ROBUST ROUNDNESS MEASUREMENTS WITH SOFT X-RAYS

Stefan KASPERL[a], Rolf BEHRENDT[b], Björn DAMM[c], Christoph FUNK[a], Randolf HANKE[a], Jochen HILLER[a], Michael KRUMM[a], Ernst NEUMANN[d], Arno REHBEIN[c], Robert SCHMITT[c], Frank SUKOWSKI[a], Norman UHLMANN[a], Raimund VOLK[e], Alexander WARRIKHOFF[f]

[a]Entwicklungszentrum Röntgentechnik EZRT, Dr.-Mack-Str. 81, 90762 Fürth, Germany;
[b]Fraunhofer-Institut IIS, Am Wolfsmantel 33, 91058 Erlangen, Germany;
[c]WZL of the RWTH Aachen University, Steinbachstr. 19, 52074 Aachen, Germany;
[d]HOMMEL-ETAMIC GmbH, Prüssingstr. 41, 07745 Jena, Germany;
[e]HOMMEL-ETAMIC GmbH, Alte Tuttlinger Straße 20, 78056 VS-Schwenningen, Germany;
[f]rtw Röntgentechnik Dr. Warrikhoff GmbH & Co. KG, Hildesheimer Str. 5–9, 15366 Neuenhagen, Germany

ABSTRACT

In this paper a novel soft X-ray (XUV) measuring system for the fast inspection of soiled, cylindrical components in the production line is presented. The application of this system is inline metrology. Concerning measuring celerity and sensitivity to environmental influences both mechanical and optical measuring instruments are inappropriate.

The measuring principle is based on projecting the shadow of a shaft onto a sensor. Contour and roundness can be deduced from the projected object edge. In contrast to geometrical shaft measurements with visible light no focusing optics are used, but XUV-light in central projection. These soft X-rays are used for increasing the contrast between work piece (e.g. steel, ceramics, glass) and possibly present distorting debris like water, oil, dust, or swarfs. Therefore an efficient (high-capacity) micro focus source and a sensitive high-resolution detector have been developed. This paper presents the main elements (see figure 3) of the novel soft X-ray projection system, analysing strategies and results with practical examples.

Keywords: inline metrology, roundness measurement, soft X-rays

1. Introduction

In the industrial production process high precision parts are manufactured with small tolerances at high volumes. But due to individual wishes of the consumers the numbers of identical parts is small. This is a challenge not only for the flexibility of the production machines but also for the attributed inspection instruments. So the industrial inspection process has to be accurate, flexible and should be robust against contaminations of the manufacturing process, e.g. cooling lubricant. The presented method uses soft X-rays to get an outer image of the dimensions of the manufactured parts and has the potential to measure even contaminated parts flexible and accurate.

1.1 Common techniques for the industrial inspection of machined parts

Rising demands in tight tolerances and the trend to a fully automated production gives need for a continuous inspection of the dimensions of the machined parts. Typically the geometric form, precise length measurements and positional tolerances has to be estimated. Manufacturers and suppliers in the automotive industry have always to deal with such problems. Parts manufactured in that industry for example are valves, rotors, transmission and gear shafts, nozzles, turbine shafts, pneumatic and hydraulic parts, cam shafts and crank shafts. But there is also a demand for high precision production metrology in other branches like the aerospace industry or medical technology.

In the industrial production of machined parts today we find different need for inspection. All phases of the production process have to be controlled. The measurement tasks can be classified in small or large scale production. Furthermore it is important how near the measurement process can be placed to or even *in* the production machine. For the segment of Dimensional Measuring in the *Post-Process* chain today we will find mostly tactile and pneumatic methods. But the trend goes from inflexible measurement techniques (large scale production) to more flexible techniques, which is more suited for small series.
Nearer to the production process the choice for the measurement tool is often a tactile or pneumatic *In-Process* measurement. The problem here is with contamination of the work pieces because there is often not enough space or time for a thoroughly cleaning of the parts before measuring. Mechanical measurement instruments use tactile sensors to estimate dimensions of work pieces. This measurement principle is well known to be precise but slow. It is not very flexible, too. This is similar true for pneumatic measurement.
Optical dimensional metrology has the benefits of fast and accurate measurements. Due to the distance to the workpiece the exact form doesn't matter so that optical dimensional measurement is very flexible. Also it is easy to operate. Furthermore the danger of a crash of the measurement hardware with the workpiece is lower compared to tactile measurement. The measurement accuracy is close to tactile technologies. But the main problem of optical dimensional metrology in the production environment is that the parts have to be clean.

