Digital holographic measurement system for use on multi-axis systems

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ABSTRACT

Hybrid manufacturing processes, high level of automation, short product service life and decreasing vertical range of manufacture in production request for increasing flexibility and speed of quality control. With HoloCut we previously introduced the world’s first wireless digital-holographic sensor system prototype for fast and precise measurements inside a machine tool. With the experience gained so far, we now present an improved, even more compact sensor system, for the use on various multi-axis systems such as coordinate measuring machines (CMM), robots and machine tools and show first results with different handling systems.

Besides improved mechanical stability, a size and weight reduction resulted from a new design approach: The arrangement of components around a central "core" made it possible to create a very compact design with a diameter of 125 mm, a height of ~180 mm and a weight of ~2 kg. The system features a 12.5 × 12.5 mm² measuring field with a lateral sampling of 4 µm. An NVIDIA Xavier embedded system enables pre-evaluations of the recorded measurement data in order to allow re-recording them, even before the complete data transmission (up to 160 MB with 2 Hz measuring rate) and evaluation. This is especially important for the use in vibration-prone environments such as multi-axis systems.

Various handling systems such as a HERMLE C32U machine tool, an undamped LEITZ Reference HP 15.9.7 CMM and a UNIVERSAL ROBOT UR16e are examined with regard to vibrations.

In future work, the behavior of the system under higher vibration amplitudes will be characterized.

Keywords: digital holography, multi-axis systems, collaborative robot, machine tool, coordinate-measurement machine, inline measurement, production control, embedded system

1. INTRODUCTION

"Highest precision even with large, complex-shaped components in minute cycles" – modern production machines such as 5-axis machining centers from MAG IAS, GROB-WERKE or HERMLE have been fulfilling this wish of the industry for quite some time. Modern production technologies, which make it possible to manufacture ever more individualized products in ever shorter cycle times, make the classic random sample in the measuring room seem antiquated, and the desire to perform a 100% inspection in- or near-line is becoming increasingly in demand¹: fast, full-field, highly automated. Therefore, new, optical measuring methods are meeting with growing acceptance in the industry. In recent years, FRAUNHOFER IPM has shown that the potential of digital holographic interferometers clearly exceeds the state of the art compared to that of other optical methods².

Digital multi-wavelength holography is a quite young technique for extremely fast and highly accurate 3D acquisition of technical surfaces. It is based on the principle of interferometry: laser light is split into an object wave and a reference wave. While the object wave is scattered by the surface to be measured, the reference wave passes through a precisely defined optical path within the sensor. The object and reference waves are superimposed on a camera. The resulting interference pattern carries the height information of the test object. Using suitable numerical methods, the shape of a technical surface can already be calculated from this interference pattern in a fraction of a second. But not only that: Because the intensity and phase of the object wave are captured precisely and holistically in digital holography, its propagation in space can also be calculated numerically. This makes it possible, for example, to measure a surface even if it was not optically sharply imaged on the camera chip.

In recent years, FRAUNHOFER IPM has shown that with digital-holographic sensors a sampling rate of ≥ 100 million points/s, single point repeatabilities better than 1 µm can be achieved even under production conditions³. For this purpose, a laser system is required which emits light of different wavelengths with a very defined frequency. The lasers are coupled into the system one after the other and measurement data is recorded. This allows various synthetic wavelengths to be
generated purely numerically during reconstruction, so that unambiguous measurement ranges in the centimeter range and accuracies in the sub-micrometer range are possible at the same time. Here, classical holography benefits from the digitization of object reconstruction, without which a measurement of rough, technical surfaces would not even be possible due to speckle noise.

For objects with small axial dimensions, the HoloTop system has been developed at IPM in recent years, which for example can be used for 100% inline inspection of precision components (Figure 1a). The HoloCut system showed for the first time that holographic measurements can be realized even under very harsh environmental conditions such as in a machine tool.

FRAUNHOFER IPM now presents its newest innovation – the HoloTop NX Sensor system. Due to its compact design, this highly integrated, digital holographic sensor (Figure 1b) even fits into tool changers of common machining centers.

