OPTICAL COOPERATIVITY IN REGARDS TO FRINGE PROJECTION SYSTEMS

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Wordcount: 3400
Images: 10

Keywords: optical metrology, fringe projection, light scattering, optical cooperativity

Fringe projection techniques provide an attractive areal and non-intrusive metrology system for industrial usage with a widely adaptable resolution and measurement accuracy. Fringe projection is based on the triangulation between a structured light source and the sensor. As such, it heavily depends on the characteristics of the measured surface. Different surface characteristics such as its gloss, opacity or material can facilitate or complicate optical measurement using triangulation technique. We summarize those characteristics into the term 'optical cooperativity'.

Two main surface characteristics stand out: surface gloss and subsurface scattering. Subsurface scattering causes a surface independent blur of the projected light such that the triangulation is affected. This effect can be prominently found in semitransparent material such as acrylic glass or other synthetic materials.

The main focus of optical cooperativity in the industrial field – and as related to metallic surfaces – is the glossiness of a surface, which is an issue with freshly finished industrial parts. The glossiness depends greatly on the submicrometer surface roughness and on the wavelength of the light projected and it can be affected by the anisotropic property of the metallic surface. Especially parts with complex geometries – such as gearwheels – become hard to measure when their surface is glossy.

The aim of the project 'Non-contact geometry inspection of finished rotationally symmetrical work pieces with optically non-cooperative surfaces' is to cover the term 'optical cooperativity' and to find methods to measure optically non-cooperative surfaces by either changing their respective surface characteristics or by changing the system parameters of the fringe projection system.

A change in the surface glossiness has been achieved via roughening of the surface mechanically by blasting it, chemically by etching it with various acids and electrochemically and by applying a thin quasi-lambertian layer onto it with water condensate or soot. In practice, the employed method has to be determined by the material used.

Here we give a brief overview of the different works performed within the project.

Introduction

The use of fringe projection (FP) systems in industrial application for quality control

has been on the rise. FP is a non-intrusive fast and areal surface measurement method with a high lateral density and easy scalability for geometric measurements ranging from few microns up to several meters.

At the Leibniz Universität Hannover, fringe projection systems have been successfully used within the scope of the collaborative research center (CRC) 489 “Process Chain for the Production of Precision-Forged High-Performance Components”. FP is used inside the process chain – as opposed to after the finishing process – since the material surface of the parts is ‘optically cooperative’ in regards to triangulation techniques [1]. Finished parts, on the other hand, feature non-cooperative surfaces which are hard to measure using FP systems because of the high reflectivity of the surface. The reflectivity leads to overexposed and underexposed parts of the measurement.

Though many publications notice the problem of optical cooperativity, few ever deal with solving it. Ri et al. [2] suggested a micromirror-based camera setup to extend the dynamic range of individual camera pixels. First a grey image is projected onto the surface and recorded by the camera. Bright pixels on the camera mean a high reflectivity of the corresponding surface area and a potentially overexposed pixel within the measurement, whereas dark pixels could lead to an underexposed pixel. A digital micromirror device (dmd) is positioned such that each micromirror corresponds to a pixel on the camera. By programming the inverted light intensity of the initial recording onto the dmd, the light intensities of each pixel can be normalized such as to extend their dynamic range. Though the method has been successfully used, it comes with the expense of a perfectly aligned dmd and an additional projection at the beginning of any FP measurement.

The industry-related transfer project T5 (“Non-contact geometry inspection of finished rotationally symmetrical work pieces with optically non-cooperative surfaces”) within the CRC 489 deals with measuring the surface geometry of finished parts by altering the scattering characteristic of their surface. The definition of optical cooperativity becomes crucial for the purpose of this research.

It should be noted that for different measurement methods different criteria have to be defined. Unless stated otherwise, any further mention of ‘optical cooperativity’ in this paper refers to FP.

Optical Cooperativity

FP is a triangulation technique, which relies on projected structured light being scattered at the object’s surface and recorded by an areal camera. Camera and projection device see the object surface under different viewing angles. The angle between camera axis and projector axis is called the projection angle β and is typically around 30°-45°. A bigger projection angle results in higher axial resolution but also in larger areas which cannot be measured because of shadowing effects due to the surface geometry.

