Image based 3D inspection of surfaces and objects

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Abstract: *The shape constitutes an essential property of surfaces and objects. It can be obtained by a variety of contact-free measurement principles based on optical images. In this contribution, common and modern methods of shape measurement based on optical images, which are suitable for determining the macroscopic shape of surfaces, are presented. The characteristic properties of the measurement principles (e.g. with respect to reflectance characteristics and inspection conditions) are highlighted and compared.*

1 Introduction

Compared to usual techniques of capturing images from a scene[1], 3D inspection requires additional effort with respect to the acquisition devices and/or the acquisition time to obtain shape properties. This additional effort must be justified by the opportunity to obtain supplementary or superior information that cannot be obtained without 3D inspection. In this context, 3D inspection of scenes mainly has three objectives:

- Measurement of the physical dimensions of the scene: in this case, the task is to obtain a measurement of geometric properties of the scene, e.g. lengths, planarity, roughness etc. and a respective confidence.
- Analysis of the surface shape: the task here is to characterize the shape properties of the scene by means of methods from texture analysis (GONZALEZ & WOODS 2007, SCHAEL 2005) and pattern recognition (DUDA *et al.* 2001).
- Detection of defects: within this task, significant deviations of shape properties (e.g. geometric measures or textural properties) from a desired property must be detected.

This contribution focuses on techniques that are able to gather shape information on a scene based on optical images, which means that cameras are used for the data acquisition. The advantage of such techniques is that industrial optics has reached a considerable degree of maturity, making such inspection techniques cost-effective.

[1] A scene in this contribution is defined as the part of the real world imaged by the camera. It usually consists of the object of interest and the irrelevant background.

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2 Modeling objects and surfaces

Concerning the representation of a three dimensional object, two different models are common in the measurement community:

- 3D models: such models contain surface points, edges or planes of the object in a fully three dimensional representation. Therefore, they are able to represent all shape properties. Views and intersections can be generated, and the models can be used for all Euclidean moves (rotations, translations) without losing significance. Such models are commonly found in Computer Aided Design (CAD).
- 2.5D models (pseudo 3D, depthmaps): in this case, the information on the third dimension (the height or depth) is indicated as a function of the location, e.g. in the representation $z = f(x,y)$ with the height value z and the location coordinates (x,y). 2.5D models are not able to describe undercuts or tunnels, where more than one height value must be assigned to a location. Such models may be modified by translations without loss of significance, however, rotations are only permitted with vertical axis (x = const., y = const.).

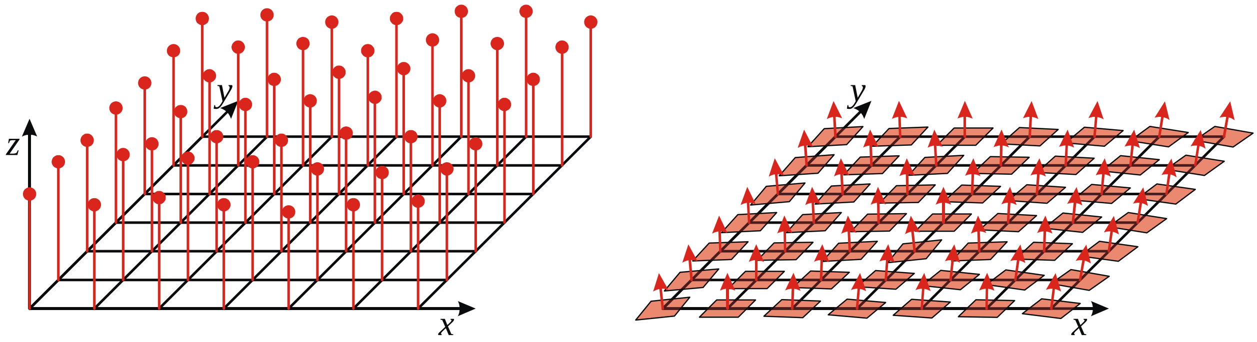

Figure 1: Comparison of two different types of shape information determined by inspection techniques: 2.5D point cloud (left) and local inclination (right)

Techniques for 3D inspection may yield to different types of shape information, see **Figure 1**. First, the information may consist in measured 3D or 2.5D points, which together form point clouds. Second, the measurement may yield the local inclination for each measuring point. Both types of shape information can be combined together with available previous information to form models on the surface to be inspected. These models can be classified with respect to the basic objects used to represent the surface:

- Vertex models: the measured points are the basic objects themselves. Information on edges, planes, or volumes is not available.
- Wireframe models: edges between measured points are the basic objects. Information on planes or volumes is not available. Such models are commonly used to give a quick overview for the display of spatial objects, e.g. for previews in real-time systems.

