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HoloPort – 3D-Sensor for machine tools

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Abstract:

Manufacturing of high-precision components requires accuracies that even the most modern processing machines are often unable to deliver reliably. Slightly worn tools, incorrectly calibrated sensors or even different trajectories can lead to component integrities that do not comply with the desired specifications. Quality control is usually performed on randomized samples in special measuring rooms outside the machine tool. Closed-loop quality control is currently a cumbersome iterative process. We present the digital-holographic sensor system *HoloPort* that measures the two dimensional surface integrity of machined components in the sub-micrometer range directly inside machine tools: To our knowledge, *HoloPort* is the first wireless (digital holographic) sensor inside a machine tool worldwide. Being fully integrated, it features not only a multi wavelength interferometer but also a miniaturized GPU. This allows full data evaluation directly in the sensor and thus inside the machine tool. A single measurement is taken and processed within 3 s in wireless operation. *HoloPort* can be easily integrated into a variety of machine tools. This contribution includes detailed information about the sensor architecture. Experimental results on milled parts show the system's performance and illustrate possible inline applications as well as perspectives of the sensor.

Keywords: Digital Holography, Machine Tool, Inline Inspection, Parallel Computing, Wireless, GPU.

Introduction

In machining production, the measurement of component dimensions and parameters is a fundamental part of quality and efficiency assurance. Therefore, the demand for on-machine metrology is continuously increasing. It avoids time-consuming realignment operations and possible loss or damage during the transportation between different machining and measuring stations. Luo et al. for example consider “hybrid machining” as one of the main future developments in production and demand a measurement technology suitable for use directly at the processing location: *“However, currently there is no method to realize on-line measurement of surface integrity.”* [1] Here, we present a sensor that addresses this problem.

Separate coordinate measuring machines (CMM) as well as scanning tactile systems which can be exchanged as a “tool” are well-established to this day but are slow and cannot resolve the surface texture [2]. Competitive optical technologies allow contact-free operation but are either limited in their application (reflecting parts for deflectometry), slow (white-light interferometry, confocal, focus variation) or have insufficient accuracy (laser triangulation) [3]. In addition, none of these techniques is commercially available for in machine-use.

Featuring high measuring speed and accuracy at the same time, digital holography has become a versatile tool for the inline 100 % 3D quality control in industry [4]. The origins of digital holography date back to the 1950s [5]. However, only the development of electronic sensors [6] and increasing computation power such as provided through graphics processing units (GPU) enabled digital holography for industrial use [7–12]. With the introduction of small, powerful computing units from the field of autonomous driving, a fully integrated wireless measuring system becomes possible.

This contribution presents the first wireless interferometer that allows a two dimensional surface measurement of freshly machined components directly inside machine tools. In order to be capable of measuring optically rough technical surfaces, the sensor system works based on the principle of multi wavelength digital holography and achieves accuracies in the sub-micrometer range. It features a multi wavelength interferometer with three stabilized single mode, single frequency laser sources and a miniaturized GPU – all fully integrated in a compact housing and allowing wireless operation.

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Sensor description

Integrating a surface-measuring optical sensor into a machine tool poses a number of challenges. In addition to the harsh environmental conditions a sensor has to withstand, tool holders are currently neither prepared for energy nor data transmission. The development of such standardized interfaces has been in progress for several years, but none is yet in use [13]. Thus, commercially available tactile sensors work wirelessly and are battery powered. In order to make the measuring system accessible for all machine tools, the standard interface according to DIN 69893 was chosen. Therefore, all electronics necessary for the operation of the sensor had to be integrated into the measuring system.

Fig. 1 depicts the system architecture: The sensor system *HoloPort* consists of the optical sensor head *HoloCut* and an integrated control system.

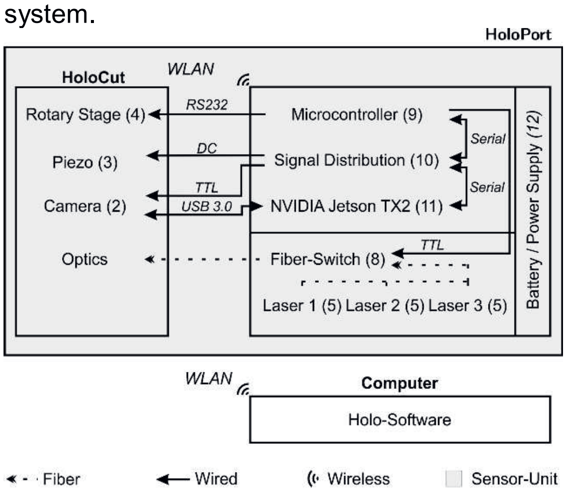

Fig. 1. System architecture: Equipped with the control module, the wired sensor head HoloCut [14] upgrades to the fully integrated measuring system HoloPort and operates completely wirelessly. Label numbers refer to *Fig. 2* and *Fig. 3*.