The measurability of a specific material surface depends on its light scattering characteristics. FP requires the light to be scattered directly on the object surface. Subsurface scattering that may occur with opaque or semitransparent materials affects the measurement results negatively, though there have been successful measurements of translucent materials by means of polarized light [3]. Transparency is of course not the main cause of optical incooperativity in the industrial field with regards to metallic surfaces.

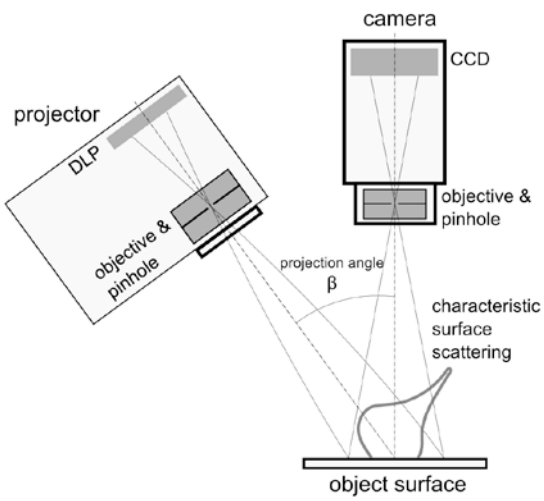

Figure 1 Areal triangulation technique

Light scattering is best described using a bidirectional reflectance distribution function (brdf), which describes the polar angle dependant hemispherical distribution of the intensity of incident light on the object's surface. Perfectly 'lambertian' surfaces describe a scattering characteristic that distributes incident light evenly over the hemisphere, whereas glossy or reflective surfaces – such as industrially finished metallic surfaces – feature a preferential reflection angle and very minimal scattering in addition to anisotropic light scattering.

To best understand the effect of different scattering characteristics on FP it is effective to adopt a model as shown in Figure 2. Starting points are the employed phase distribution Φ and the geometry that is being measured. Φ is then prepared to be projected. The function *I(*Φ*)* in Figure 2 includes both the initial modulation and phase-shifting of the phase distribution as well as the projection in form of light intensities. Typical values for Φ and I(Φ) are

$$\Phi(x_p, y_p) = p_\Phi \cdot x_p$$
$$I(\Phi) = K \cdot \cos^2(\Phi + \varphi) \qquad (1)$$

where x_p and y_p are the pixel coordinates of the projector, p_Φ is the pitch of Φ, *K* is a coefficient to expand the range to the full black-white-contrast of the projector and φ is the phase-shift used.

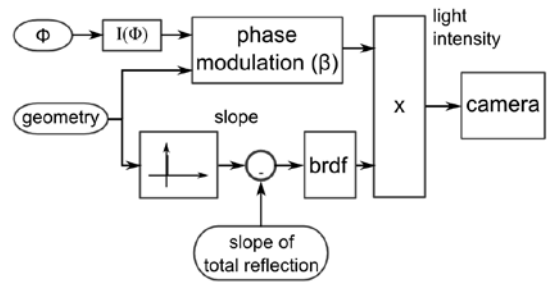

Figure 2 Diagram for areal triangulation

The projected light is then phase modulated due to the projection angle and the geometry. The reflected light depends not only on the phasemap but also on the reflection characteristics of the material. A simple way to model this is to take the slope (or measurement geometry derivative) and calculate the difference to the slope of total reflection. The slope of total reflection is the slope of the surface for which the normal vector is exactly between projection and viewing vector. For telecentric projector and camera objectives this slope is constant over the whole measurement area. Otherwise the slope of total reflection is a function of the coordinates in question.

The difference can then be used within the brdf-function to calculate the unitary reflection characteristics at a specific angle. The light intensity that reaches the camera lens can be calculated by multiplying the modulated phase with the reflection characteristics for the angle on the objects surface.