- Surface models: such models consist of the combination of analytical surfaces (planes, cylinders, spheres etc.) or approximating surfaces (e.g. based on splines). Visible and occluded surfaces can be distinguished; information on the volume is not available.
- Volume models: basic objects are three-dimensional bodies. The models are built by combination of fundamental bodies (e.g. in CAD) or by determination of the closed surface from surface models.

4 A classification of image based 3D inspection methods

Image based inspection methods can be divided into the methods using active and the ones using passive illumination, see **Figure 2**. The characteristic property of the previous ones is the need for an illumination device that has certain specific properties with respect to the illumination field generated by them.

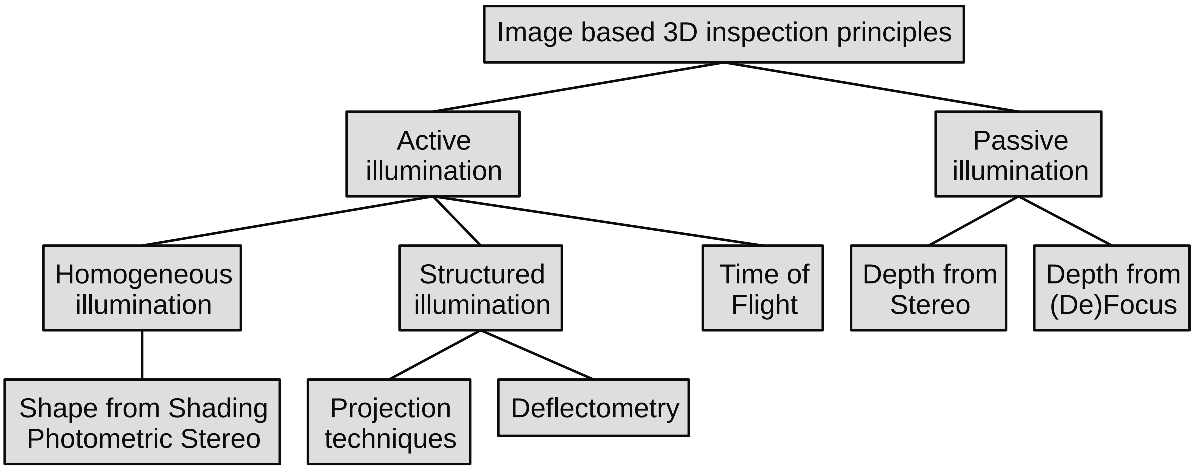

Figure 2: Classification scheme for image based 3D inspection methods

4.1 Active Illumination

The basic principle of active illumination approaches is that the shape of the surface to be inspected acts as a kind of modulation for the predefined illumination field, see **Figure 3**. The modulation result acquired by the camera is then processed in the image evaluation in order to obtain the desired quantitative (e.g. in form of a shape reconstruction or a normal field) or qualitative information (e.g. to detect defects) on the surface.

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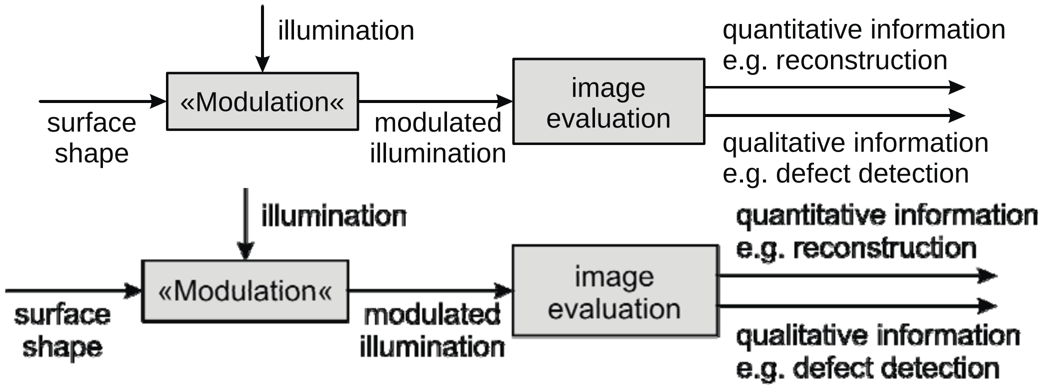

Figure 3: Inspection principle for active illumination approaches

Among the approaches using active illumination, methods of homogeneous illumination (like e.g. photometric stereo), of structured illumination (like e.g. projection methods and deflectometry), and methods based on the measurement of the time of flight can be subdivided.