The optical design of HoloCut [15] – shown in Fig. 2 – is based on the industrially proven HoloTop sensor [4]. With a focus on the form factor, the height of a standard tool was set as the mechanical boundary condition for the mechanical design. Miniaturization of the sensor and mounting in the center of gravity (1) were achieved by a three-dimensionally folded beam path as shown in Fig. 2. The sensor head itself has a size of 235 × 140 × 215 mm³ at 7.5 kg. For further details regarding the optical and mechanical design, please refer to our publication [14].

At least three temporally phase-shifted interferograms [16] are recorded with a 9 Megapixel camera (2), corresponding to a lateral sampling rate of 7 µm × 7 µm and an (*x, y*) measurement area of 20 mm × 20 mm. Phase shifts are introduced by a piezo actuator (3). An integrated controlled rotary motor (4) allows the sensor to be adapted to different surface conditions.

For the reasons set out above, the control system has also been miniaturized and directly integrated onto the sensor head. The 19" control system (500 × 500 × 640 mm³) of *HoloTop* was reduced below the size of a shoe box (235 × 140 × 75 mm³).

Fig. 3 shows a computer-aided design (CAD) model of the complete measuring system *HoloPort*. Due to the sensor's field of application are technical surfaces, *z* measurement ranges of at least a couple micrometer are needed. To achieve this, multiple lasers are used to record interferograms at different wavelengths [17]. These are used to numerically generate interferograms at so-called *synthetic* wavelengths, corresponding to the resulting 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 [4].

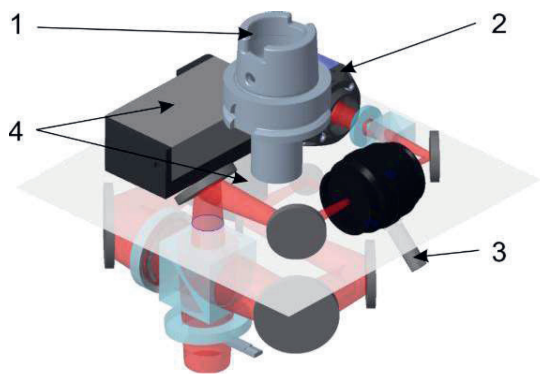

Fig. 2. Simplified sketch of the optical HoloCut sensor head with interfaces to the control unit: camera (2), piezo actuator (3) and rotary stage (4). The machine integration in the center of gravity of the sensor (1) is realized by a three-dimensional layout of the optical beam path.

The lasers are mounted onto an aluminum block (6) and insulated thermally (7). A fiber switch (8) sequentially couples these lasers into the sensor head. The system can be configured with different laser wavelengths. The results shown in this paper were achieved using synthetic wavelengths of 60 µm to 88 µm. The extension of the measurement range to several millimeters has already been shown by using additional lasers [9] or specialized algorithms [18].

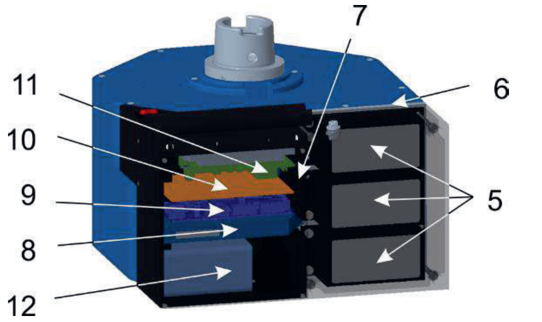

Fig. 3. CAD model of the integrated control system including a battery powered (12) embedded architecture (9-11), a fiber-switch (8) toggling a three-laser system (5).

The previously introduced components are controlled by a microcontroller (9). Energy supply and signal distribution is performed by a specially designed circuit board (10). Since the speed of the sensor system determines the economic efficiency and benefits in the machine tool decisively, a powerful CUDA capable computing unit has been integrated: A Jetson TX2 board (11) allows not only wireless data transfer according to the state of the art, but also allows data reduction inside the sensor itself. The resulting camera data of up to 270 MB per measurement can be pre-processed internally and thus reduced by half – a processing time of less than 3 s is achieved for 9 million sample points. The pure measuring time is less than 1 s.