It should be pointed out that the brdf-function does not only depend on surface parameters like roughness, material and anisotropy but also on the wavelength of the light projected and its polarity. For sake of simplicity we shall ignore these

parameters here.
The light intensity that reaches the camera lens is a function of the intensity of the modulated phase distribution multiplied by the brdf-function at the specific slope of the geometry. For every point (or small area) on the surface (corresponding to a pixel on the camera chip) a maximum of light intensity can be measured:

$$I_{\max,x,y} = I_p \cdot brdf(\Theta_i, \Theta_s) \qquad (2)$$

$I_{max,x,y}$ is the maximum light intensity reaching the pixel with the coordinates x and y. Θ_i and Θ_s are the incident and scattering angles compared to the surface normal.
Inside the camera, the light intensity (or more precisely the amount of photons n_p that arrive at the chip within the shutter time) is translated to an electric current (number of electrons n_e). Digital cameras also show dark noise, which is a small current, observed even if no photons fall unto the chip. The dark noise is mainly dependant on the temperature at the chip.

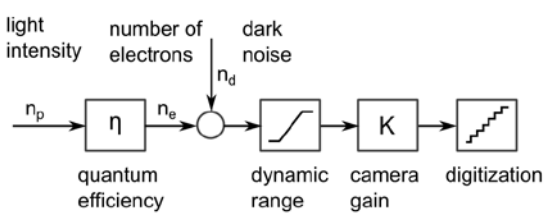

Figure 3 Diagram of light translation to digital value [4]

The camera gain and digitization actually translate the electric charge into a digital number but before that there is a very important saturation step. The sum of electrons storable in one pixel is limited. Any additional electrons are 'spilled' over to neighboring pixels (depending on which chip technology is used). This means that there is a maximum amount of photons that can hit a pixel before that pixel goes into saturation. On the other hand, only a number of electrons greater than the dark noise resulting from random electron discharge due to the surrounding temperature can be considered for evaluation. The dynamic range of the chip can be calculated using equation (3).

$$DYN = \frac{\mu_{p,sat}}{\mu_{p,\min}} = \frac{\mu_{e,sat}}{\mu_{d0}} \qquad (3)$$

Where DYN is the dynamic range of one pixel, $\mu_{p,sat}$ is the mean number of photons collected if the camera is saturated and $\mu_{p,min}$ is the absolute sensitivity threshold (i.e. the mean minimum amount of photons needed so that the charge of a pixel can be recognized). Equally $\mu_{e,sat}$ is the saturation capacity of one pixel and μ_{d0} the mean number of dark current electrons. As long as the maximum and minimum values of $I_{max,x,y}$ for all pixel tuples (x,y) lie inside the dynamic range of the camera chip, all pixels exhibit a valid value above 0 and are not saturated. Therefore a surface is optically cooperative with regards to FP systems if one can find a set of parameters (light intensity, camera shutter and gain) for which no pixel is oversaturated and all points feature a satisfactory amount of contrast.

Measurement Setup

Reflective surfaces would be no problem for triangulation techniques, if the surface geometry in question was as simple as a plane. In this case the light intensity, camera shutter, gain, and the viewing and projection angles have to be accordingly adjusted. Technical surfaces of finished parts such as gears or synchronization sleeves feature very complex surfaces that include different surface slopes and curvatures. In this case, high values of the surface reflection are recorded from specific surface slopes near to total

reflection conditions as well as low-intensity scattered light from other slopes. In this case it is hard to set the camera and projector parameters to fit all intensities into the dynamic range of the camera.

In the case of low gain, only small areas of the surface are visible under conditions of total reflection. All other areas won't generate enough contrast to be measureable. If the camera gain is increased the intensity of the light peaks mentioned before will increase to the point of saturation and will become not measurable. In this case normal ccd-chips exhibit a blooming-effect where oversaturated pixels 'spill' their electric charge to neighboring pixels, thus making their signals unusable. Accordingly, the area that cannot be measured is larger than simply the spots where the surface slope results in a surface normal lying exactly between the incident light vector and the viewing angle.

In the past we have suggested an easy measurement setup to determine the optical cooperativity of a cylindrical sample [5]. It records the light intensity of different slopes using the triangulation angle in one image. Since the maximum scattering intensity of rather reflective surfaces usually lies in the direction of total reflection, it is also possible to only measure two surface slopes, as shown in Figure 4.

