Optical 3D Measurement of Scattering and Specular Reflecting Surfaces

R Tutsch$^1$, M Petz and C Keck
Institut für Produktionsmesstechnik, Technische Universität Braunschweig, Schleinitzstraße 20, 38106 Braunschweig, Germany

r.tutsch@tu-braunschweig.de

Abstract. This paper gives an introduction to the geometrical measurement of objects with scattering and specular reflecting surfaces using optical pattern projection techniques. While the measurement of scattering surfaces using structured illumination has found wide-spread application in research and industry, the raster reflection technique for specular reflecting surfaces is a new development. In both cases, predefined patterns are projected on the surface to be measured. Electronic cameras record the resulting images, which are evaluated using photogrammetric methods. The paper describes basic measurement setups, and outlines the evaluation of the measurements, together with the underlying models. Measurement examples illustrate the capabilities of both techniques.

1. Introduction
Research and industry demand geometrical measurements of object surfaces with high resolution and high precision. Most suitable for these measurement tasks are optical measurement techniques, which combine high resolution with adequate precision and high measurement rates. Moreover, optical measurements do not require mechanical contact to the measured object, making it especially suitable for the measurement of objects with low mechanical strengths.

For the precise measurement of object surfaces the structured illumination technique has found wide-spread application in research and industry. The structured illumination technique [1] is a triangulation measurement technique employing light patterns, which are projected onto the object surface. Electronic cameras record the distorted pattern, followed by a numerical evaluation of the images.

In case of specular reflecting surfaces, the distortion of the projected pattern does not only depend on the position of the surface points in space, but also on the local orientation of the surface, requiring a different approach in the form of the raster reflection measurement methods [4].

2. Structured illumination
The structured illumination technique requires optically cooperative object surfaces. Under illumination, the surfaces should produce enough scattered light to permit recording of the distorted patterns by electronic cameras, but should not directly reflect incident light. White or silvery coatings may be used to enhance the optical behaviour of the surface [2].

$^1$ To whom any correspondence should be addressed.
2.1. **Measurement setup and procedure**

For the structured illumination technique different measurement setups can be used [1]. Preferably a measurement setup according to figure 1 is used. It requires at least two electronic cameras and a single pattern projector. The cameras are placed symmetrically to the axis of the projector. The electronic cameras require calibration, while the projector should show a good short-term stability, but does not require geometrical calibration. This measurement technique is called passive structured illumination, as the projected patterns are only used to produce images and to identify points on the surface of the measured object.

If the projector has a good long-term stability, it can replace a camera. This technique is called active structured illumination, as the projector not only allows for the production of images and the identification of the surface points, but also contributes with its calibration information to the measurement result. Active structured illumination is passing out of use in industry, as it requires the calibration of the projector, which is much more difficult than the calibration of a camera, using optical plates, for instance.

2.2. **Handling projective ambiguity**

All optical measurements based on the triangulation principle have to cope with the problem of projective ambiguity, as an image recorded by the two-dimensional sensor of a camera may be associated with an infinite number of surfaces having different three-dimensional shapes. The structured illumination technique [1] employs sequences of Gray code and sinusoidal patterns, which allow for an unambiguous identification of surface points sharing the same plane in space, as shown in figure 2.

2.3. **Measurement models for structured illumination**

The measurement models for structured illumination setups are based on a pin-hole camera model [1]. Any light ray coming from the object surface passes through the perspective centre of the camera and reaches the camera image sensor, as shown in figure 3.
The so-called collinearity equations relate the coordinates \( P = (X, Y, Z)^T \) of the surface point in the three-dimensional world coordinate system and the coordinates \( P' = (x', y')^T \) of the corresponding image point in the two-dimensional image sensor coordinate system:

\[
\begin{align*}
x' &= x_0' - c \cdot \frac{r_{11} \cdot (X - X_0) + r_{21} \cdot (Y - Y_0) + r_{31} \cdot (Z - Z_0)}{\Delta x'} + \Delta x' \\
y' &= y_0' - c \cdot \frac{r_{12} \cdot (X - X_0) + r_{22} \cdot (Y - Y_0) + r_{32} \cdot (Z - Z_0)}{\Delta y'} + \Delta y'
\end{align*}
\]

The parameters of the collinearity equations can be divided into two subsets. The first subset consisting of the offset \((x_0', y_0')^T\), the camera constant \(c\) together with the optical distortions \(\Delta x(x', y')\) and \(\Delta y(x', y')\) characterises the imaging properties of a camera, the so-called inner orientation.

The second subset with the position of the camera centre \(P_0 = (X_0, Y_0, Z_0)^T\) and the direction angles \((\omega, \varphi, \kappa)^T\) define the camera's line of vision, known as outer orientation. In the collinearity equation, the direction angles appear in the form of the elements \(r_{ij}\) of the rotation matrix \(R\):

\[
R = \begin{bmatrix}
\cos \varphi \cos \kappa - \sin \varphi \sin \omega \sin \kappa & - \sin \varphi \cos \omega & \cos \varphi \sin \kappa - \sin \varphi \sin \omega \cos \kappa \\
\sin \varphi \cos \kappa - \cos \varphi \sin \omega \sin \kappa & \cos \varphi \cos \omega & \sin \varphi \sin \kappa - \cos \varphi \sin \omega \cos \kappa \\
- \cos \omega \sin \kappa & \sin \omega & \cos \omega \cos \kappa
\end{bmatrix}
\]

### 2.4. Evaluation of structured illumination measurements

In the course of the measurement evaluation, the coordinates of the points on the object surface have to be determined. The coordinates of the surface points are referenced to a predefined coordinate system, which has to be provided by the user. The evaluation involves the following steps:

- identification of the reference points in the recorded images,
- measurement of the matching points in the images recorded by the cameras,
- determination of the inner and outer orientations of all cameras,
- determination of the coordinates of points on the object surface.

