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COMBINED OPTICAL SENSOR FOR 3D GEOMETRY AND ROUGHNESS MEASUREMENT

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ABSTRACT

Manufacturing functional relevant mechanical parts with high surface quality is time consuming, resource intensive, and therefore, expensive. Thus, the optimization of the manufacturing process as well as its control is crucial. Examples of application reach from transmission of force and torque in bearings and guide over sliding parts of gears to engine and generator parts. Their behavior is influenced by the form and surface micro structure of the functional surfaces.
The paper presents a new combined optical sensor which can be used to measure micro structures in areas of 1 x 1 mm² up to 10 x 10 mm² with highest resolution. It combines a fringe projection 3D geometry sensor with a 3D surface roughness sensor. This new combined optical sensor enables roughness measurement on grinded metal surfaces. Furthermore, the combined sensor is designed so that both sensors measure on the same position. Thus, it is possible to measure functional surfaces with one setup. Because of its compact and robust design, the combined sensor can be integrated in the manufacturing machine. In the present paper, the function and design of the combined optical sensor is described. Measurements on samples with different materials, geometry, and surface roughness show the potential of the combined sensor.

Index Terms – optical sensor, 3D geometrical measurement, roughness measurement

1. INTRODUCTION

In a broad range of applications, especially in the automotive sector, in wind power drives, or power generators, optimal functional surfaces typically lead to less friction and lower wear. Thus, they can help to reduce energy consumption or dissipation as well as friction induced vibrations and defects in mechanical systems.
A direct integration of 3D geometry and roughness measurements in the manufacturing process is important because it will improve time, energy, and resource efficiency significantly. Furthermore, the integration leads to more knowledge about the process and its parameters. Thus, wear or failures on tools can be identified before defect parts are produced. But it is also possible to reduce manufacturing steps because each step can be improved itself. Using a manufacturing integrated measurement system also reduces setup time while parts need not to be changed in its position.
The most imported requirement on manufacturing process integrated measurement technology is the measurement speed. This is the major advantage of optical measurement principles

compared to standard tactile measurement methods for 3D geometry and roughness. Therefore, more information about the object to be measured can be generated. Another very imported aspect is the increasing miniaturization which leads to continuously smaller roughness, especially on metallic surfaces. Typical roughness values R_a for these applications are between 0.1 µm and 5 µm. Such surfaces could not be measured with standard tactile measurement sensors. Therefore, the aim is to use optical measurement technologies for 3D geometry and roughness.

Optical 3D geometry characterization can be realized by using pattern or fringe projection, 3D scanners based on triangulation, stereo camera systems. Several systems are commercially available especially for measurement areas of 100 x 100 mm² or more. But in a broad range of applications smaller measurement areas are necessary to achieve the required accuracy of a few microns.

Today, optical roughness measurement is limited to polished plain surfaces (rms 0.2…30 nm) and often uses only 2D scattering profiles. Therefore, it is required to combine different optical measurement technologies for roughness measurement on curved surfaces and for different materials.

2. COMBINED OPTICAL SENSOR SYSTEM

2.1 Goal

The sensor realizes the possibility to obtain light scattering measurements and 3D surface measurements of an object from the same position without any movement of the sensor or the measurement object. This is the main advantage of the combined optical sensor system in comparison to two separate sensor systems. Therefore, the complete measuring time can be reduced significantly.

The knowledge of the geometric shape of the object's surface may improve the measurement accuracy of the light scattering measurement.

Because the surface of objects is usually not measured tactilly, a contactless measurement technique should be used in order to obtain the objects topography. The fringe projection method is such a technique. The surface geometry data are obtained automatically and may support the light scattering measurement. So it becomes possible to perform light scattering measurements on curved surfaces, too.

2.2 Arrangement

The main challenge for the realization of the same measurement position is the mechanic size of the sensors: two sensors cannot be arranged exactly at the same position. So the classical geometries of both systems were redesigned. The main novelty of the development was an interlacing of the light scattering sensor and the 3D surface sensor.