4.1.1 Homogeneous illumination

Approaches using homogeneous illumination are characterized by a spatially constant illumination field, i.e. the direction, the intensity, and the spectrum of the irradiance is constant within the surface to be inspected. The major approach to use homogeneous illumination for 3D inspection is Shape from Shading (HORN 1989), where the shape information is contained in one or several observations of the surface under different homogeneous lighting directions.

A common realization is established by Photometric Stereo, where at least three illumination directions are used. The lightings can be switched subsequently in order to obtain an image series with varied illumination or applied simultaneously if lightings with distinct spectra are used. Inclined surfaces appear with different radiances that are characteristic for the respective inclination. By means of a suitable modeling of the surface reflectance, the local inclination can be obtained. As an additional outcome, the reflectance of the surface is obtained. The precondition for the applicability of the approach is that the reflectance model must be known a priori, e.g. the Lambertian model in the easiest case. In addition, the surface must not show perfectly specular reflection. Objects with volume scattering, very dark surfaces, strongly instationary reflection properties or steep slopes should be avoided.

Figure 4 shows the example of a packaging foil. Whereas in each image of the illumination series, the shape and the reflectance information are strongly coupled (left image), the photometric evaluation reveals the surface inclination and the reflectance as separated properties of the surface (right images).

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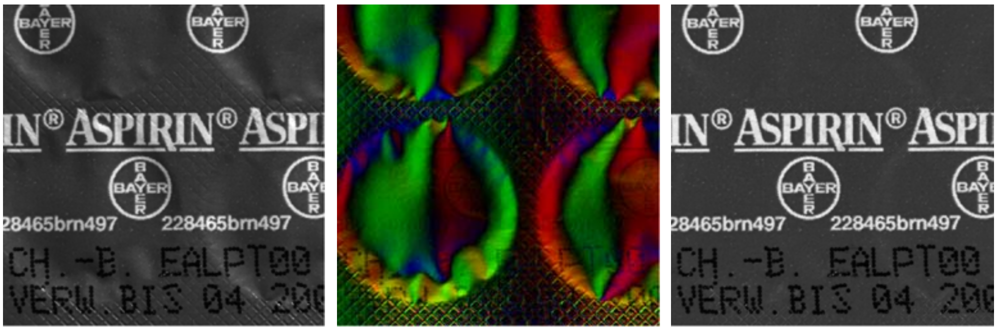

image from the series with directional lighting | surface inclination (color: azimut, intensity: polar angle) | surface reflectance

Figure 4: Photometric inspection of a packaging foil

4.1.2 Structured illumination

In the case of structured illumination, the effects of the interaction between an inhomogeneous lighting pattern and the surface shape are evaluated. An advantage of the principle is its applicability for many surfaces of practical importance, since it is independent to a large extent of the exact optical properties of the surface such as color, reflectance or scattering properties. Depending on the predominant reflectance component (diffuse or specular reflection) projection techniques and deflectometry are preferably applied, see **Figure 5**.

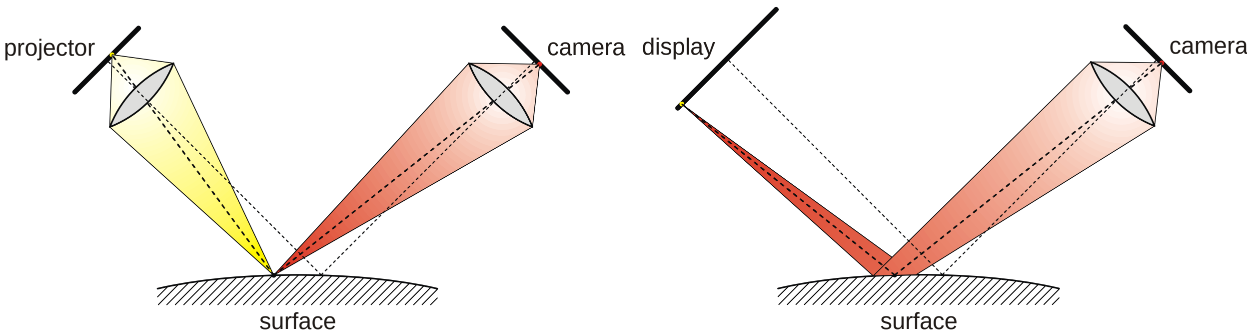

Figure 5: Principle of projection (left) and deflectometry (right)

