of the linear detector array. The depth resolution is determined by the precision of the position measurement for the image spot. For a linear detector array, one might be tempted to associate the pixel pitch with the uncertainty of the position measurement. When a spot covers several pixels, however, the centre of gravity in principle may be determined with subpixel-precision. Anyway, for a sensor equipped with 1,024 pixels in a linear detector array, a depth-resolution in the order of per mill of the working range is a good guess.

Scheimpflug Rules

When the surface of the object under examination moves along the z-direction, the image will move out of focus in the detector plane as shown in figure 2. The lens will produce a sharp image in the detector plane only for object points in an object plane which is perpendicular to the optical axis. The distance-variation Δz, however, is along the line of propagation of the laser beam, tilted with reference to the object plane of the lens-detector-compound. For a detector plane perpendicular to the optical axes, the image of the laser spot will thus immediately move out of focus and become blurred when the image of the spot shifts out of the central

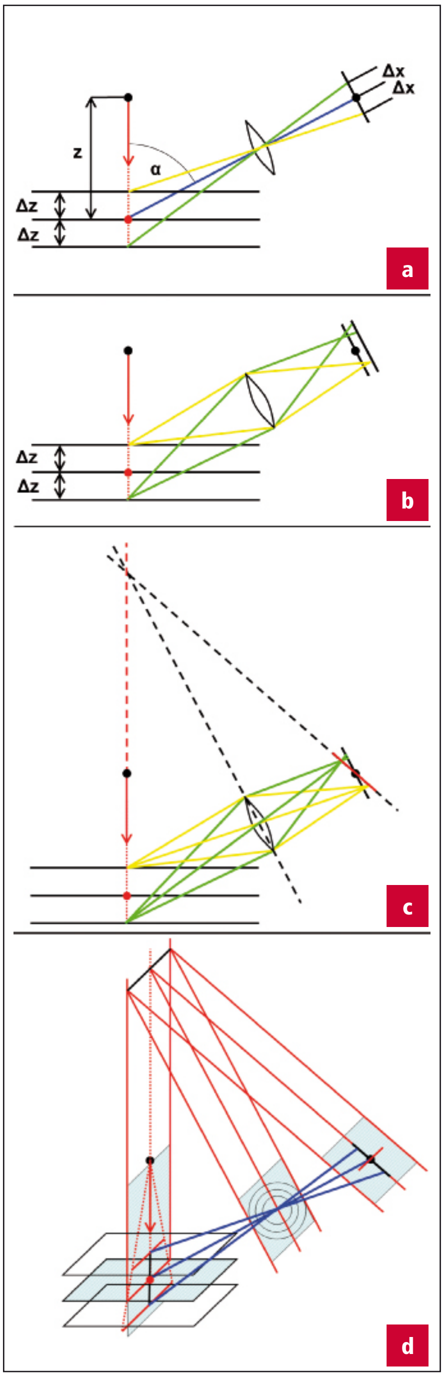

Fig. 2: Optical set-up of a triangulation device. To get a sharp image on the detector array, lens plane, object plane and image plane have to intersect in a single line (Scheimpflug's rule).

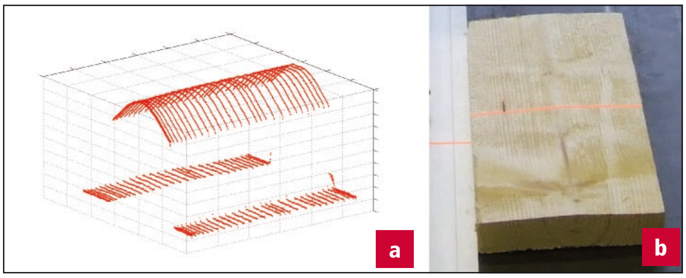

Fig. 3: A measurement with a light section sensor. The object is moved with the direction of motion perpendicular to the laser line. Stacking subsequent profiles produces a 3D-visualization of the surface as a point cloud.

position. Blurring may be compensated, however, by tilting the detector around the central point where the optical axis intersects the detector plane. The tilt-angle is determined by Scheimpflug's rule [1]: lens plane, object plane and image plane have to intersect in a single line or a single point, respectively, as shown in figures 2c and 2d. For a triangulation sensor, the object plane is defined by the laser beam, since every point which can be addressed by the laser beam within the working range should be imaged as a sharp spot onto the detector plane. This consideration easily opens up a well-known extension of the simple triangulation sensor, the light section sensor. Instead of a pencil beam, a light section device projects a laser line onto the surface of the object. Due to the surface topography, the laser line appears to be distorted when viewed at the triangulation angle by a camera with an array detector. The image of the laser line contains the distance information for every single corresponding point of the laser line on the surface of the object. The object plane in accordance with Scheimpflug's rule in this case is defined by the laser line and the direction of propagation of the central beam of the laser projection device. The object plane thus is identical with the plane of the laser light fan. Figure 3 shows an example for a measurement with a commercial light section sensor. The laser line is aligned perpendicular to the direction of motion of a conveyor belt, which moves the object through the line of sight of the sensor. For every light section the measurement results in a surface profile in the plane of the laser fan. The whole contour of the object may thus be probed slice by slice and can be depicted as a point cloud by stacking subsequent profiles.

Further Considerations

For triangulation with a device as sketched in figure 2, a target surface with diffuse reflection is required. To get a signal, the laser beam shining at the surface must in part be scattered into the aperture of the pick-up lens. Shining objects with strictly reflecting surfaces are thus not well suited for this method. The same holds true for dark areas with low remission, which will result in low image contrast and lead to problems with the precise measurement of the position of the laser spot on the detector array. For some materials, scattering does not only take place at the geometrical surface of an object. Certain plastics, e.g., are opaque due to scattering of light which has penetrated the surface and is backscattered by small particles embedded in the material like sunlight being scattered by water droplets on a misty autumn morning. Scattering efficiency may strongly depend upon wavelength. Materials which are opaque in the visible range may well be transparent in the near infrared [3]. The wavelength of the laser beam in a triangulation sensor thus must be carefully considered with regard to the application scenario. For the optical layout, it should be borne in mind that Scheimpflug's rule is just a first-order correction. A lens with strong optical distortion and prominent field curvature will result in additional blurring and further variation of the magnification along the detector array. Perspective warping due to the central projection in standard-lenses will add further problems. Reflections from the background may occasionally enter the pick-up optics, and an additional spot may appear in the image, giving rise to severe problems in discriminating between signal spot and reflection. In general, the laser spot or laser line must show a significant grey level difference to the background. In this context, image processing methods come into play. Algorithms as well as laser beam shaping can be designed to support the robust detection and processing of the laser spot in the image. In addition, optimization of the projection optics is mandatory whenever the lateral resolution limit perpendicular to the distance-shift, dictated by the laws of physics, shall be realized. Extensions of the simple light section principle are sensors based on groups of parallel lines or fringe patterns for illumination.

References

[1] A. Donges, R. Noll, Lasermesstechnik, Hüthig, Heidelberg 1993
[2] INSPECT 1/2006, Stereo-Vision, p. 18
[3] INSPECT 2/2006, NIR-Imaging, p. 14

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