

Optical Sensors for In-Process Monitoring

Conceptual Considerations for the implementation of Optical Sensors into the Production Environment

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Abstract:

In this contribution some conceptual considerations regarding the implementation of optical sensors for process control will be given. Therefore first a classification of monitoring systems related to the level of process integration is made. In a second step there will be a description of relevant features for the characterization of the process state. Furthermore there a description of factors resulting from the machining process that have possibly an impact upon the measurement result is given.

As an exemplary implementation of an optical sensor near the machining process a concept for a robust and miniaturized sensor probe based on chromatic confocal microscopy with gradient index (GRIN) lenses will be presented.

Introduction

Due to the rising requirements regarding the functionality of the products, fabrication is getting more complex. To guarantee high process monitoring of manufacturing is necessary, to be able to respond to external influences that would disturb fabrication [1].

Because of that, process control has become more and more important for modern production systems [2, 3]. While in the past the main challenge for monitoring systems was to prevent damage to the production machine or the tool and to operate the machine within the given specifications depending on factors like temperature, humidity or vibration, in the last years the control of quality relevant features was becoming more important.

Therefore new concepts for quality monitoring and control are needed, because today's monitoring systems are in general not able to collect relevant data. Optical measurement systems are in general able to obtain quality control. But the available concepts for optical sensors are in most cases not suitable for the integration near the production process. For that reason quality control is often implemented as a post-production process. But in case of malfunction there is always a certain time lack. To reduce the feedback time and with that the possible production waste, the aim is to implement the systems for quality control as near as possible to production. An example for the integration of an optical sensor for quality control

in a production machine for diamond tools is given in [4]. But to guarantee a successful process monitoring, considerations regarding the implementation of optical measurement systems in the production environment has to be obtained.

Classification of monitoring systems

For the implementation of monitoring systems into the machining process there exist different approaches [5–7]. To give a systematic overview of the different concepts the monitoring systems will be classified regarding their degree of integration [8, 9]. With respect to the location of the inspection system they have to be differentiated and classified as (see Fig. 1: Different degrees of integration of optical sensors into the production processes):

off-line, where the machined object has transported to a separate test location. The information is collected there and the result is reported to the production machine, machine integrated (*in-situ*), where the inspection system is integrated into the manufacturing system but still separated from the direct machining, and tool integrated (*in-process*), where the sensor is located nearby the processing tool or embedded into the tool.

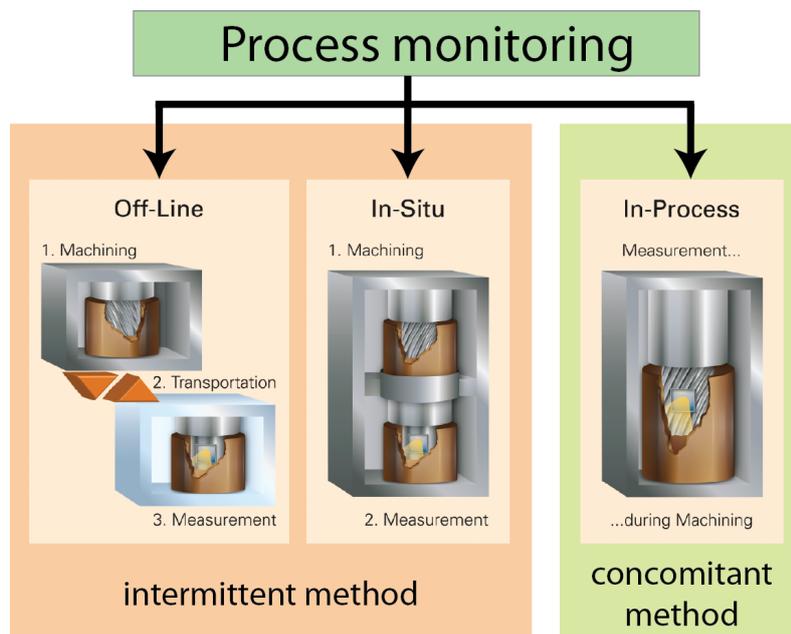


Fig. 1: Different degrees of integration of optical sensors into the production processes

On the one hand the time between error detection and implementation of corrective action is decreasing with an increasing integration depth from off-line, machine integrated to tool integrated monitoring. But on the other hand the difficulty for a successful implementation of the measurement system is rising with a higher integration level.