Using this setup a recording includes both the highest and a realistically low scattering intensity. We used different camera and projector parameters to shift the light intensity range of the triangulation setup.

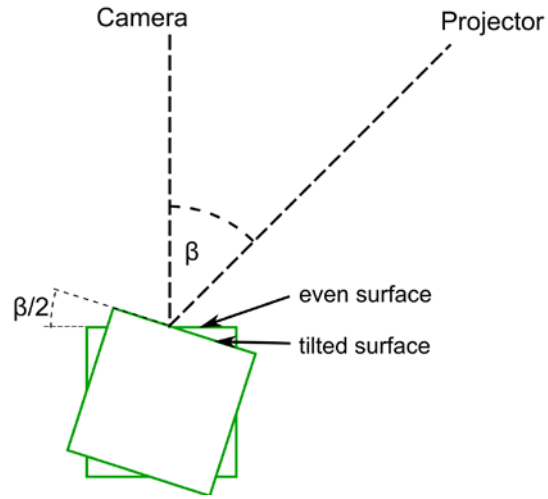

Figure 4 Test of optical cooperativity - setup

The expected results are shown in Figure 5. The chart shows two line graphs contrasting the percentage of measurable points (i.e. exhibit enough contrast and are not saturated) on the even and the tilted surface for different light intensities. The tilted surface is expected to be fully visible for low light intensities and gets saturated with higher intensities. The even surface on the other hand is expected to exhibit low contrast for low light intensities and becomes more visible with higher intensities. The range of light intensity for which both surfaces exhibit a visibility that is beyond a threshold value p_{th} can be used to measure the optical cooperativity of the surface.

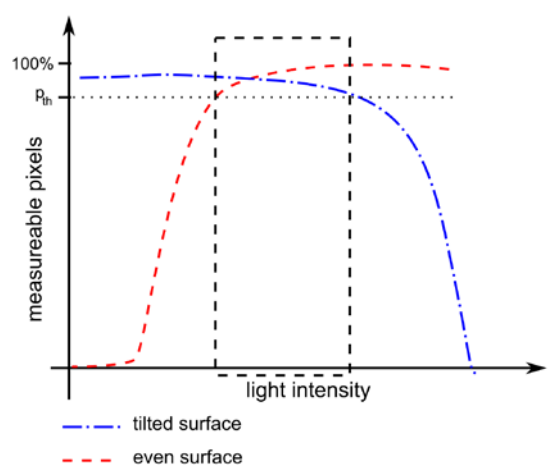

Figure 5 Test of optical cooperativity - expected result

Optical Cooperativity and surface topography

A correlation between the surface topography and the light scattering characteristics of the surface is suggested in numerous references [6]. For smooth surfaces (according to the Rayleigh smooth-surface criterion) a correlation between the brdf-function and the power spectral density of the surface topography is reciprocal. Still, for rough surfaces it should be possible to estimate the brdf out of the power spectral density.

We used the c++ library SCATMECH [7] and the corresponding software "Modeled integrated scatter tool" (MIST) to estimate the brdf of different surfaces. We measured the surface topography using a tactile roughness measurement instrument. The psd is defined as the Fourier transform of the autocorrelation function of a signal.

$$PSD(f) = \int R(\tau) \cdot e^{-2\pi i f \tau} d\tau \qquad (4)$$

where $R()$ is the autocorrelation function.

In MIST we used the Microroughness_BRDF_Model, which expects the psd either in form of a parameterized function or a table. We used the psds of untreated polished surfaces and those of treated surfaces (see below).

The initial output of the program is a brdf function for a fixed incident angle and a variable scattering angle. Again, the aim is to see whether maximum and minimum scatter within a predefined range fits within the dynamic range of the camera.

Surface Treatment Methods

Within the project different surface treatment methods have been used to create optically cooperative surfaces. Table 1 depicts the treatment methods with their respective parameters. Generally speaking, we used mechanical, chemical, electrochemical and physical surface treatment methods.