1.2 Robust measurement strategies

In the industrial inspection process there are often big metallic parts to be measured. For example in the automotive industry high precision parts for combustion engines are manufactured at high volumes. The common material for those parts is iron. The surfaces of the machined parts are most often contaminated by residues of the manufacturing process, e.g. cooling lubricant. Non destructive testing of even huge metallic parts can be done as well by ultrasonic waves [9], but the transducers has to be in close contact with the measured workpiece which makes the method difficult to adapt to always changing part geometries in a production process with small part numbers. Contaminations may not be a problem because normally a contacting fluid is anyway needed.
On the other hand measurement can be done by computed tomography (XCT) [2]. But measuring big iron parts needs high voltage X-ray sources which are difficult to handle and to protect against. So XCT is most often limited to iron parts of only smaller dimensions. While XCT measurement needs the complete transillumination of objects to get the inner structures, the use of X-rays to measure only the outer form of an object will be presented.

2. XUV measurement

The goals of the development of the optical dimensional metrology are to remove the biggest disadvantage from the optical shaft measurement: The cleanness of the manufactured parts. Furthermore there should be future potential to improve the measurement accuracy.

2.1 A new approach

The key is to change the light source. In the short range of the electro-magnetic spectrum the absorption length of the radiation in the contaminations on the work pieces can be much longer compared to the absorption length of said radiation in the dense material of the workpiece. The residues on the manufactured part consists mainly on oil, dust, water or a mix of that. In spite of that the manufactured parts consist on metal, mainly steel. The light used for imgaging the object should give a strong contrast between the contaminations and the body of the workpiece – contaminations should be nearly transparent and the object should be opaque. Further benefits are that there is only little influence of scattered light [10].

If the wavelength is chosen *short enough*, i.e. below a corresponding acceleration voltage of about 5 kV, the absorption in normal pressured ambient air is negligible. This means that there is no need to operate in vacuum as in similar approaches in the lithography working at EUV at 13.5 nm. On the other hand the wavelength has to be *above a certain limit* which means for the acceleration voltage that it has to be below an upper limit. Below that limit the workpiece is sufficient opaque to the radiation. There exists no exact criterion but the limit is about below 100 kV. In that wavelength range the measurement machine is quite easy to shield. Closed machine housing is anyway necessary for touch protection against the moving parts of the machine.
The outer edges of the workpiece will be imaged with a sharp shadow nearly independent on the contamination layers as a residuum arising from the manufacturing process. In spite to the visible region of the electromagnetic spectrum only minor problems with scattered light are expected. Choosing a suited wavelength may also image both edges: The outer edge between air and the contamination layer and also the inner edge between the contamination layer and the workpiece. In that region of the electromagnetic radiation all indices of refraction are nearly the same – it all is very close to 1. This means that there is only negligible refraction of ray's incident under angles not equal to the normal of the boundaries. In other words: The rays propagate strictly straight away. So it is possible to determine the inner edges, too.

2.2 Principle of operation

Of course it would be nice to have x-ray optics, light sources and detectors as well the established powerful devices available in the visible range. Due to the lack of powerful x-ray imaging optics we chose a central projection setup.
There is one central XUV-point source, illuminating the workpiece in front of the detector. The workpiece in Fig. 1 will cast a shadow on the detector. The image of the shadow will be processed. With well known geometries of the setup the geometrical position of the illuminated edge of the workpiece can be estimated.

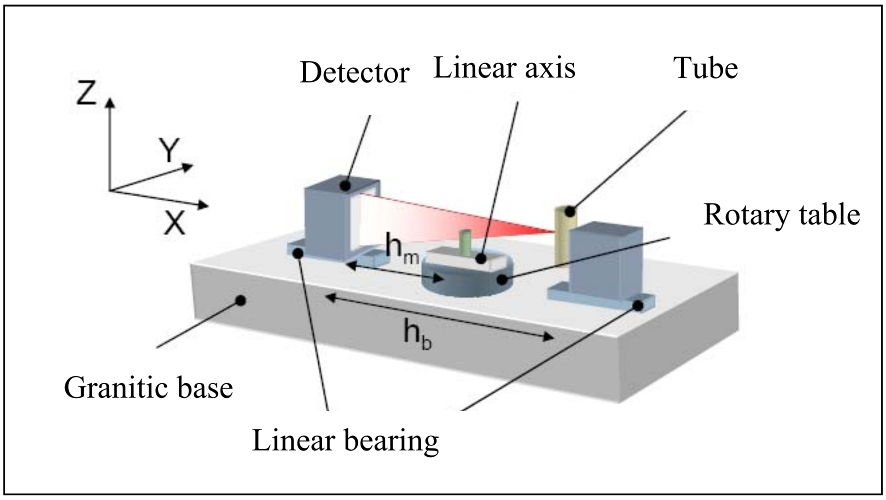

Fig. 1: Experimental setup. The workpiece (Shaft) is mounted on the linear stage which is fixed on the rotary table. [6]

