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Digital Holography: Evolution from a Research Topic to a Versatile Tool for the Inline 100% 3D Quality Control in Industry

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Abstract:

Digital multiwavelength holography is a technique for precise 3D height measurements of optically rough surfaces. We demonstrate measurements on a milled surface, using four wavelengths between 514 and 532 nm, and achieve precision in the submicrometer range. Height structures of < 400 nm can be resolved up to an unambiguous height of 370 µm and with a lateral resolution of 7 µm. Acquisition times of < 400 ms, including the time needed for parallel processing of the data, make our sensor a versatile tool for high-throughput 100% inspection in manufacturing environments.

Key words: Digital Holography, Inline Inspection, Phase Retrieval, Parallel Computing, GPU.

Introduction

Holography is used to precisely measure 3D structures of surfaces. Unlike photography, holography records both, the amplitude and the phase information or rather the height information. The use of electronic sensors for recording holograms dates back to the 1960s [1], and became more important in the 1990s [2],[3]. Computation times of one hologram larger than several seconds made holographic measurements suited for laboratory use but incompatible for controlling high throughput industrial processes [1],[3]. With the increasing computing power as well as the use of graphics processing units (GPU), the requirements of fast production cycles are met with computing times in the millisecond range [4],[5],[6],[7]. Furthermore, the steady increase in resolution and size of the camera chips makes holography nowadays a versatile tool for industrial applications.

Many technical surfaces are optically rough, i.e. the surface roughness exceeds the visible wavelength range. At the same time, these functional surfaces can have tolerances of only 10 µm, requiring measurement techniques with submicron precision. Moreover, structure heights of several hundred micrometers have to be measured unambiguously. Using multiwavelength holography these challenges can be met by recording interferograms at multiple wavelengths [8]. Out of these, interferograms at different synthetic wavelengths are computed. The synthetic wavelengths correspond to the beat frequencies. The wavelength difference determines the unambiguous height measurement range: The smaller the difference, the larger the synthetic wavelength. Large measurement ranges result in less accurate measurements.

The combination of more than two wavelengths allows cascading the measurement ranges, and thus increases the ratio of measurement range and accuracy.

Here we present new results of a digital multiwavelength holography sensor using four different wavelengths resulting in an accuracy of a few 100 nm covering an unambiguous height of 370 µm, generating 3072×3072 measurements on an area of $20 \times 20\ mm^2$ in less than 400 ms.

Sensor description

Four lasers emitting wavelengths between 514 and 532 nm are used, resulting in synthetic wavelengths between 752 µm and 15 µm. The laser beams are coupled into fibers and connected to a fiber switch, which turns the individual laser beams on and off. The simplified beam path inside the sensor head is depicted in Fig. 1. After leaving the optical fiber (1), object and reference beams are generated by a beam splitter (2), with both beams being expanded to fit the size of the object and the camera chip. The reference beam is deflected by a mirror (3) mounted on a piezoelectric actuator. Thus the phase of the reference beam is shifted by moving the mirror slightly. The object beam illuminates the sample under test (4). An object lens (5) images the light scattered by the sample onto the camera sensor (6). The object and the reference beam are superimposed on the camera chip. The resolution of 3072 px × 3072 px corresponds to a lateral resolution of 6.7 µm × 6.7 µm, at a measurement area of 20 mm × 20 mm.

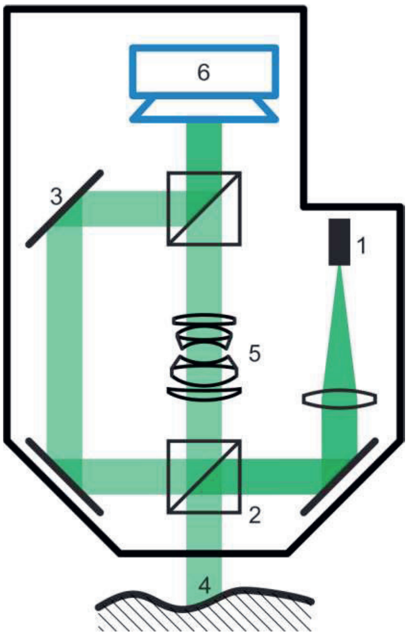

Fig. 1. Simplified sketch of the digital multiwavelength holography sensor: Light coming from the fiber (1) is split by the beam splitter (2) into object and reference beam. The mirror (3) in the reference beam is mounted on a piezoelectric actuator, used to introduce a phase shift to the reference beam. The object beam illuminates the object (4). The scattered light is imaged by an object lens (5) onto the camera (6), where it is superimposed with the reference beam.

Three phase-shifted holograms are recorded for each of the four different wavelengths, so all in all 12 images, each with 9 MPx are taken. The phase shifts are determined by the method of Cai *et al.* [9].

To achieve fast production cycles, a CoaXPress camera is used for fast data acquisition and all phase-extraction computations, and filtering operations are performed in parallel using CUDA-programming on a consumer graphics card.

Experimental results

To demonstrate the unambiguous measurement range, the height topography of a 10 Euro Cent coin measured with the sensor described above is shown in Fig. 2. Despite the optically rough surface, height differences of 200 µm can be resolved easily.