Similar requirements as for the HoloTop system were set for the specifications: The measuring field covers at least $12 \times 12 \text{mm}^2$ within one measurement. To resolve milling structures, a lateral sampling of $10 \text{μm}$ should be achieved. A value of $1 \text{μm} (1\sigma)$ is targeted for the axial repeatability. The axial measurement range shall cover more than $10 \text{mm}$ and be unambiguous within at least $0.5 \text{mm}$. Coaxial illumination, i.e. the fact that the illumination is from the same direction as the observing image, is an essential requirement, since this is the only way to measure short-wavelength structures on complex component geometries such as drilled holes. A measurement and evaluation time of less than one second is required for economical operation without significantly affecting the production process. HoloTop NX meets these specifications in a lightweight (< 2 kg) and modular sensor system.

Figure 1. (a) First digital holographic sensor integration (HoloTop) inside a production line. (b) The particularly compact HoloTop NX measuring system next to typical machine tools show the same proportions.
2. SENSOR DESIGN

In the following, the fully integrated, complex mechatronic sensor system will be introduced in terms of optical, mechanical, and electronic design.

2.1 Optical design

Figure 2 shows the optical components of HoloTop NX. With a focus on compactness and minimal weight of the sensor, the beam path was folded several times in three dimensions and "wrapped" around a central core. In the following, mirrors are not explicitly mentioned as optical elements and neither labeled in Figure 2. The beam path is exemplarily shown in red, however, the measuring system can be used with lasers ranging from 400-700 nm.

For the results presented within this paper, a laser system consisting of multiple stabilized diode lasers (632.91 nm, 633.84 nm and 642.87 nm) was connected to the fiber input (1) using polarization-maintaining single-mode fiber and a fiber-switch. A subsequent polarizer (2) ensures a constant polarization of the light inside the sensor. A half-wave plate (3) can be used to adjust the beam ratio of the two beam components (object beam and reference beam) split in the polarizing beam splitter cube (5). A priorly passed lens (4) collimates the light and provides an evenly illuminated measuring field of 12.5 × 12.5 mm² with a pixel sampling of 4.1 μm and a numerical aperture of ~0.06. The working distance was set to be 110 mm. However, using numerical propagation, digital holography can measure far beyond the geometrical depth of field so that even a sensor internal reference target at a distance of more than 110 mm can be refocused and thus reconstructed.

The object beam path to and from the target passes through a quarter-wave plate (6), an 85 mm focal length objective lens (7) and is then deflected by 90° by another beam splitter cube (8). There, a polarizing filter (11) allows both beam paths to interfere before they are imaged on a camera (12).

The reference beam passes through a second lens (9), which provides an inter-focus on a piezo actuator (10). Subsequently, the beam splitter cube (8) and polarizing filter (11) are also passed before the interferogram is recorded on the camera (12).

For further information, please see 5,9 where the equivalent unfolded beam path has already been introduced in more detail.
2.2 Mechanical design

Figure 3 shows the full mechanical design of the sensor. Two main components (top - yellow and bottom - blue) are connected via the objective lens (red) and hold all the optical components. To achieve the most compact design possible and a minimum weight, complex, weight-optimized 5-axis milled parts were manufactured.

The design using two interchangeable lids allows the sensor to be extended in height by additional modules such as an integrated laser system or a deflection unit for measuring inner cylinders which is to be developed in future projects. In addition, the required stiffness is achieved via a cylindrical aluminum housing (see Figure 1b) fixed over the two round covers. Figure 4 shows a modal analysis with eigen frequencies above 500 Hz and thus significantly higher than the frequencies typically encountered in multi-axis systems as shown in Section 3.2. The third and fourth frequency shown in Figure 4 (c) and (d) are membrane vibration with even higher frequencies up to 2000 Hz.

Figure 4. Modal analysis for HoloTop NX mechanical sensor design with the first four natural frequencies: (a) 520.3 Hz (b) 582.28 Hz (c) 1879.4 Hz (d) 1947.3 Hz.
2.3 Electronic design

With the experience already acquired on multi-axis systems, and thus the need for internal data preprocessing, an embedded system for sensor-internal data evaluation has been designed. Figure 3b shows an exploded view of the sensor including the electronics stack (green rectangle) consisting of three printed circuit boards (PCB): NVIDIA® Jetson Xavier™ NX, CONNECT TECH Quark Carrier, and HoloTop NX PCB. It provides the possibility to control and measure parts of the sensor system, preprocess, evaluate and transmit the data, and communicate with our software ecosystem.