The shadow is cast without any other imaging optics. So there is no risk on suffering on aberrations of any optics. The image sensor is a detector array classified for the XUV-radiation. It works in principal as a line camera. For the experimental setup a special arrangement of 256 parallel line-cameras on a single chip were chosen. The line-cameras arrange to a matrix of 1.024 x 256 pixels.
The circumference of the workpiece is reconstructed of a lot of shadows each projected under a different angle relative to the coordinate system of the workpiece. The reconstruction is performed as the alpha-hull [3] of all tangential bordering rays. In Fig. 2 three pictures shows the process of the reconstruction. For a better understanding the coordinate system of the workpiece was fixed.
The left picture shows the first projection. The only information on the workpiece after that measurement is that it has to be inside the dark triangle between the point source and the edges of

the shadows of the workpiece on the detector line. The middle picture shows the result of two measurements. The possible region for the outer dimension of the workpiece is already reduced. Doing this process very often, say every 0,5°, results in the roundness profile of the workpiece showed in the right picture. Rising the number of projections lead to the exact profile of every convex formed workpiece.

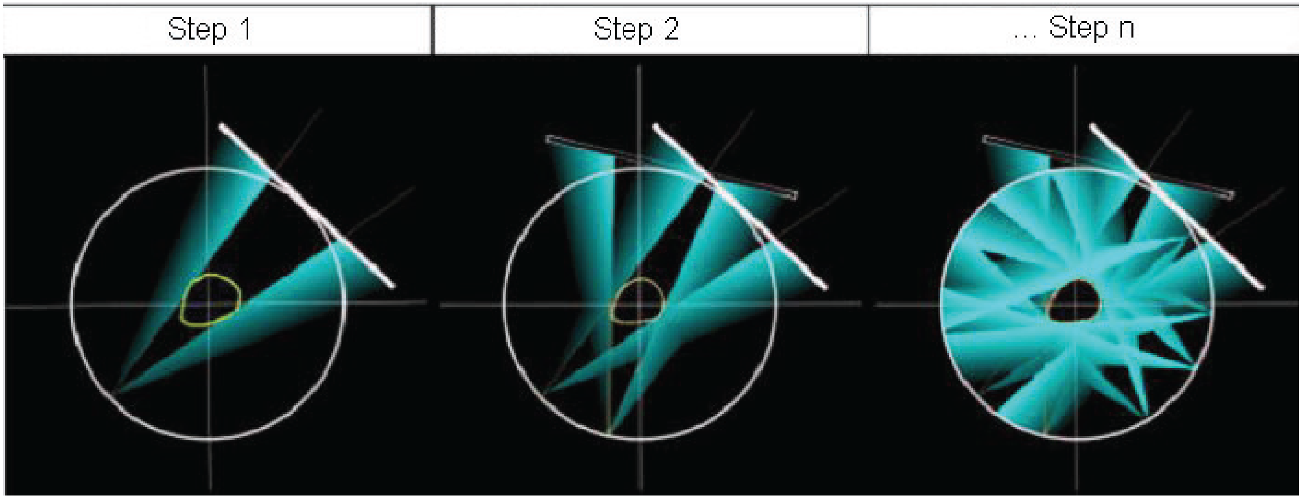

Fig. 2: Tangential bordering for reconstruction of the profile of the outer circumference of the workpiece. Here the workpiece remains in position while the measuring setup moves around the workpiece.

Moving the arrangement of the point source and image sensor perpendicular to the drawing plain while holding the rotational position fixed can measure the axial profile of the workpiece.

3. Experemental Setup

The experimental setup was sketched in principle in Fig. 1. The real laboraty setup with all components is described in the following section.
The *XUV* measurement system consists of the components visualized in Fig. 3. The *XUV* tube (vendor: rtw) is producing low energy X-Rays (with a maximum of 50 kV). These X-rays are detected by a time delayed integration camera (*TDI* camera), an in-house development of the Fraunhofer Institute for Integrated Circuits IIS. Located between these two components is a rotary table with precise rotation (vendor: Hommel Etamic), mounted on a linear axis. The object to be inspected is mounted onto that device via a three jaw chuck. This allows for the object to be moved into eccentric positions, thus enabling the simulation of a crankshaft. The object, located within the *XUV* beam, is mapped onto the detector by its shadow. A radiography of the object is *not* occurring. The exemplary setup of the components is shown in Fig. 3.
For determining the circularity the turn table is rotated around 360° and at defined positions shadow projections of the object are acquired. To compute the course of the edges an edge tracking algorithm (developed by the project partner WZL, see chapter 4.2) is used. From this course of the edges measured values can be computed that represent the tactile touch points from coordinate measuring at the surface of the object. Using these data the computation of diameter, circularity etc. of cylindrical objects is done. Calibration of the system setup is including a precise determination of geometric parameters. Knowledge thereof is required for the computation of dimension and form of the object. To do so a cylindrical measurement standard is located within the central beam in two positions. By using the two different shadow projections, the known traverse path and the calibration value of the measurement standard, the values in question (focus-detector-distance, focus-object distance and enlargement factors) can be determined.