In addition, the computing power can be used for in situ quality control of the acquired raw data. Interferograms disturbed by vibrations are internally evaluated for sufficient interference contrast [19] even before the wireless data transmission takes place. The power consumption of the whole system is in the range of 20 W. Powered by a 5.2 Ah battery; it lasts for up to 7 h and is charged via a magnetic connector within 30 minutes.

HoloPort is the first wireless (digital holographic) sensor inside a machine tool worldwide.

Applications

HoloPort has been developed for use in machine tools and quantitative full field analysis of manufactured surfaces. Those can be classified into two main categories: Engineered surfaces and non-engineered surfaces. Engineered surfaces such as bearings and seals are generally manufactured to provide functional properties or are subject to special safety requirements [20]. Fig. 4 shows a photograph of the sensor system inside a Hermle C32 U 5-axis milling machine at Fraunhofer IPM.

Fig. 4. Inspection of a typical milling surface by HoloPort inside a Hermle C32U 5-axis milling machine at Fraunhofer IPM.

In this Fig. 4, a typical non-engineered milling surface is inspected. *HoloPort* easily resolves the milling structure of the surface revealing height differences *h* between individual milling paths of up to 10 µm as shown in Fig. 5. A cross section of ten individual measurements at the same position illustrates the repeatability in the sub-µm range. With a measuring field of up to 20 mm × 20 mm at 9 million sample points, irregularities within the microstructure as well as machine faults quickly become apparent. In contrast to the tactile state of the art sensors, the system cannot only resolve long-wave components but also short-wave structures and defects of the milling operation. Due to the inherent morphological filtering of the probe head, tactile sensors in principle cannot detect these characteristics.

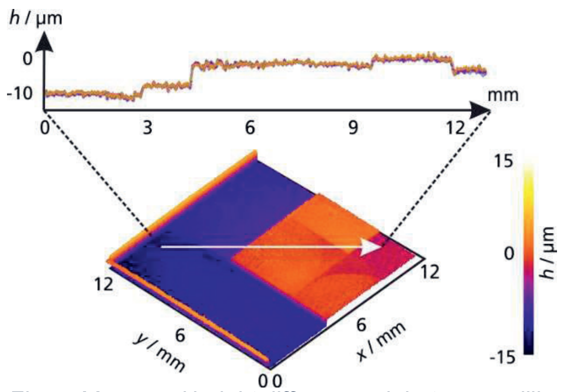

Fig. 5. Measured height differences h between milling paths of a typical milled part in the range of 10 µm. A cross section of ten individual measurements at the same position demonstrates the measuring repeatability.

For example, hidden machine faults could be observed like an incorrectly calibrated temperature sensor leading to unpredictable surfaces displacing whole milling paths by more than 10 µm [19]. For the human eye, this defect is not visible on the surface and the machine was unable to register the error at all.

Fig. 6 and Fig. 7 show measurements of a surface machined with an end mill at 5.5 mm axial tool infeed, respectively.

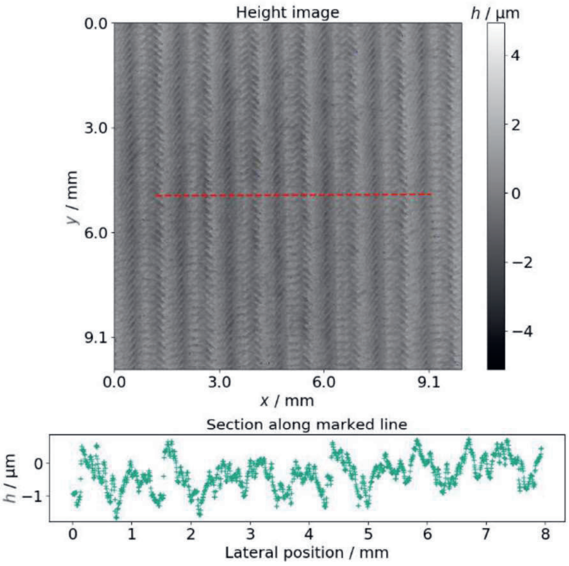

Fig. 6. Milling surface machined with an end mill under 5.5 mm axial infeed alternate milling.