In projection techniques, a projector (e.g. a laser or a beamer) casts a known sequence of patterns on the surface to be inspected, see **Figure 5** left. The camera receives the mapping of the projected pattern, which is deformed by the surface. The principle is based on the evaluation of the triangles which are established by the projection and the imaging of patterns on the surface. It requires that a part of the incident light is diffusely reflected, whereas the exact reflectance or color is irrelevant. As result, projection techniques provide spatial positions of surface points, which can then be combined to obtain shape information on the surface. Common realizations are laser triangulation, line scanning, and stripe projection.

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Figure 6 shows the principle of projection techniques on the example of a line scanning sensor. A line laser projects a line pattern on the surface. A matrix camera is applied as detector. Within one image of the camera, the spatial positions of surface point on a scanning line are acquired. In order to obtain information on an area, the sensor must be moved relative to the surface. That way, shape information is acquired line by line.

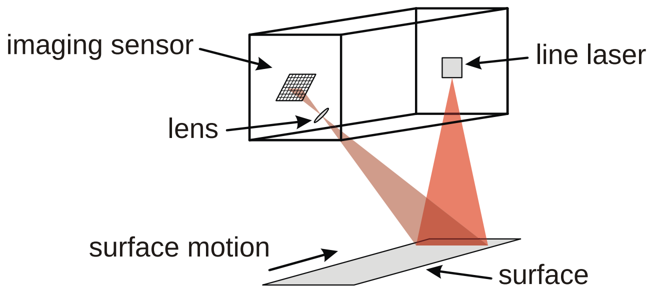

Figure 6: Inspection principle of a line scanning sensor

The principle of deflectometry can be compared to the way a human observer inspects specular surfaces: instead of looking on the surface itself, he observes the reflection of a structured environment in the surface (BALZER 2008, KAMMEL 2005, PETZ 2006), see **Figure 5** right. If the surface is not ideally even, the reflection of the environment is deformed. Thus, the surface becomes part of the imaging system. By evaluating the deformation, the human observer as well as a deflectometric inspection system obtains information on the shape of the surface in form of the local inclination.

The major precondition of the applicability of deflectometry is a significant specular reflection on the surface. If the surface shows mainly diffuse reflection (e.g. matte or rough surfaces), a transition from visual light to larger wavelengths (e.g. near infrared) can be helpful, since the portion of specular surface reflection increases with the wavelength. Moreover, objects with multiple reflections (e.g. glass plates or glass mirrors) cannot be inspected.

In contrast to projection techniques, deflectometry is sensitive to variations of the local inclination, see **Figure 7**. When the local inclination is varied, the camera observes another point on the display in a deflectometric setup (right), whereas for projection techniques, a change in the local inclination causes no direct measurement effect (left).

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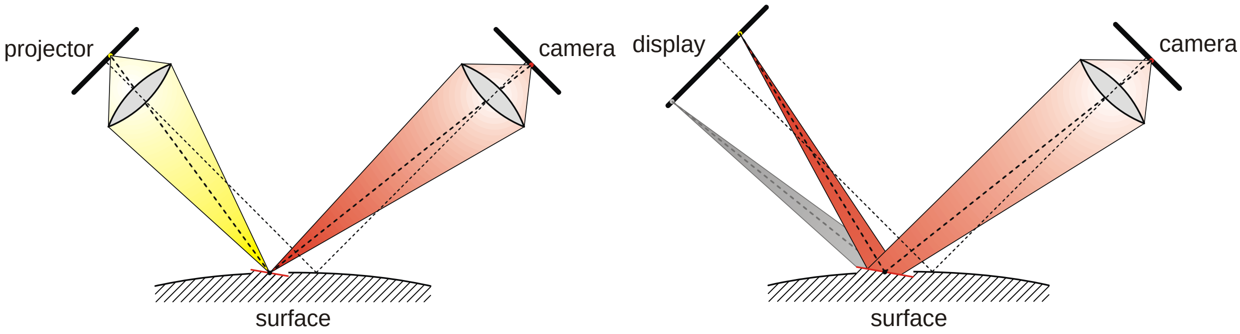

