Conceptual consideration for the integration of optical sensors for In-Process monitoring

David Fleischle[1,2,#], Wolfram Lyda[2], Florian Mauch[2] and Wolfgang Osten[2]

1 Graduate School of Excellence advanced Manufacturing Engineering, Universität Stuttgart, Nobelstr. 12, 70569 Stuttgart
2 Institut für Technische Optik, Pfaffenwaldring 9, 70569 Stuttgart
Corresponding Author / E-mail: fleischle@ito.uni-stuttgart.de, TEL: +49-(0)711-685-69892 FAX: +49-(0)711-685-66586

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Optical sensors are often not robust enough to be used on the shop floor. Therefor already in the development of the concept for new optical measurement systems the implementation near the production facility has to be considered. To give the optic designer a guideline, which factors have to be considered and what measures can be taken to prevent or reduce the effect of the production environment on the measurement result, a conceptual consideration of the most relevant factors will be given.
At first a classification of monitoring systems with regard to their level of process integration is given. In a second step there will be a description of relevant parameters for the characterization of the process state. Furthermore a description and specification of factors resulting from the machining process that possibly have an impact upon the measurement result is given. Different approaches to reduce or correct for this impact will be discussed. These approaches include robust mechanical design as well as model based approaches that use simulation of the optical system to estimate the impact of the production process. Concluding the considerations, a guide to estimate the measurement error due to the process impact will be given.

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NOMENCLATURE

OPD = optical path difference

Hz = Hertz (SI-Unit for frequency)

1. Introduction

In today's manufacturing systems a continuous monitoring and control of the machining result and the product quality is needed to guarantee the requested product performance [1]. Because of that, process control was in the last years an operation that becomes more and more important for modern production systems [2, 3]. Nevertheless quality control is since many years an established segment in almost every company; it is still a bottle neck for a continuous monitoring of the production output. Though, while almost any relevant data from the production process is gathered and transferred to a data-warehouse, the information about the product quality is generally only collected for random examples.

However, a consistent database of each product is requested for future manufacturing systems, quality data for every product and production step is needed as well. Only with that information a continuous data chain containing all information about manufacturing of the product can be established. Therefor new concepts for quality monitoring and control are needed, because todays quality systems do not, or only with a high effort, allow a collect of all relevant data.

For this reason new concepts for in-line process monitoring based on optical measurement systems will be suggested. With the proposed approach a supervision of quality relevant features during the machining process should be possible and for this reason offer the possibility to establish a consistent information database over the whole manufacturing process of a product.

2. Classification of monitoring systems

For monitoring of machining processes there are different approaches [4–6]. These will be introduced and classified for a systematical consideration which approach can be used for in-line monitoring of quality relevant features during the machining processes. While monitoring systems are essential for a reliable machining and are already state of the art in modern production machines, the specifications vary strongly for different applications. Monitoring systems suitable to ensure a reliable production might not be suitable for the supervision of quality relevant features during machining.

2.1 Direct vs. Indirect monitoring

A crucial differentiating factor is given by the correlation of the detected signal to the monitored parameter; hence monitoring systems can be classified into *direct* and *indirect* systems (see Fig. 1).

Indirect monitoring is given if the recorded data is not directly related to the observed parameter, but can only be resolved with a correlation of the measured data. Symptomatically an absolute determination of the desired parameter is in most cases not possible instead relative change of the process state can be detected.

Direct monitoring systems allow a direct determination of the desired parameter. A correlation of the measured data is not necessary; hence direct monitoring is in general more precise than indirect monitoring, because each correlation implies a loss in accuracy.

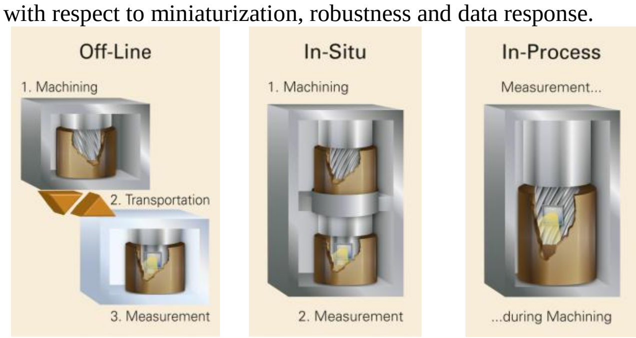
Fig. 1 Classification of process monitoring regarding the relation of the measured signal to the monitored parameter

2.2 Classification regarding the degree of process integration

Sensor systems used for monitoring of manufacturing processes can also be classified regarding their degree of integration [7, 8]. With respect to the location of the inspection system they have to be differentiated and classified as (see Fig. 2 Different degrees of integration of optical sensors into the production processes):

- *off-line*, where the object after machining has to be taken and transported to a separate test location. The needed 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/*in-line* integrated, where the sensor is located nearby the processing tool or embedded into the tool.