In order to make the system attractive for industrial applications, it is necessary to fix the measurement system in different orientations. Additionally, the absolute orientations should be free and to be selected by the user. In order to satisfy these conditions, it was necessary to build up the system using composite materials which are both lightweight and stable.

Finally, the sensor system was realized as a combined light scattering and 3D surface measuring fringe projection sensor with different measurement field sizes shown in Figure 1 and integrated in an optical measuring machine shown in Figure 8.

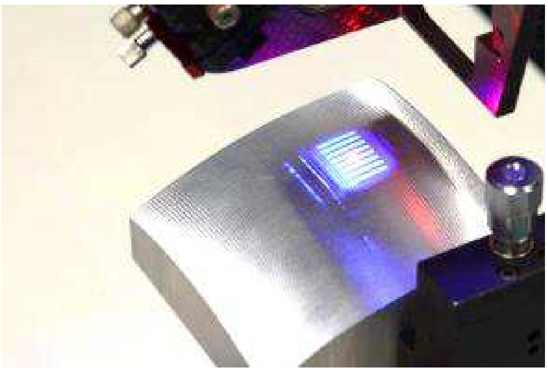

Figure 1: View of the measurement field of the combined sensor system (red illumination spot for light scattering measurements; blue fringes for 3D measurements)

3. PATTERN PROJECTION SYSTEM

3.1 Pattern projection unit and measurement principle

The 3D surface sensor unit consists of a projector and two cameras as optical components as comparable 3D sensors [Mun2007] based on fringe projection technique [Schre2000].
A sequence of fringe patterns (sinusoidal and Gray-code patterns [San1999]) are projected onto the measurement object and recorded by the two cameras. The positions and orientations of the active optical elements as well as possible lens distortion effects are known from the calibration [Schre2000]. The fringe sequence is processed resulting in phase images. The corresponding positions in the two cameras observing the same phase value are used for triangulation in order to calculate the 3D position of an object point.

3.2 Problems and solutions in this application field

The main problem for the 3D surface determination was the different sizes of the measurement objects. This problem was solved by the realization of varying measurement field sizes up to 10 mm x 10 mm obtained by a re-arrangement of the cameras and the projector shown in Figure 2. This means additional re-arrangement and re-calibration effort. For the re-calibration, however, a low-effort methodology [BB2012] can be applied.

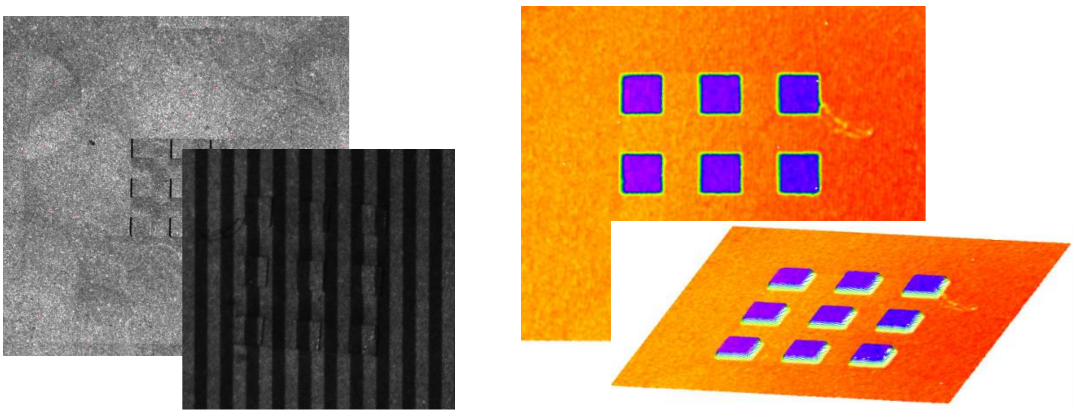

Figure 2: Specimen with fringes (left) and cloud of 3D points (Measurement field size = 10 mm x 10 mm)