Environmental influences to optical measurement system

The greatest challenge for optical sensors for in-line process monitoring is the influence due to the production environment. In machining there are in general disturbances due to temperature variation, vibration and contamination of the surface by cooling liquid and chips.

Temperature variation has an effect on the optical measurement because the temperature dependency of mechanical elements has an effect on the optical path length of the sensor. With that comes a change in the detected signal which leads to a false measurement result.

Mechanical vibration leads to a relative movement between sensor and object. Even if a single shot measurement is obtained, a certain exposure time is needed. With that comes that there is in any case a small failure in the measurement result because of vibrations.

Another main reason for failures in the in-line measurement during machining with optical sensors is given by the contamination of cooling liquid or metal chips on the surface. Especially liquid on the surface has due to the differing refractive index an effect to the measurement result because the optical path difference (OPD) will change. An approach to measure with cooling liquid existent at the object surface is given in [10].

Optical Design of the Sensor system for process integration

For the implementation of an optical sensor near the machining tool it is necessary to have a robust principle that has the potential for a high miniaturization. A promising approach is chromatic confocal microscopy. It facilitates one-shot measurements and it allows a miniaturized, simple and robust design of the sensor. Therefore the design of a chromatic confocal point sensor will be presented, that is suitable for implementation into the production environment, e.g. near a lathing tool.

For the assignment of appropriate sensor parameters it is important to have a look at the designated measurement task and the operation area. In Fig. 2 the most important criteria that have to be considered are displayed. The measurement task gives the needed resolution, uncertainty and measurement speed. For an implementation of an optical sensor into a lathing process with a production accuracy of 10 μm (standard tolerance class IT 7 [11] for parts smaller than 3 mm) a resolution of the measurement system of roughly 0,1 μm is needed. Because the measurement sensor is aligned in normal direction to the object surface, this resolution is needed in the axial direction. To measure surface roughness the spot radius needs to be smaller than 5 μm corresponding to the defined radius of the probe tip of typical tactile roughness measurement devices [12].

The general requirement is to implement a miniaturized design of the sensor to enable an In-process integration. Therefore gradient index (GRIN) lenses will be used for the optical

setup. The basic principle is that a material with an inhomogeneous refractive index is used [13]. Due to the continuously increasing refractive index in a glass rod an arched light path is generated and with that a lens effect is obtained. For this reason it is possible to design optical systems with small dimensions (i.e. a diameter of a few millimetres and a length of a few tens of millimetres).

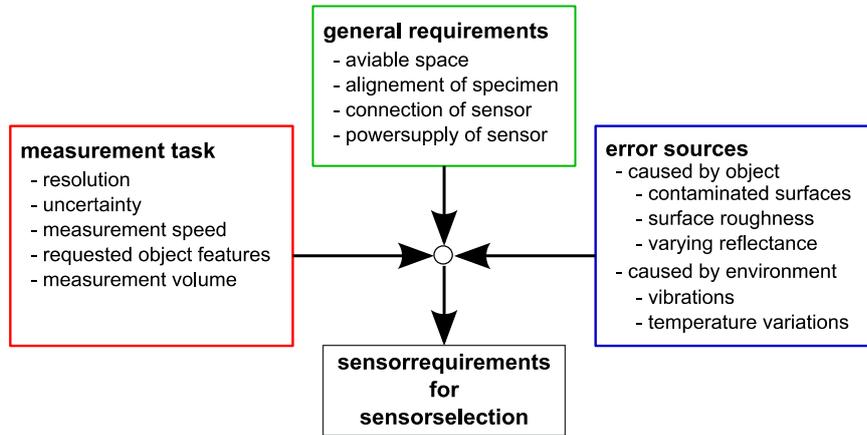


Fig. 2: Important criteria for the selection of appropriate sensor parameters

In Fig. 3 the proposed design of the chromatic sensor is displayed. To generate a wavelength dependent focal position a diffractive optical element is used to generate a chromatic split. To have a design with the fewest possible elements, that could induce errors the DOE is directly written to the front surface of the GRIN element. As a light source a fibercoupled superluminescence diode with a bandwidth of 60 nm is used and is connected to the GRIN sensor using a Y-coppler. With the proposed design a measurement range of 300 microns is realized. The single mode fiber acts as the confocal pinhole for the detection of the reflected light. The relevant data of the proposed setup is summarized in Table 1 and in Fig. 3 the designed layout, the achieved spot digramm for the point detector, the wavefront map and the phase plot for the DOE is displayed. As displayed in Fig. 3 c) a diffraction limited imaging is obtained.