Off-line inspection allows in general only spot testing of the produced objects. Consequently, if the significant parameters are running out of the specification there is in any case a certain delay until the result is reported to the production machine. Due to that, using off-line inspection a, certain amount of reject has to be accepted. With a machine integrated inspection the time delay is already reduced and a in case of a production failure, an appropriate counteraction can be enforced much faster. However, a simultaneous inspection during the processing is only achieved with real in-line integration. Here the inspection is done while the product is still in processing and the response is reduced to a minimum. But the challenges for the sensor are comparatively high with respect to miniaturization, robustness and data response.



a) b) c)

Fig. 2 Different degrees of integration of optical sensors into the production processes

3. State of the art in process monitoring

Process monitoring is already state of the art regarding the monitoring of the condition of a production process. For example wear of guides in machines is estimated evaluating the energy consumption [9]. There are many other examples where data of the machine (e.g. energy consumption, driving speed,…) is used for a correlation to obtain a measure for a parameter that is relevant for an undisturbed operation of a machine [10, 11].

But there is a drawback of these monitoring approaches. Even though they are suitable to avoid a breakdown of the production machine, a conclusion about the quality of the produced product is in general not possible. While there are some approaches to come to a statement about the quality even with monitoring of indirect parameters, these conclusions about product quality are in general not reliable and do not substitute quality control.

Hence, monitoring of quality relevant features can only be obtained by capturing signals that have direct connection to this feature. In Fig. 3 some common approaches for monitoring systems are shown, regarding there complexity needed to come to a statement about the product quality and there feasibility for a direct integration into production processes. It can be seen, that those systems that allow the highest integration depth, have the highest complexity needed for correlation.

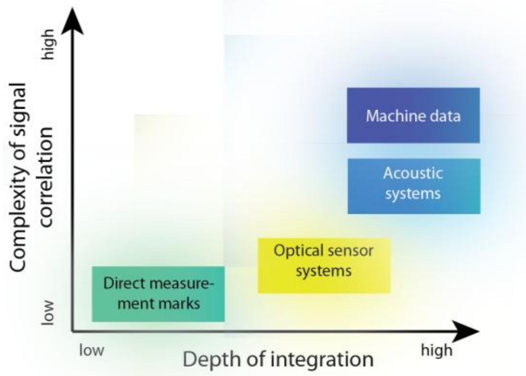


Fig. 3 Complexity of the correlation to come to a statement about the product quality of some monitoring systems

While direct measurement marks, i.e. strain gauges that are bonded to the object surface, have the simplest correlation to the monitored parameter, they show the lowest integration depth.

Because the measurand can only be extracted after machining has occurred.

The forth possibility for monitoring of quality relevant features are optical sensor systems. They are already state of the art for the offline measurement of object properties, like geometry, form and surface roughness. Even though they have the potential for a high depth of integration into the production process, they are usually not robust enough to obtain reliable measurement during machining. However in the last years, some investigations have been done to overcome these problems. For example in a research project a grinding machine for diamond tools is developed where an interferometric sensor is integrated into the machine to obtain monitoring of the production state [12].

4. Optical measurement systems for process control

There are many optical measurement principles for the acquisition of form and surface parameters, each having its advantages and disadvantages. A short overview of measurement systems that are suitable for monitoring of quality relevant features shall be given. In this contribution we will focus the review on systems with a high lateral and depth resolution. With that systems like distance sensors based on the evaluation of detected light intensity reflected by the object can be neglected because they have a very low lateral resolution. With respect to their operation method the sensor systems can be classified into three groups, i.e. triangulation based systems, focus systems and interferometric systems [13].

	Measurement of rough surface	One-shot sensor setup	Mechanical scan	Complexity of signal evaluation	Sensor miniaturization
Lasertriangulation	+	+	No	+	0
Fringe projection	++	-	No	0	0
Deflectometry	--	0	No	0	0
Auto-focus systems	++	-	Yes	+	++
Confocal microscopy	+	-	Yes	0	++
Chromatic confocal microscopy	+	+	No	0	++
Conoscopy	-	+	No	-	++
Interferometry	--	-	Yes	-	0
Heterodyne interferometry	--	-	Yes	-	0
White-light interferometry	+	0	No	-	+
Spectralinterferometry	+	+	No	-	+
Chromatic-confocal Spectralinterferometry	+	+	No	-	+

Table 1: Summary of the most relevant optical principles for measurement of quality relevant features

In Table 1 a selection of measurement systems is summarized and evaluated according to the most important requirements for the intended application. Though the focus will be at the most robust class of sensors, the point sensors, a criterion for the complexity of the implementation of such a sensor design is added. Reviewing that summary there are only a few sensor principles that seem to be applicable for operation near the machining tool. To find the best suited sensor further investigation has to be done considering chromatic confocal microscopy, spectral interferometry, chromatic-confocal spectral interferometry and white-light interferometry. Though all these sensors show potential to handle the challenges, i.e. they are able to detect a height profile in one shot and show the ability to measure rough surfaces.