4. LIGHT SCATTERING

4.1 Principle

At Fraunhofer IOF, instruments have been developed for angle resolved and total scatter measurements at various wavelengths from the Extreme Ultraviolet over the visible to the Infrared spectral ranges with exceptional sensitivities [Schrö2010]. The instruments are used to characterize surfaces, coatings, and materials with respect to roughness, homogeneity, and defects as discussed for example in [Tro2012]. Scattering theories provide the link between light scattering and its origins. For roughness-induced scattering and small to moderate roughness levels (up to rms roughness of some percent of the wavelength of light), these theories can be rather simple: The angle resolved scattering (ARS) is proportional to the surface power spectral density function (the roughness spectrum):

$$ARS(\theta_s) = \frac{\Delta P_s(\theta_s)}{\Delta\Omega_s P_i} \mu \frac{16\pi^2}{\lambda^4} \cos^2\theta_s \cos\theta_i QPSD(f) \quad . \tag{1}$$

ΔP is the power scattered into a certain direction, $\Delta\Omega_s$ is the detector solid angle, P_i is the incident power, and θ_i and θ_s denote the polar angles of incidence and scattering measured with respect to the sample normal. Q is the so called optical factor that is close to the Fresnel reflectance for metallic surfaces and moderate angles of incidence and scattering.
The total scattering, which can be calculated by integrating ARS over the scattering hemisphere, is proportional to the square of the (relevant) rms roughness. For the total backscattering of a metallic surface with reflectance *R:*

$$TS_b = R\left(\frac{4\pi\sigma_{rel}}{\lambda}\right)^2 \quad . \tag{2}$$

These simple relationships enable predicting scattering properties from roughness data but also to measure surface roughness by analyzing scattered light. Because light scattering measurements are non-contact, robust, fast, and yet highly sensitive, light scattering is an exceptionally powerful technique. In order to use this potential also in manufacturing environments, a compact scatter-based roughness sensor was developed at Fraunhofer IOF [Schrö2012, Her2013]. The tool is schematically shown in Figure 3. Laser diodes, basically in the visible range, are used as light source. A special beam preparation system, with a spatial filter as key element, is used to shape and clean the beam incident on the sample (typical spot diameter 2 mm). The light reflected and scattered off the sample is then recorded by a special detector matrix that has been optimized with respect to linearity and dynamic range. After calibration pixel by pixel using a Spectralon™ white standard and using a special high-dynamic range measurement routine, the tool directly provides absolute ARS and roughness data within less than 1 second.

However, the range of validity of Eq. (1) and (2) and thus the application of the sensor is limited to rather low roughness values corresponding to mirror-like surfaces. At an operation wavelength of 650 nm, this means surfaces with roughness levels of 50 nm and smaller. The lower roughness limit, corresponding to the sensitivity of the sensor, is about 0.5 nm. This is more than sufficient for surfaces generated by polishing or molding. In order to extent the application range to technically rough surfaces with higher roughness and more pronounced structures, the data acquisition and evaluation methods had to be modified. The limitations of existing models as well as approaches to overcome the smooth surface limitation were discussed in numerous papers. We follow the approach discussed in [Har2012] and verified in [Sto2012] by comparison with rigorous models. One part of this is to use the expression:

$$TS_b / R = 1 - \exp\left(\frac{4\pi\sigma_{rel}}{\lambda}\cos\theta_i\right)^2 \qquad (3)$$

instead of Eq. (2). Eq. (3) is valid for arbitrary surface roughness and it is straightforward to show that Eq. (2) is the first order approximation of Eq. (3) for small roughness.
In addition, the main sensor concept has been implemented into the new multimode detector head shown in Figure 8.