Figure 7: Measurement sensitivity of projection (left) and deflectometry (right)

4.1.3 Time-of-flight imaging

The basic principle of Time-of-Flight imaging is to determine the time that light needs to travel from a light source to the surface and back to a camera and to calculate the distance by means of the speed of light (ZHANG 2003). There are two major realizations of the principle, see Fig. 8. Within the pulse detection principle, the delay of a single reflected light pulse is detected. For the phase detection principle, the intensity of the emitted light is harmonically modulated. In the detector, the phase change of the reflected beam resulting from the distance travelled is registered, which is preferably done by means of Photonic Mixer Devices (PMD), a special sort of CMOS sensors.

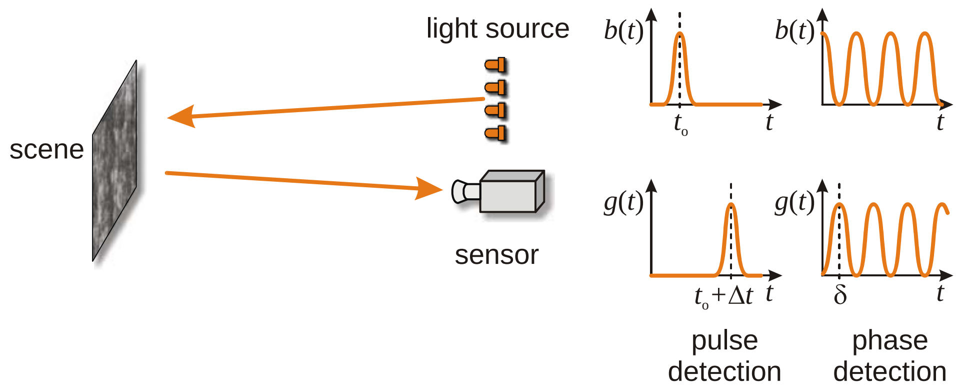

Figure 8: Measurement principles of Time-of-Flight imaging

Like projection techniques, Time-of-Flight imaging requires that a part of the light is diffusely reflected, whereas the exact reflectance is irrelevant. This measuring principle provides spatial positions of surface points. Although measuring time instead of a geometric quantity is a promising principle, it is not yet commonly used in automated inspection, which is mainly due to heavy measuring noise in the data, which up to now avoids reliable results.

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4.2 Passive illumination

Inspection principles using passive illumination only need enough light such that the camera can obtain an image. The exact property of the illumination field is not crucial. Stereo methods, which evaluate the perspective deformation of a spatial scene, and depth from (de)focus, which both use the restricted depth of field of a lens system, belong to this class.

4.2.1 Stereo imaging

The measuring principle underlying Stereo imaging is the evaluation of triangles that are present when a scene point is observed from at least two different camera positions (HARTLEY & ZISSERMAN 2008), see **Figure 9**. The different camera positions cause that the scene point is mapped onto points at different positions in the images, depending on its distance to the cameras. For a given image point in one camera, the position of the corresponding image point in the second camera varies on the epipolar line depending on the distance of the scene (blue lines in **Figure 9**). The main task in Stereo imaging is therefore to determine correct correspondences in the images on the epipolar lines. The principle requires that the scene to be observed contains distinct scene points, that the scene has a comparable appearance from all camera positions and that a large part of the light is diffusely reflected. A drawback of the principle is that its sensitivity decreases with the distance. As results, spatial positions of surface points are determined.