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**Figure 3.** Mapping of a point on the object surface to the image sensor.

**Figure 4.** Bundle triangulation, shown for a measurement setup with four cameras.
The evaluation steps can be worked off sequentially one-by-one (sequential evaluation), in a single pass (simultaneous evaluation), or iteratively in multiple passes.

Bundle triangulation [1] evaluates the measured images (bundles of rays) in a single pass, as shown in figure 4. It uses a global numerical model to determine the inner and outer orientations as well as the coordinates of surface points by minimizing the total least-squares error of the geometrical constraints. The most important geometrical constraint is, that corresponding rays should intersect in the surface point with minimum inconsistency [1]. While bundle triangulation is an accurate and powerful method requiring only a minimum number of reference points to define the object coordinate system, it still depends on a good initial guess for all unknowns.

2.5. Measurement example

The measurement of a con-rod illustrates the capabilities of the structured illumination technique. The con-rod, shown in figure 5, is made from cast aluminium and has a length of 190 mm with a maximum width of 65 mm and a maximum height of 15 mm. In preparation of the measurement, the surface was spray-painted in order to obtain an optically cooperative surface with a silk finish. The measurement was conducted with a two-camera passive structured illumination system similar to figure 1. Measurements were made in five different positions, as the entire surface was not visible to both cameras at the same time. Circular reference marks were used to merge the results from the five different views into a single point cloud by stitching. The resulting point cloud is shown in figure 6.

![Figure 5. Con-rod as prepared for structured illumination measurement.](image1)

![Figure 6. Structured illumination measurement results for the con-rod in figure 5 after stitching.](image2)

3. Raster reflection photogrammetry

Twenty-five years ago, the raster reflection method was developed for the inspection of reflecting surfaces and for the measurement of deformations in materials testing [3]. In a raster reflection measurement, a single pattern is projected onto the surface under test, and the measurement result is determined from the deviations between the reflected image and the original pattern.

3.1. Conventional raster reflection method

The principle of this conventional raster reflection method is shown in figure 7. The surface under test reflects the reference raster onto the image plane of an electronic camera. A ray connects the measured surface element with the corresponding point of the reference pattern. Another ray runs from the surface point through the perspective centre to the image plane of the camera, which can modelled as an pin-hole imaging system with central projection. The directions of these two lines are not only determined by the position of the surface element, but also by the local slope of the surface element.
The raster reflection method also suffers from an ambiguity problem, as only a planar reference pattern is used, and infinitely many combinations of position and local slope exist for the reflecting surface element, all leading to the same observation. Three-dimensional coordinates can only be determined, if the inspected surface does not include discontinuities or has a two-dimensional character.

3.2. Active raster reflection photogrammetry
In order to overcome the ambiguity problem of conventional raster reflection methods, the active raster reflection method [4] employs at least two planar reference patterns in different distances from the reflecting surface. In practice, the two reference patterns are realised by moving a single planar pattern into different positions by a linear translation stage, thus forming a virtual three-dimensional reference structure.

As illustrated in figure 8, this arrangement allows for the point-wise measurement of absolute three-dimensional object coordinates by applying the triangulation principle. If a pinhole projection is assumed for the imaging system, the camera and the reference structure each provide two points – the image point and the perspective centre on one side and the two observed points of the reference structure on the other side – allowing the construction of two rays whose intersection defines the object point.

3.3. Passive raster reflection photogrammetry
The measurement of surface points is also possible, if the reflected raster pattern is simultaneously observed by two imaging systems with different lines of sight. This method is called passive raster reflection photogrammetry [4]. To obtain the coordinates of the surface point, the geometry of the measurement setup and the law of reflection have to be taken into account, which bring the images in both cameras into relation to each other.

The evaluation procedure, based on a pinhole camera model, is illustrated in Figure 9. One of the imaging systems, in this case camera 1, is chosen as the leading system for the evaluation process. The surface point in question lies on the straight line defined by the image point 1 and the perspective centre of camera 1. Starting with an initial guess of this surface point, the corresponding surface normal can be computed from the observation of raster point 1 and the law of reflection. In a subsequent step the quality of this estimation is tested against the observation of camera 2 by comparing the raster point that should be observed in image point 2 to the raster point that is actually observed. Using the deviation of these two points as optimisation criterion the coordinates of the surface point can be found iteratively starting with an initial guess.
3.4. Measurement of a tea spoon

As an example for an active raster reflection method, the results of a measurement of a tea spoon with a single camera are shown in figure 10. Due to the limited size of the reference raster, the tea spoon had to be measured in four different views. Additional reference targets were attached in defined positions close to the tea spoon, which were employed to reference the single measurements to a common coordinate system before merging them by stitching. The stereogrammetric measurement of the three-dimensional coordinates of these reference targets required a second camera.

4. Summary

The structured illumination technique is suitable for the high-resolution measurement of objects with volumes reaching from a few cm³ to several m³. The measurement precision of structured illumination measurements strongly depends on the optical properties of the object surface, with typical values between $10^{-4}$·$L$ and $10^{-3}$·$L$, with $L$ being the length of the longest spatial diagonal of the measurement volume. An important prerequisite is an optically cooperative scattering object surface, which must permit the recording of the distorted patterns by electronic cameras, but should not directly reflect incident light. Coatings may be used to enhance the optical behaviour of the surface. For the optical measurement of specular reflecting surfaces, the raster reflection method was developed.

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