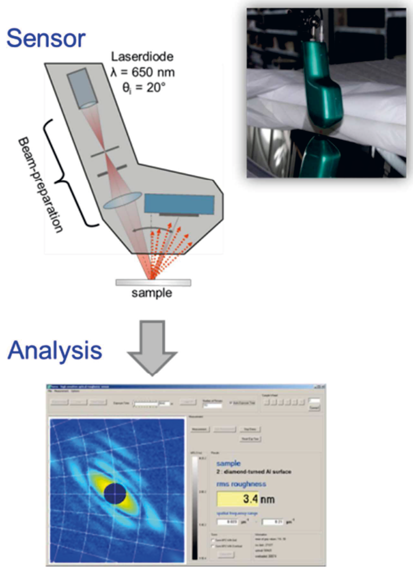

Figure 3: Compact optical roughness sensor (horos) developed at Fraunhofer IOF for light scattering-based roughness characterization in manufacturing environments.

4.2 Problems and solution in this application field

4.2.1 Camera system

The design of the combined optical sensor required the development of a camera module in order to fulfill both the technical demands of light scattering measurements and the geometrical design constraints for integration into the complete sensor system.
The solution of the design task requires the selection of an appropriate imaging sensor for the measurement of roughness by scattered light and the development of an optimal, geometrical shape and position of front-end electronics.

The aim was to find a flexible geometrical design for the combined sensor which allows the adaption to various applications and fields of view regarding different size and resolution.
Crucial criteria for direct operation as scattered light sensor are:

- ensuring high dynamics
- avoidance/minimization of smear and blooming effects
- selection of sensors with a large imaging area to gain maximized detection angles (opening angles)
- availability of imaging sensors with removed cover glass and without micro lenses in order to avoid internal reflections

Regarding the integration into the combined module, some additional criteria are to be met:

- advantageous relation between active light-sensitive area and total area of the sensor housing
- selection of sensors with various housing types for development of electronics with minimal PCB area
- minimization of PCB area near imaging sensor in order to reduce optical shadowing effects
- minimization of the distance between light-sensitive area and module edge, sensors with minimal edge distance

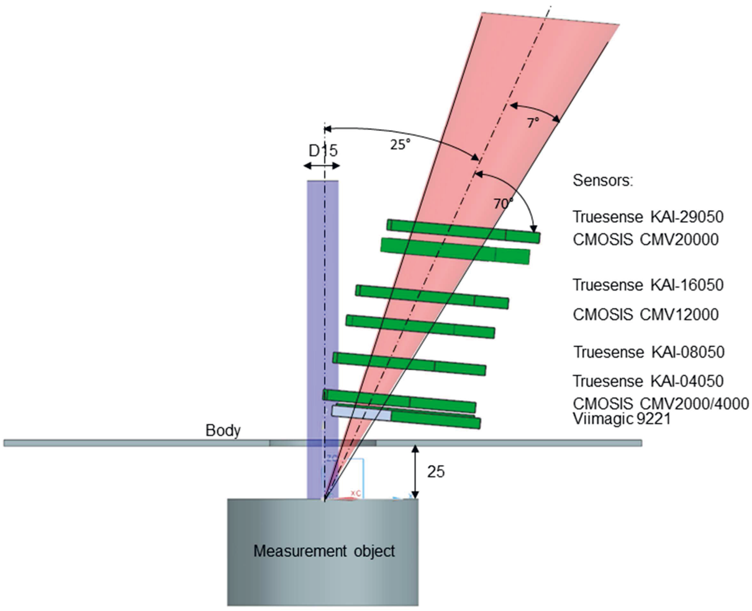

Figure 4: Sensor selection based on the geometrical chip dimensions and the possible installation space of the combined sensor system

A conflict occurs between the application of large area sensors and the need for minimal geometrical size shown in Figure 4. Large sensors yield high signal noise ratios in images of low-scattering samples but may block light paths of other parts of the optical system and reduce design flexibility. As a result of these considerations a camera design based on the CMOSIS CMV4000 chip [CMO2013] was realized, as shown in Figure 5.