Figure 5 shows the architecture of the integrated electronics stack: The NVIDIA® Jetson Xavier™ NX serves the function of an embedded computing board, which can run a Linux-based operating system and provides up to 21 TOPS of computing power. It consumes as little as 15 W, and contains 384 NVIDIA CUDA® Cores, allowing to run neural networks or process data from high-resolution sensors such as HoloTop NX, in a small form factor of 70 mm × 45 mm.

The Quark Carrier by CONNECT TECH is compatible with the NVIDIA® Jetson Xavier™ NX. It is used as a breakout board and features several inputs and outputs, for example, USB 3.1, Gigabit Ethernet, MIPI CSI interfaces, and many other communication protocols to interface embedded systems. In its handy size of 82.6 mm × 58.8 mm, the Carrier is used as an interconnect between the NVIDIA® Jetson Xavier™ NX and the HoloTop NX PCB.

The last component, namely HoloTop NX PCB, serves as an interface between the computing unit and holographic sensor and comes in the same size as the NVIDIA® Jetson Xavier™ NX. With its microcontroller core, which makes it possible to communicate with the embedded system using USB type C, it collects acceleration and temperature data and controls three stepper motor drivers and a piezo actuator driver. The PCB also contains several buck and boost converters to supply both laser and Carrier with 15 W, to power the motors, and is also able to charge and manage a battery. It uses USB type C Power Delivery, enabling to get up to 100 W of power. Without a USB connection, the system can be powered by a built-in battery pack.

![Diagram](image_url)

Figure 5. HoloTop NX Stack block diagram and interface overview: The embedded system consists of three parts serving as processing unit (NVIDIA Jetson Xavier NX), interface unit (Quark Carrier) and control unit (HoloTop NX PCB).
3. RESULTS

After introducing the measurement data quality of the HoloTop NX measurement system on a stationary fixture, vibration investigations on different carrier systems are presented. The focus will be on the collaborative robot UNIVERSAL ROBOT UR16e; first measurements were presented in 12. In previous studies, the 5-axis machine tool HERMLE C32 U has been introduced and characterized in detail in with our prototype sensor HoloPort 9, 13, 5. Measurement results can be found in 2, 5, 14. Additionally, first vibration studies on a LEITZ Reference HP 15.9.7 coordinate measuring machine will be presented.

3.1 Sensor

Figure 6 shows measurement results of the HoloTop NX sensor on a 10 Euro Cent coin, recorded on a conventional worktable without any damping. Figure 6a shows the height map of a single measurement – impact marks of the coin in the micrometer range are clearly visible. Figure 6b demonstrates the pixel-wise standard deviation over five measurements. Except for the steep edges of the mintage, the standard deviation is always well below 1 µm. The achievable axial measurement accuracy is determined by the choice of lasers and is typically less than 1/50 of the smallest synthetic wavelength used.

For these stationary measurements, we used the temporal phase-shifting configuration with three phase-steps4. Three fiber-coupled diode lasers with wavelengths of 632.91 nm, 633.84 nm and 642.87 nm and a maximum fiber output of 50 mW. The camera exposure time was set to 5 ms. Two of three possible synthetic wavelengths at 432.48 µm and 40.8 µm were used for height reconstruction. Height data was filtered using an amplitude-weighted 2 px radius mean filter.

3.2 Carrier Systems

As an interferometric measurement method, digital holography is very sensitive to vibrations, making its use on multi-axis systems a major challenge. In the direction of the sensitivity vector, oscillations are particularly disturbing that they directly affect the interference contrast and thus the quality of the measurement data. Lateral displacements lead to blurring and decorrelation of the speckle images in the range of the speckle size and thus about one order of magnitude less critical9. In the further course of the paper, mainly oscillations in the direction of the sensitivity vector are investigated.

The z motion introduced by an occurring oscillation with an amplitude $A_z$ and a frequency $f$ during the exposure time $t_e$ has a maximum of

$$\Delta z_{\text{max}} = 2A_z \sin(2\pi f t_e / 2)$$

(1)
However, a motion in measuring direction has a twofold effect on the optical path length of the object beam, so that the influence on the measurement result is doubled.