Treatment method	**Parameters**
Blasting with fused alumina EKF1000	3-6 bar blasting pressure, 5-20s
PVD etching with argon/nitrogen plasma	2.5 h, HF power 700-1400 W
Etching in H_2SO_4 (20 %wt)	1-15 minutes
Electrochemically etching in H_2SO_4 (20 %wt)	1-5 minutes, 1-2 A/dm^2 anodic
Electrochemically etching in 1-M HCl	1-5 minutes, 1-2 A/dm^2 anodic
Chemically copper-plating	1h, various additives

Table 1 Surface treatment methods used

It should be noted that all implemented methods in this context are abrasive methods which erode part of the surface and therefore have to be considered individually for each industrial use case. Further methods exist, which put a thin layer on top of the surface. We shall confine ourselves here to the methods listed above.

Results

We used a fringe projection system and the surface setup shown in figure 4 to determine the amount of measureable pixels on the surface. Beforehand we measured the range of light intensities that can be produced with the projector with a luminance meter. Figure 6 illustrates a typical result. The two red circles denote the surfaces – the upper one being the even one, whereas the lower one is the tilted surface. The measurement is taken using a relatively low light intensity. The light intensity reflected from the even surface is obviously below the temporal dark noise of the camera.

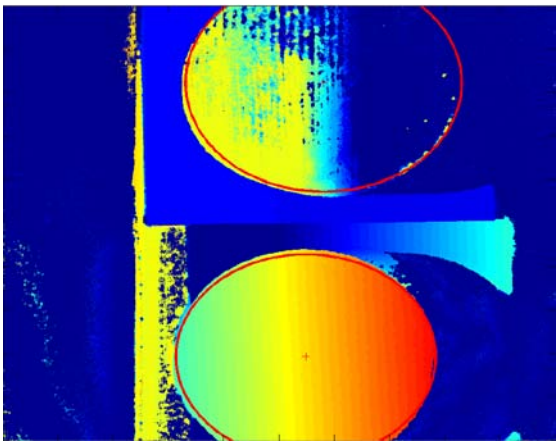

Figure 6 fringe projection measurement of tilted and even surface

After fitting a plane to the pixels of each surface, the pixels are filtered according to their respective distance to that surface. The percentage of measureable surface points is evaluated in relation to the number of pixels inside the red surface area. Then this percentage is contrasted to the light intensity used for the measurement.

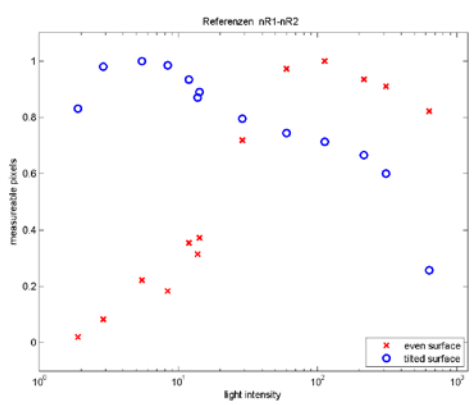

Figure 7 Measureable pixels in relation to light intensity

Figure 7 shows a typical measurability curve for polished and optically uncooperative surfaces. The blue circles denote the visibility percentage of the tilted surface as a function of the relative light intensity used for the projector. Accordingly, the red crosses represent the visibility of the even surface as a function of the light intensity. As expected the tilted surface is measureable for a small low range between 2 and 7 lux, whereas the even surface is only measurable around 100 lux. There is no light intensity range where both surfaces are fully measureable.
In contrast, Figure 8 illustrates the measurability curves for a surface that has been blasted for 10 s with a pressure of 6 bar and from a distance of 5 cm.

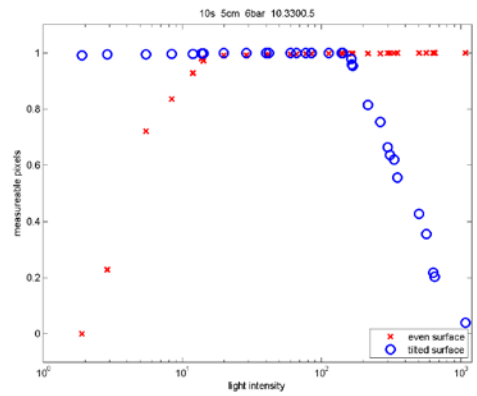

Figure 8 Blasted surfaces feature a wide light intensity range in which they are fully measureable

Between the light intensities of 10 lux and 100 lux both surfaces are fully measurable. The specifications of the camera used for the fringe projection system are found in Table 2.