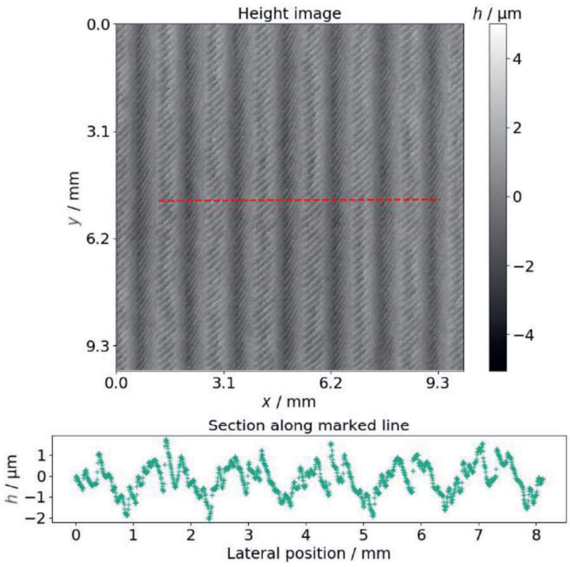

Fig. 7. Milling surface machined with an end mill under 5.5 mm axial infeed parallel milling.

Looking at the two-dimensional surface plot, a clear difference can be observed. However, since the surface roughness is within the range of only 3 µm, a tactile probe could not resolve these short-wave structures due to its inherent morphological filtering. Calculating the material ratio curve e.g., parameter optimization can be carried out directly inside the machine. In case of an engineered surface with requirements on the contact ratio, the high resolving two-dimensional plot is much more significant.

Fig. 8 shows the milling result with reduced axial infeed of only 0.5 mm using alternate milling. With a reduction of the axial infeed, a lower surface roughness is to be expected. In fact, the surface roughness decreases, but with a varying tilting of the individual toolpaths towards each other (manually marked in orange). This effect is beyond the machine accuracy and can be caused by the tolerances between tool, tool holder and spindle during the tool change itself. Further possible causes are insufficient cutting pressure or even a tilted or defective spindle.

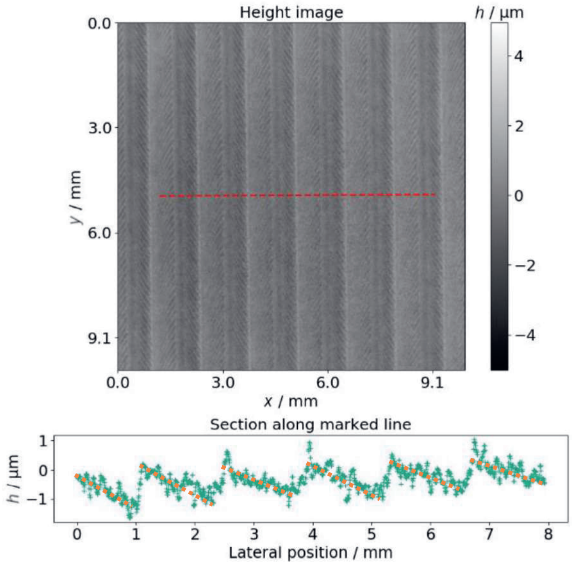

Fig. 8. Improved, less rough milling surface of an end mill with only 0.5 mm axial infeed. The varying tilting of the individual toolpaths towards each other is manually marked in orange.

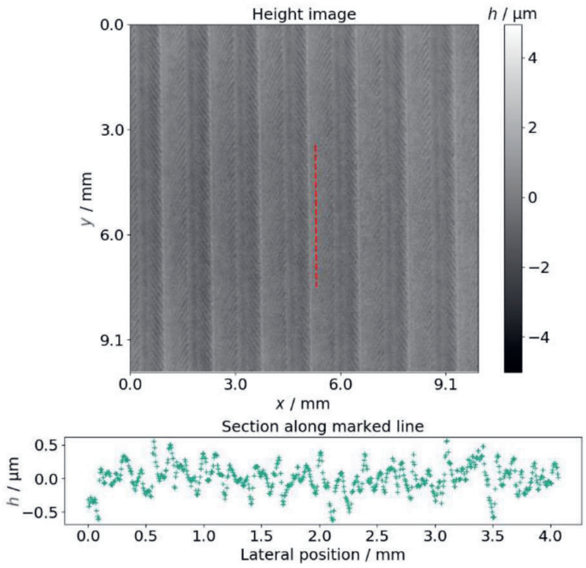

Fig. 9. Line section within a single milling path. Without the share being caused by the path tilts, the surface roughness ranges only within 1 µm.