With temporal phase shifting, the different lasers are coupled to the sensor one after the other and several phase steps are recorded per laser. Thus, additional movements between the exposure times affect the measurement data with a maximum amplitude of the vibration itself and superimpose on the phase steps of the temporal phase shifting Δφ:

\[
\Delta \phi = \frac{\lambda}{n} \sqrt{2}
\] (2)

For three phase steps \( n = 3 \) and a laser wavelength \( \lambda \) of 633 nm, this is 150 nm for HoloTop NX with a 45° mounted piezo actuator. With a typical exposure time of 1 ms, a theoretical camera frame rate of 1000 Hz becomes possible. For the camera used in HoloTop NX, the maximum frame rate is 30 Hz and therefore falls within the scope of the vibration range of multi-axis systems\(^9,15-17\).

Machine Tool

Machine tools must handle very large dynamic forces and are accordingly robust and rigidly built. Compared to collaborative robots and coordinate measuring machines, they represent the most rigid system and were therefore selected as the first carrier system to develop holography on multi-axis systems. The resulting first sensor prototype HoloCut/HoloPort has already generated extensive experience regarding vibrations on HERMLE C32U and RÖDER RXP DS500 machine tools.

With a dominant frequency of 84 Hz at typical 50 nm vibration amplitude, the maximum expected vibration amplitude for an exposure time of 1 ms is 26 nm and thus still clearly smaller than a phase step of the temporal phase shifting. In past investigations, only the highly dynamic spindle control showed a very disturbing influence on the measurement data quality.\(^9\)

Due to the rigid design of the Hermle C32U machine tool, it is assumed that no metrologically relevant differences from the previous HoloCut/HoloPort sensors will be observed in future investigations with HoloTop NX.

Coordinate Measuring Machine

Coordinate measuring machines usually feature a similar gantry-type design compared to machine tools. However, due to the application they differ significantly in terms of mass and stiffness of the gantry and the z-axis.

Initial investigations on a Leitz CMM with HoloCut showed vibration amplitudes of 100 nm in a quiet environment. With a dominant frequency around ~50 Hz (10-80 Hz observed) during an exposure time of 1 ms, this leads to a maximum motion of 31 nm. In \( x \)- and \( y \)-direction more than 100 nm amplitude each were measured. It is suspected that the weight-optimized, long z-axis is easily excited to vibrate by the additional load of the 7.5 kg HoloCut sensor. Compared to the machine tool, this is the most obvious difference. While bending and twisting of the z-axis with a length \( l \) about an angle \( \alpha \) have an effect in the z-direction of only \( l \cdot (1 - \cos \alpha) \), the influence in the \( x \)- and \( y \)-direction is \( l \cdot \sin \alpha \).

Since the test machine was only decoupled from the substrate by passive damping (in contrast to the available active damping package), movements in the z-direction of more than 1 \( \mu \)m could be observed during a jump next to the machine. FRAUNHOFER IPM plans to provide more data from its LEITZ Infinity CMM with HoloTop NX later this year.

Robot

Robots are characterized by a very high flexibility and diversity. This makes them particularly interesting for increasingly tighter manufacturing cycles and production applications. In addition to established handling and assembly tasks, much of the research focuses on using them for machining tasks\(^18\). In this context, modal analysis plays a major role in evaluating robot behavior in the workspace\(^15-17\) and hence increasing achievable accuracies\(^18\).
This makes the use of fast measurement technology in production particularly interesting, as it offers the potential to monitor and compensate for 100% of production errors.

However, according to the current state of the art, in terms of accuracy and in respect of vibrations, robots pose a much greater challenge for interferometric measuring systems such as digital holography than typical machine tools and coordinate measuring machines. Early investigations with the HoloCut sensor on a KUKA KR300 R2500 for use in manufacturing were promising, even if only a few consecutive measurements were successful.

FRAUNHOFER IPM therefore first chose a collaborative robot of the type UNIVERSAL ROBOT UR16e, which allows a much simpler operation, and which will be characterized in the following in terms of controller behavior and resulting oscillations in interaction with HoloTop NX.

Figure 7 shows the experimental setup used for the vibration measurements: Two poses were investigated – a pose with a (a) long lever arm of \(~900\) mm and (b) a short lever arm with \(~200\) mm. HoloTop NX was mounted directly onto the robot. Measurement were conducted using a MICRO-EPSILON confocalIDT IFS2402 confocal sensor and a MICRO-EPSILON confocalIDT IFC2451 controller for frequencies up to 10 kHz. The sensor was mounted directly on the beam exit of HoloTop NX and, for maximum resolution, aimed at a vise-mounted mirror as the measurement object.