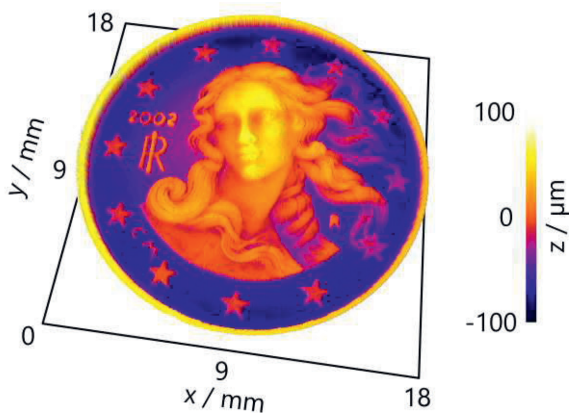

Fig. 2. Topography of a 10 Cent € coin measured with the digital multiwavelength sensor.

To demonstrate the high axial resolution, the measurement results of a milled surface (see Fig. 3) with a borehole are shown in Fig. 4. The height map clearly resolves the milling grooves. The difference to a line fit on the height data along the blue line is shown as well in Fig. 4. As the surface structure can be seen in the height map, this is a combination of the sensor noise level and the surface roughness. Consequently, the sensor accuracy can be assumed to be better than 400 nm. This measurement was taken in 85 ms, and subsequent processing took just 300 ms.

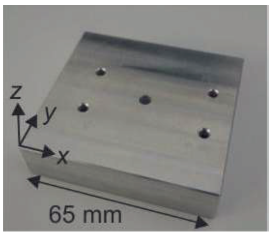

Fig. 3. Milled surface with boreholes, the metal piece has an area of 65 mm × 60 mm.

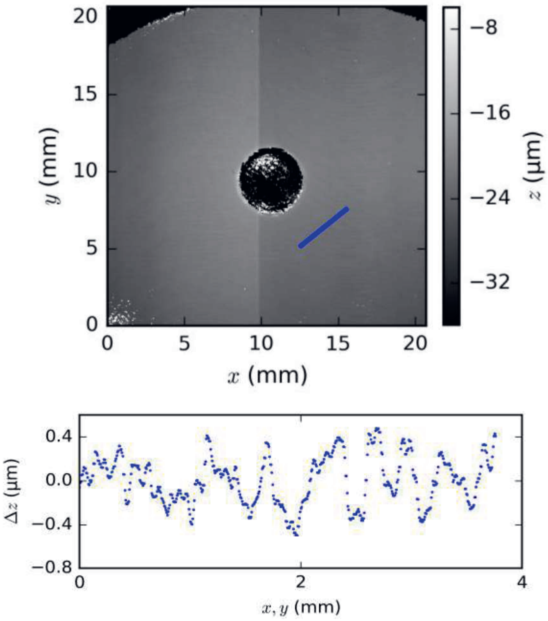

Fig. 4. Top: Height map of the milled surface with borehole. Bottom: The difference to a line fit in the section along the blue line displayed in the top part of the figure is shown.

Inline Application

The sensor head has an overall dimension of 440 mm × 250 mm × 105 mm and weights 11.5 kg. In addition, a computer and a laser rack are needed. The working distance is typically 15 mm. Figure 5 shows the sensor installed in a production line. There, it is used for 100% quality control of precision turned parts. Using three lasers emitting light from 633 - 636 nm, an axial repeatability of < 1 µm on an unambiguous measurement range of 500 µm is achieved. A coin-sized measurement area of 18 mm in diameter corresponds to a lateral resolution of 6 µm × 6 µm. The time between two measurements is 1 s, including image acquisition (< 60 ms), data evaluation (< 150 ms) and handling (< 800 ms).

In 2015 a holographic sensor has been installed at Werner Giessler GmbH in Elzach, Germany. There the sensor is used for inline inspection of high pressure sealing surfaces for Diesel injection systems. 100% of the produced sealing parts are checked for correctness of various geometric features and micron-sized defects. Handling and inspection of each individual part is done within one second.

Fig. 5. Digital multiwavelength holography sensor installed at the company Werner Gießler GmbH in Elzach, inspecting one piece per second, synchronized with a production cycle of 1 Hz.

Perspectives

The high precision of this technique shows the potential to be applied in optimizing milling and similar processes. Therefore, we are aiming at smaller sensor dimensions to be able to include this technique into machine tools for in-situ measurements providing feedback to the machine. Furthermore, measurements on moving objects at speeds of several mm/s have been demonstrated recently [10], opening up new applications, simplifying the handling and thus increasing the upper limit for production cycles, as the measurement can be done continuously.

Summary

The high precision of digital multiwavelength holography was shown to be able to resolve structure heights of a few 100 nm with 370 µm height unambiguity on an area of 20 × 20 mm^2 using parallel computing to generate 3072 × 3072 measurement points in less than 400 ms.
Inline integration of a digital multiwavelength holography sensor has demonstrated the suitability of this technique for 100% quality control at a production cycle of 1 Hz.
Miniaturized sensors for in-machine tools or holographic measurements on moving objects will push the field even further.

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