5. Environmental influences to process relevant parameters

The greatest challenge for optical sensors for in-line process monitoring is the influence due to the production environment. Which parameters have the biggest influence depends on the considered process. But 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.

6. Counteractive measures to prevent influences to the measurement

Even though the presented optical sensors are in general able to measure quality relevant features, challenges to use them in-line in production processes are still present. New concepts have to be applied in sensor design and signal evaluation to overcome the problems going along with the production environment. A few approaches will be presented. But even if it is not possible to eliminate all influences to the measurement signal, an estimation of the impact to the measurement has to be obtained. For the operator beeing able to decide if the reliability of the measurement is high enough to guarantee the desired quality or if a separate, more precise control has to be obtained.

To simplify the problem of the failure consideration a schematic approach for the treatment of the different fragments of the signal formation process will be obtained. In Fig. 4 this process is displayed. The sensor signal is given by the interaction of the specific answer of the sensor system, the response of the reflected light by the object and the influences of the environment. It is assumed that the measurement is taken in the production machine, because of that besides the sensor signal some machine data about the state and position is needed to obtain the signal evaluation. The last step to get the topography is, to apply a suitable algorithm for signal evaluation. This algorithm has to be considered too, to get a complete consideration of the topography description.

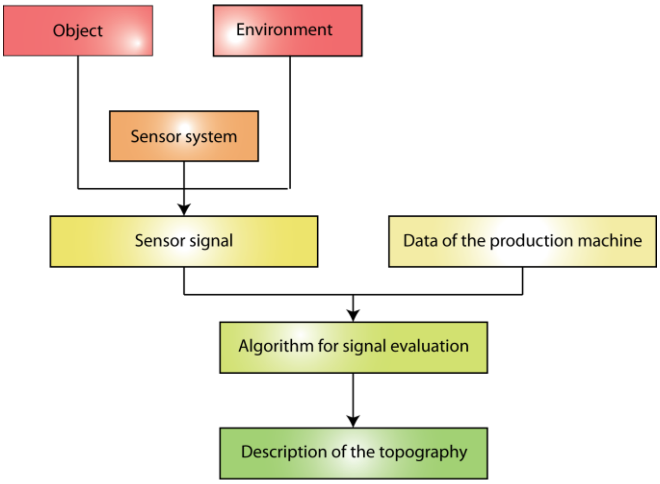


Fig. 4: Schematic signal formation process to obtain the description of object topography

In general the most important measure to eliminate or reduce the influence of the production environment is to imply a robust sensor design. With a theoretical model-based approach to investigate into to the influences of the environment, the main error sources can be determined and interpreted. This knowledge can be used to design a sensor that can adapt to the given environment.

6.3 Robust sensor design

To guarantee a reliable measurement the optical sensor has to produce traceable result even if the characteristics of the surface and the environment are changing. Only if that is possible a robust sensor design is given.

The sources for the impact of failures are in the mechanical design the single elements (i. e. lenses, apertures, optical filters,…). By reducing the number of elements, the measurement uncertainty for the whole system will be kept as low as possible. Let´s consider each element in the optical setup as an independent source for failure impact. In this case for each element the described influences of the environment in chapter 5 will have an impact add to the uncertainty u_y for the whole system all uncertainty by the single elements u_i has to be evaluated considering error propagation for independent error sources according to:

$$u_y = \sqrt{\left(\frac{\partial y}{\partial x_1} u_1\right)^2 + \left(\frac{\partial y}{\partial x_2} u_2\right)^2 + \cdots}$$

Let´s assume that the contribution of uncertainty for each element is the same and is normalized to 1. In this case the measurement uncertainty for the whole system depending on the numbers of elements in the sensor system is shown in Fig. 5. It is obvious, that with the number of elements the cumulative measurement uncertainty is rising.