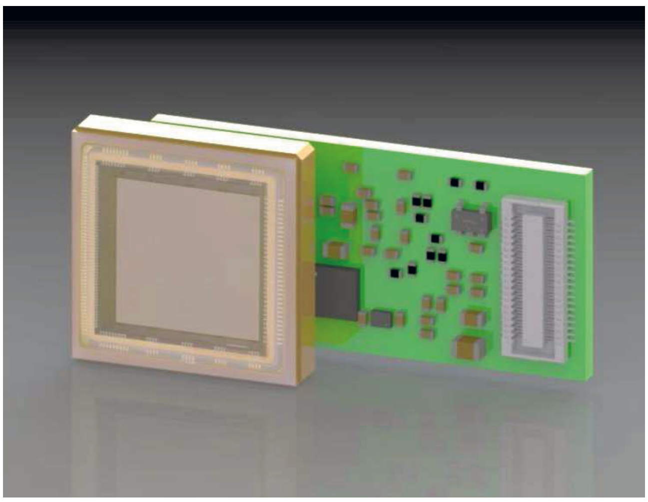

Figure 5: Camera design for light scattering system based on CMOSIS CMV4000

4.2.2 *Detection of imperfections during the production process by analysis of light scattering images*

Common artifacts during the production process of surfaces are for example scratches, pits, or particles. The goal of the manufacturing process is to reduce these imperfections. All types of defects influence the light scattering distribution and cause typical scattering patterns which can exhibit a drastic increase of the scattered light pattern in specific directions. Hence, it is possible to analyze the scattering images measured with the light scattering module to characterize and classify artifacts. A possible method was for instance presented in [Her2013] which enabled the determination of the main dimensions of elliptical defects such as particles, inclusions, or pinholes in the material.

5. MEASUREMENT RESULTS

The main procedure for the characterization of surface roughness using the scatter sensor is illustrated in Figure 6 for a ground surface. The light scattered off the sample is detected by the sensor as 3D-ARS image. The scatter image is then analyzed to check for isotropy or identify dominant directional features and their orientation angles. If the surface is isotropic, the ARS can be averaged azimuthally around the direction of specular reflection (center of image). From ARS, the surface PSD and TS can be calculated as described above. From TS, the rms roughness can then be calculated directly using Eq. (3). Further analysis of the PSD provides additional information such as correlation lengths.

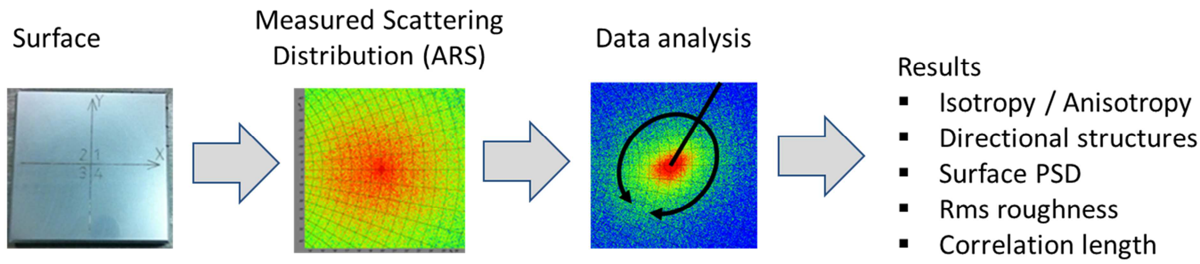

Figure 6: Procedure for scatter-based roughness characterization.

Measurement results of a variety of different metallic surfaces are shown in Figure 7. Up to the sample with 31 nm rms roughness, all surfaces are mirror-like in the visible spectral range. Beyond 50 nm, roughness measurements are not possible using Eqs. (1) or (2). Instead, alternative approaches have to be applied, such as Eq. (3).