Fig. 9 shows a single section in milling direction. The inclination of the individual toolpaths to each other is not visible within a single line cut. If one could eliminate the tilting of the milling paths by suitable measures, the surface roughness could be approximately halved. Especially in the production of injection molds with subsequent polishing, the surface quality and frequencies are of great importance. Certain spatial frequency components can be removed much better than others during polishing [21].

The benefit of the measuring system in the optimization of milling parameters quickly becomes obvious at this point.

For comparison to a white-light interferometric and confocal laboratory reference 3D measuring devices, surface parameters according to ISO 25178 were evaluated previously: All three measuring methods deliver comparable results and are able to detect both an increasing roughness of the surface due to wear of the milling cutter and a machine error [22].

Not only the analysis of surface parameters, but also the extensive measurement of different inspection parameters represent applications for quality monitoring [21]. Fig. 9 shows a milled laser heat sink with mapped surface measurement.

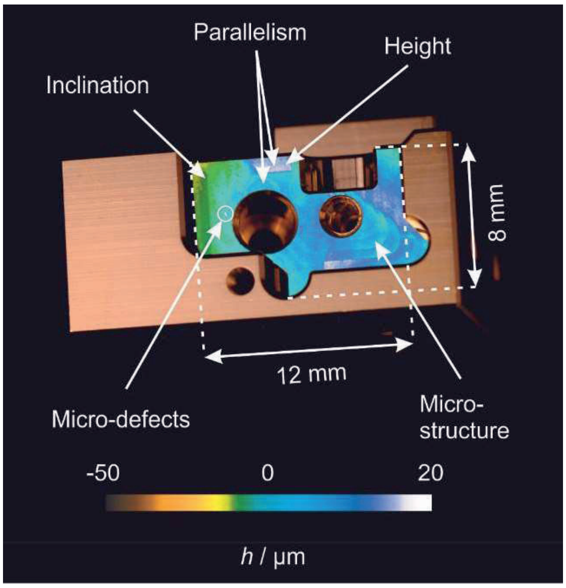

Fig. 10. HoloPort maps the component surface in the fraction of a second with micrometer accuracy directly in the machine tool (as in the example of a heat sink for laser assembly). Alongside the geometry, relevant surface parameters such as micro-defects and microstructures as well as the height, parallelism and inclination of surfaces can be measured simultaneously.

The full field measurement shows the surface quality and in addition allows the quantitative extraction of geometrical parameters: Micro-defects and microstructures as well as the height, parallelism and inclination of surfaces can be evaluated based on the gathered measurement data.

Using the dynamic numerical control (DNC) interface of the machine tool, axis positions can be read out and used for a CAD comparison – the system becomes a full-field CMM. Even complex work pieces can be inspected completely and directly within the machine for the first time [23]. The accuracy of a complete point cloud of the surface is limited by the accuracy of the machine tool axes, which is typically in the single micrometer range.

Further test measurements of a complex formed milling part have been carried out to demonstrate feasibility of quality inspection directly in the machine tool instead of using an additional CMM situated within a temperature controlled measurement room. The combination of more than 30 measurements for flatness determination has been carried out with an extension of 100 mm × 60 mm which corresponds to almost 300 million data points. Evaluation of the combined data set shows flatness information within the single micrometer range. The determination of lateral distances between reference marks located on the measured surface in the range of the lateral sampling of the sensor at 7 µm appears realistic.

Perspectives

An optical sensor measuring the surface integrity at a large field of view directly inside the machine tool opens up new possibilities for process control and optimization [24].

The feedback of the measurement results into the manufacturing process is a key point, especially in hybrid manufacturing – the automated batch size 1 production according to industry 4.0 becomes possible. Since the Jetson module was developed for autonomous driving purposes, the system is also prepared for machine learning approaches.

The system is also prepared for the use on CMM and robots – the possibilities and limits will be determined in future studies. In addition, the measuring system will be further miniaturized to be compatible with smaller size tool changers.

Digital holography has been proven to work even on moving objects at speeds of several mm/s [25]. With a resulting simplified handling, the upper limit for production cycles can be further decreased. The limits of a scanning sensor in a multi-axis system will be analyzed in future experiments.

Summary

On-line measurements of surface integrity in machined production have been motivated. Digital holography meets the requirements for measuring accuracy in the µm range at high measuring speed at the same time.

A new digital-holographic sensor system for two-dimensional surface measurements inside a machine tool has been presented. The sub-µm precision of the system on an area of up to 20 mm x 20 mm was demonstrated with various milled samples. Due to the short processing time of 3 s (pure measuring time less than 1 s), closed-loop quality control directly inside the machine tool is feasible for the first time.

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