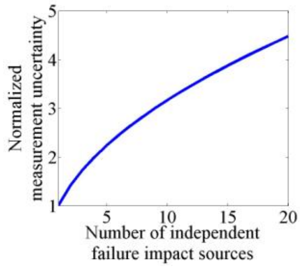
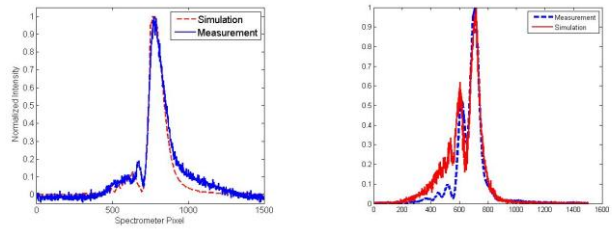


Fig. 5: Evaluated measurement uncertainty considering error propagation for a set of independent elements with a normalized uncertainty for each element

6.4 Model-based approach for theoretical determination and elimination of errors

The more sophisticated approach to investigate into the influences of errors uses a theoretical investigation. It is based on a ray-tracing simulation of the behavior of the sensor system. The intention is to generate an exact model of the optical sensor used for the in-line process monitoring. With the ray-tracing simulation and the implementation of environmental influences and characteristics of the object into the simulation at least the impact on the measurement result can be estimated.

In [14] an approach was presented that allows an estimation of the micro-topography by the simulation of a rough and micro structured surface. In this approach a huge set of different micro-topographies, i. e. steps, groves, tilted surfaces,…, was simulated and merged to a look-up table. In a algorithm to the best fit of the simulated signal and the measured signal of a random rough surface was computed (see Fig. 6). The estimation of the height position was obtained for the signals by the fitting process of simulated signals to measured signal and in a separate evaluation using a classical center of gravity evaluation. With both methods comparable results could be achieved. But for the simulation based approach the additional information of the micro-topography was obtained. Even if there was no possibility to verify that the simulated surface feature was present at the measured position, a good accordance between the simulated signal and the measured signal was observed (see Fig. 1).



a) b)

Fig. 6: Fitting of simulated signals to measured signals; red lines: simulated signal; blue line: measured signal. a) Measurement and simulation of a plan mirror b) Measurement of a rough surface and simulation of a micro step with roughness

In addition to the simulation of rough surface and the behavior of an optical sensor system to it, other environmental influences can be simulated too. Therefor a similar approach can be used. The basis for that investigation is also a simulation model using ray tracing. For the simulation and the evaluation of the influence of vibration a exemplarily result for a chromatic confocal sensor is shown in Fig. 7. The vibration was simulated as a relative movement of the object with a given frequency. For a given exposure time the object is moved with a given amplitude of the vibration and for each position a separate simulation was obtained. In the end the result for each simulation position of the object was combined. In Fig. 7 the simulation was obtained for vibration amplitude of 1 micron and frequencies starting from 50 Hz to 5000 Hz are superposed. It is obvious that with longer measurement times the error due to vibration is averaged and with that is decreasing.

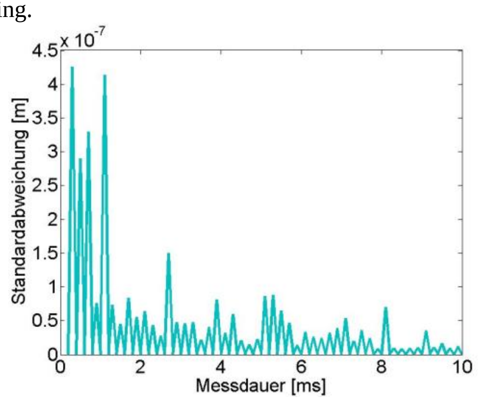


Fig. 7: Measurement uncertainty for different exposure times of the sensor by a superpose of vibration frequencies from 50 Hz 5000 Hz

The influences and possible solutions for contamination of thin cooling liquid films on the surface were investigated by Jackisch [15]. This approach is based on detecting not only the object surface but also the surface of the liquid in the measurement signal. If the refractive index of the liquid is known, not only the exact position of the object surface can be computed but also the thickness of the liquid film.

7. 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 in general they are not robust enough for reliable measurements in production environment. Therefore some approaches where presented that might help to solve that problem.

It was stated, that a robust sensor design is essential to obtain a reliable measurement. But also more sophisticated approaches seem to be a possibility to improve the reliability of the measurement result. Besides the use of a fitting procedure of simulated signals to measured signals to estimate the height position of the object, a simulation of the vibrations of the object have shown that there is a direct link between measurement uncertainty and exposure time.

However, to make optical measurement systems a reliable alternative to monitor quality relevant features in-line in the production machine, further investigations into the behavior of sensors in the specific environment of the production have to be obtained.

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