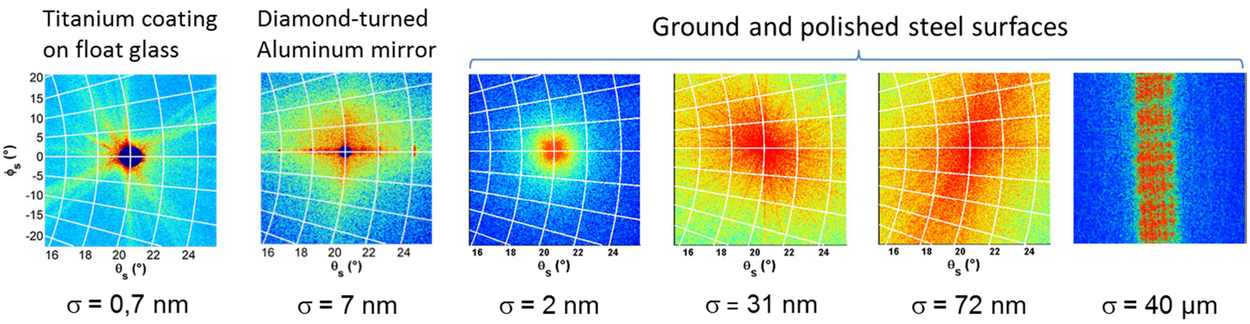

Figure 7: Results of scatter-based roughness characterization of different metallic surfaces.

6. SUMMARY AND OUTLOOK

In this paper, a novel optical sensor is presented which combines the optical measurement technologies fringe projection and light scattering. The classical geometries of both sensor systems were redesigned to make the sensor attractive for industrial applications. A new camera module with a special design of the camera front-end, presented in chapter 4.2, was developed to realize a compact sensor design. The field of view of both sensors is combined in the same local position to reduce measurement time. No movement of the sensor or the measurement object is necessary to measure 3D geometrical features and roughness of the surface.
In the first step, the 3D geometry of the measurement object is measured with the 3D surface measuring fringe projection system explained in chapter 3. Afterwards, this geometrical information can be used during the roughness measurement with the light scattering system explained in chapter 4. The geometrical information can help to improve the measurement accuracy of the light scattering measurement. Furthermore, an alternative approach for rougher technical surfaces (rms roughness over 50 nm) was presented.
In conclusion, a new combined sensor for roughness and 3D geometry measurements on curved metallic surfaces is presented. This compact sensor system can be mounted in different orientations. In a first application, the sensor was integrated in an optical measuring machine, shown in Figure 8.

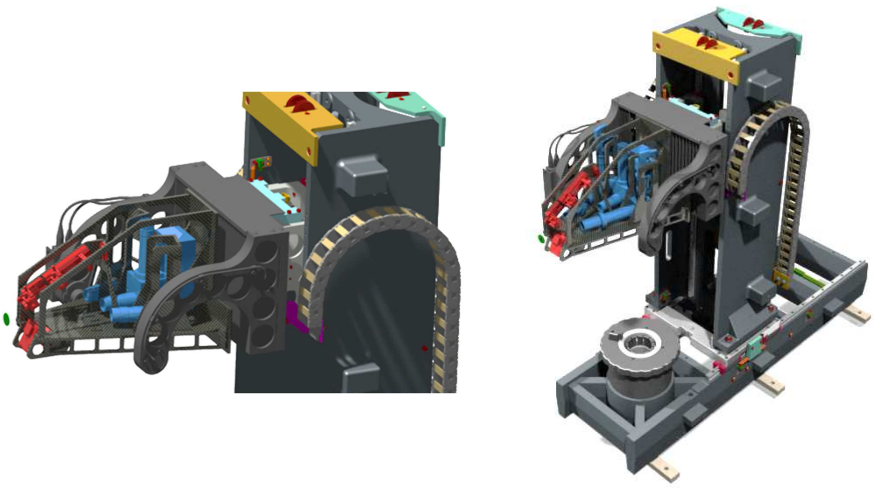

Figure 8: System realization - Combined optical sensor system integrated in a Mahr measuring machine. The blue parts are the components of fringe projection system and the red parts are the components of the light scattering system.

With this kind of application, the first industrial experience could be made. In future work, the sensor will be tested in an industrial production process. The sensor will be integrated in a manufacturing machine directly in the production line. This causes new requirements on the sensor, especially on the housing of the sensor system.

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