![Experimental setup for vibration characterization](image)

Figure 8–Figure 11 show exemplary selected measurements in time and frequency domain. The observations collected during the measurement campaign are summarized below. For a complete characterization, a modal analysis has to be conducted\(^{15-17}\).
Figure 8. Steady state measurement in $z$-direction with long lever configuration and payload compensation turned off. Despite the steady state, movements in the range of several micrometers are clearly visible. Observed frequencies are well below 100 Hz.

Figure 9. Steady state measurement in $z$-direction with long lever configuration and payload compensation turned on. No axial movements observable. Occurring frequencies are well below 100 Hz.

Figure 10. Dynamic measurement with $0.5 \times v_{\text{max}}$ in $z$-direction with short lever configuration and payload compensation turned on. There is no overshoot, however a dominant remaining frequency of ~60 Hz is present.

Figure 11. Dynamic measurement with $0.5 \times v_{\text{max}}$ in $x$-direction with short lever configuration and payload compensation turned on. A strong overshoot takes place, no dominant remaining frequency can be observed.
Frequency and amplitude of the vibrations strongly depend on the measuring direction and the lever of the robot. For short levers, dominant frequencies are in the range of 30-40 Hz (Figure 10, Figure 11), whereas for longer levers, they decrease down to 10 Hz (Figure 9). Frequencies of 10-70 Hz were observed over the entire workspace, but no components above 100 Hz. The influence of the robot's closed loop could not be noticed when payload compensation was activated. This is particularly important for dynamic measurements. However, for external excitations, the positive influence of the closed loop clearly shows up since disturbance are eliminated more quickly. With the payload compensation deactivated, movements in the micrometer range are visible even after several seconds (Figure 8). Otherwise the robot position is typically settled after 1 s for short levers and maximum speeds up to \(-0.5 \times v_{\text{max}}\); for long levers we determined times up to 3 s. For higher maximum speeds such as \(-0.75 \times v_{\text{max}}\) strong overshoots could be observed which resulted in a longer transient response. However, no obvious relationship was found between lever arm, speed, and type of overshoot. Still, for low speed, these could be compensated faster in each case.

In the best case, residual vibration amplitudes of 0.5 µm could be observed in the \(x\)-direction and \(y\)-direction, and even 1 µm in the \(z\)-direction. If possible, measurements should therefore not be taken in the \(z\)-orientation to decouple increased oscillations from the sensitivity direction of the measuring system. Compared to the carrier systems already presented, during exposure, a maximum motion of 156 nm for an exemplary frequency of 50 Hz can be expected. This value is exactly in the range of the internal phase steps and will certainly have a strongly disturbing effect.

Algorithmic approaches such as cascaded data assessment\(^9\) or the spatial phase shifting setup will be mandatory.

4. SUMMARY

We presented a new sensor design for the use on multi-axis systems such as machine tools, coordinate measuring machines and robots. With a diameter of 125 mm and a height of only 180 mm it is small enough for automatic loading from a typical machine tool changer. Its weight of less than 2 kg enables it for use with coordinate measurement machine interfaces such as HEXAGON Senmation. An integrated embedded system allows system control and pre-evaluation of recorded data and thus iterative measurement acquisition. This is especially useful for the use of environments prone to vibrations.

Exemplary measurements of a coin recorded at a static mount with pixel-wise sub-micron precision across the full 12.5 \(\times\) 12.5 mm field of view demonstrated the data quality of the new sensor system.

Knowledge gained in previous work at our institute regarding vibrations on machine tools and a coordinate measuring machine was collected and new results were obtained on a collaborative robot.

5. OUTLOOK

In future works, we are going to work on sensor-internal vibration compensation using the integrated embedded system for measurement on multi-axis systems with vibrations in the micrometer range. FRAUNHOFER IPM will operate its own LEITZ Infinity CMM with Senmation interface for this purpose. A modular deflection unit is intended to make even hard-to-reach surfaces accessible.

In addition, we are planning to integrated the yet external laser system as a separate module for the system to work independently and automatically from a machine tool changer.
6. REFERENCES