Temporal Dark Noise μ_{d0} [e^-]	17 (1.5)
Saturation Capacity $\mu_{e,sat}$ [e^-]	13,000 (300)
Absolute Sensitivity Threshold $\mu_{p,min}$ [$p^{\sim}$]	26

Table 2 Specification Data of fps-camera (Basler scA1400-30gm). Values in brackets represent the standard deviation

The dynamic range can be calculated using equation (3). Factoring in the standard deviations the dynamic range of the camera reaches a value of 680.
We look at the scattering estimations given by the software MIST. Figure 9 and Figure 10 show the brdfs for the polished and blasted surface respectively.
The ratio between maximum and minimum light intensity for the polished

surface of over 710 is clearly outside the dynamic range of the camera.

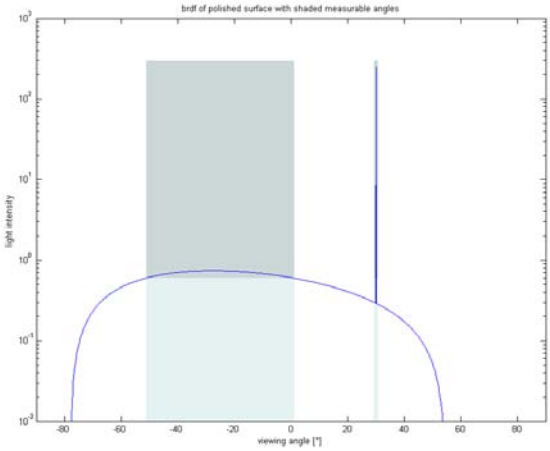

Figure 9 Scattering estimation for polished surface

On the other hand, the scattering characteristics of the blasted surface (10 s, 5 cm, 6 bar) shows a ratio of only 35, which means, that it is rather easy to set up projection and camera parameters to include the intensity range of the surface scattering within the dynamic range of the camera.

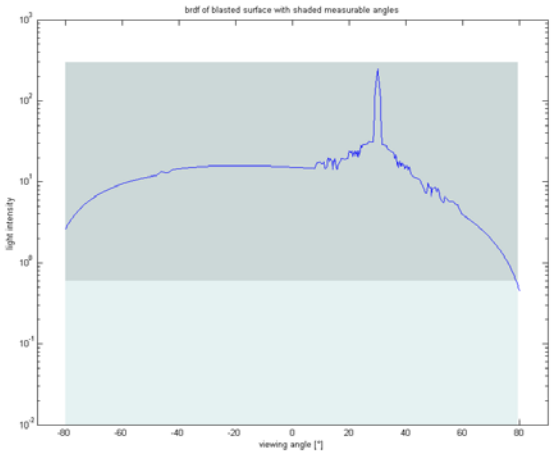

Figure 10 Scattering estimation for blasted surface

The scattering estimations depend on the wavelength of the light used. For our simulations we used a wavelength of λ=532nm.

Summary and Conclusion

The need for a definition of optical cooperativity with regards to fringe projection systems is industrially mandated. We have shown that the main problem with measuring industrially finished parts with triangulation techniques is the reflectivity of the surface. A scale for the optical cooperativity of a surface can be found either by optical measurement of the reflectivity or by measuring the surface topography and simulating the bidirectional reflectance distribution function of the surface. A correlation of the those two measurement methods is in work.

Though selecting a camera with a wide dynamic range for the fringe projection system enables measuring a wider range of surfaces, sometimes it is necessary to change the surface characteristics of the part as to make it optically more cooperative.

Further research is needed to investigate further surface treatment methods and their effectiveness with different materials and finishing processes. This includes also methods that overlay the surface with an optically cooperative layer.

Acknowledgement

The authors would like to thank the German Research Foundation (DFG) for funding the project T5 “Non-contact geometry inspection of finished rotationally symmetrical work pieces with optically non-cooperative surfaces” within the CRC 489.

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