Table 1: Specification of the chromatic confocal sensor

| | |
|-------------------------|---------------------------|
| Bandwidth | 800-860 nm |
| Numerical Aperture | 0.17 |
| Airy spot radius | 2.9 μm |
| Depth measurement range | $\approx 300 \mu\text{m}$ |
| Sensor diameter | 2 mm |
| Sensor length | $\approx 15 \text{ mm}$ |

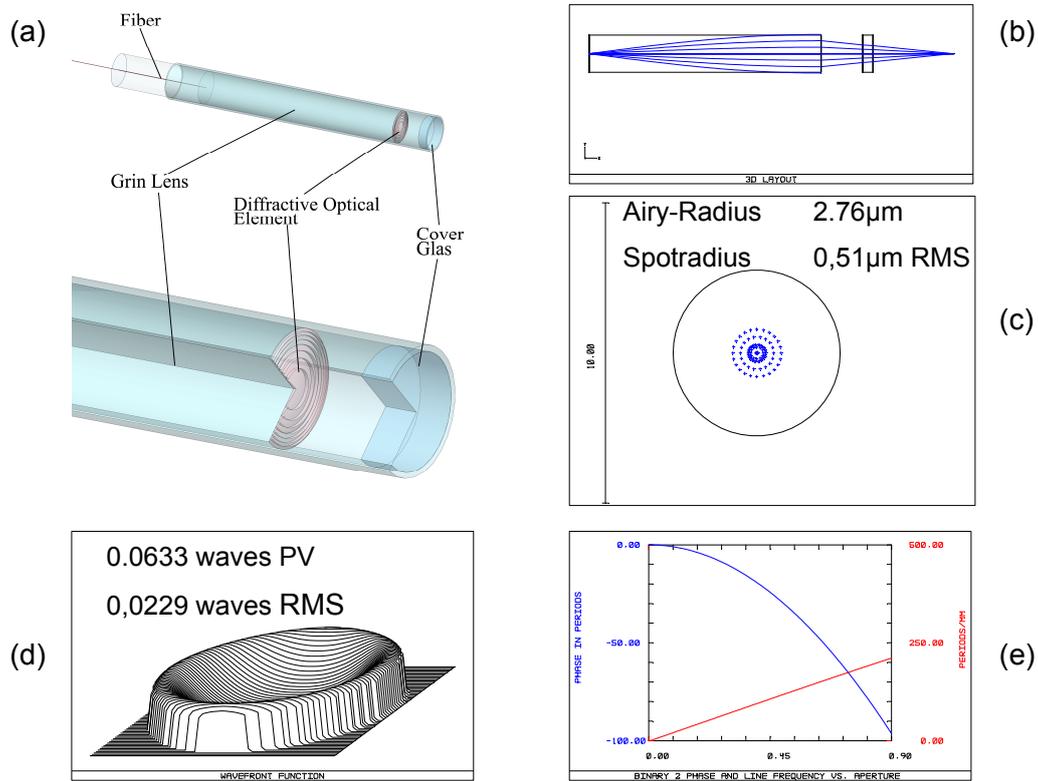


Fig. 3: Design of a chromatic confocal sensor: a) concept of the sensor based on GRIN lenses and DOE, b) sensor layout c) Spot diagram at 830 nm, d) wave front map of the middle wavelength e) phase plot of the DOE

Conclusion

In a systematic consideration different approaches for process monitoring have been shown and classified. For in-line process monitoring of quality relevant features optical systems seem to be a promising solution. But these sensors have to handle some critical aspects that are resulting from the measurement environment. These are mainly vibrations, temperature variation and contamination of the surface. However, a design of a chromatic confocal sensor was presented that has a miniaturized design and is very robust due to its simple set up. The design with a DOE written on the front side of the GRIN lens realizes a high depth measurement range even with a comparably small bandwidth of 60 nm. In future works the implementation of the proposed sensor setup into a production process has to be obtained.

Acknowledgement

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