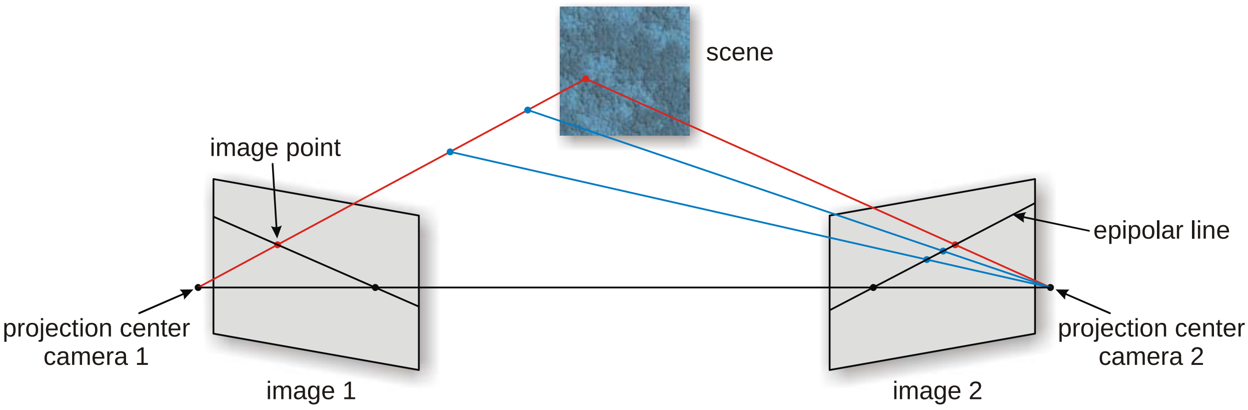

Figure 9: Measurement principle of Stereo Imaging

4.2.2 Depth from (de)focus

The principles Depth from Focus and Depth from Defocus base on the restricted depth of field of a focusing camera lens. Whereas Depth from Defocus models the blurring of the lens and determines the object distance based on this model (e.g. by using the width of blurred edges), Depth from Focus evaluates an image series that is taken while the focusing (e.g. by varying the image distance) or the object distance is changed.

Each scene location is then imaged in focus only once in the series. In order to determine the correct distance to a scene point, the parameter setting that leads to the sharp imaging of the scene point has to be identified, e.g. based on local contrast measures.

Figure 10 shows the principle of Depth from Focus by means of a firing pin print (HEIZMANN 2008): from an image series with varied object distance (left), the image with the optimal local contrast is determined and written into a map with its image number, which can be interpreted–with a proper scaling and smoothing–as depth map (middle). An additional outcome is a synthetic image with enhanced depth of field, which can be obtained by combining the focused image regions of the image series (right).

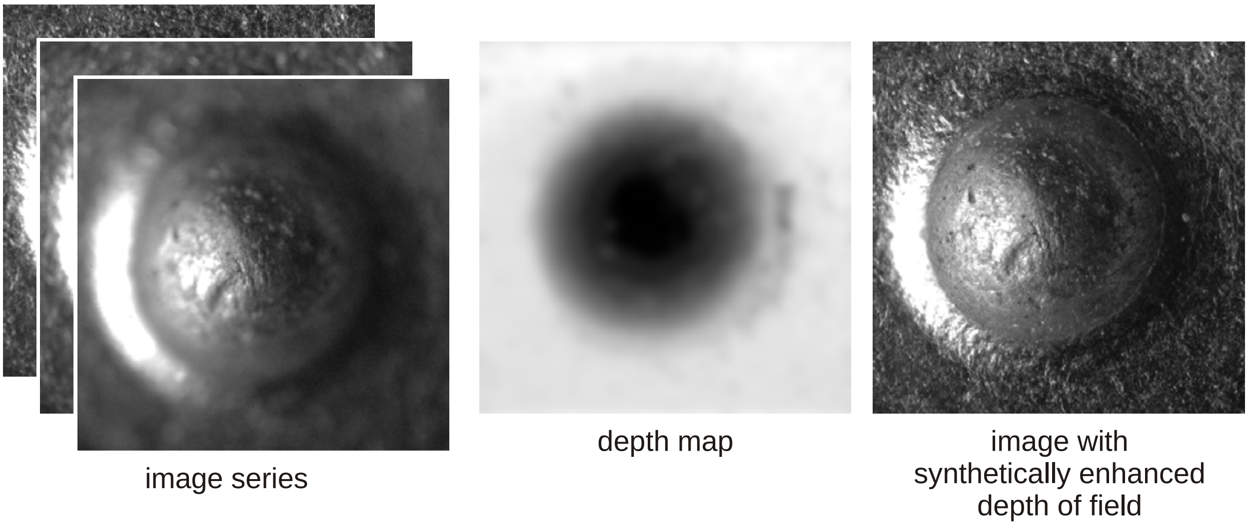

Figure 10: Depth estimation by means of Depth from Focus

5 Conclusions

To determine shape properties of surfaces and objects, numerous image based measuring principles are available. They can be distinguished on basis of the determinable surface property (point position or local inclination), the requirements for the surface properties, the environmental conditions, the sensitivity and resolution, and the time needed for the acquisition. By means of sophisticated methods from image acquisition and signal processing, powerful inspections systems are achievable, which are able to reliably represent the macroscopic properties of surface shape.

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