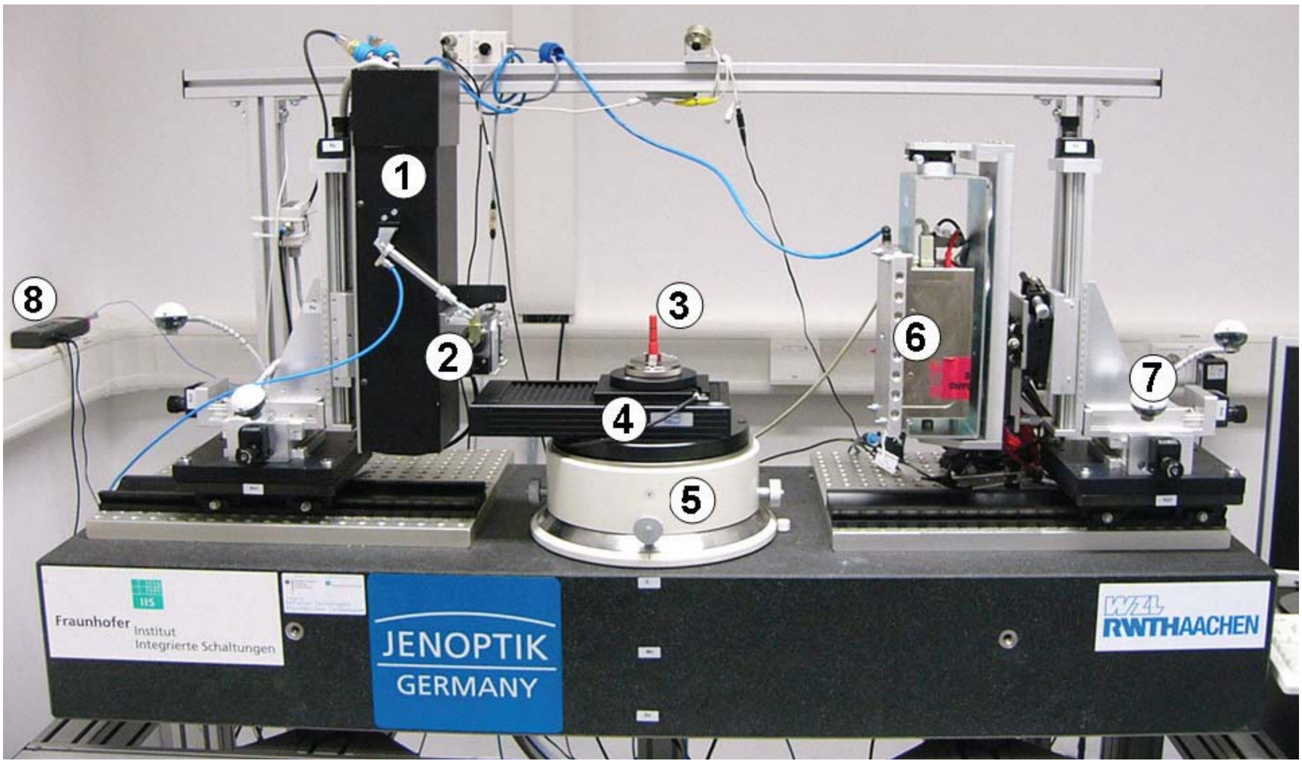

Fig. 3: System setup.

Caption: 1. X-ray tube, 2. Shutter, 3. Object, 4. Linear Axis, 5. Rotary table, 6. Camera, 7. Web cams, 8. Thermometer

4. Measurement

4.1 Measurement on the system

The measurement on the system can be characterized by the chain of information processing which leads from a shadow on the detector to a final roundness profile (Fig. 4). After the shafts shadow has been cast on the detector two edges have to be detected accurately. The next step is the definition of a triangle. This triangle can only be defined if certain geometric parameters of the system are known which is done by calibration algorithms and therefore also has great influence on the measurement uncertainty of the system. After the definition of the triangle different triangles that originate from different angle shots can be intersected to find an inner polygon. This polygon defines the values for a mean diameter or a roundness measurement [6].

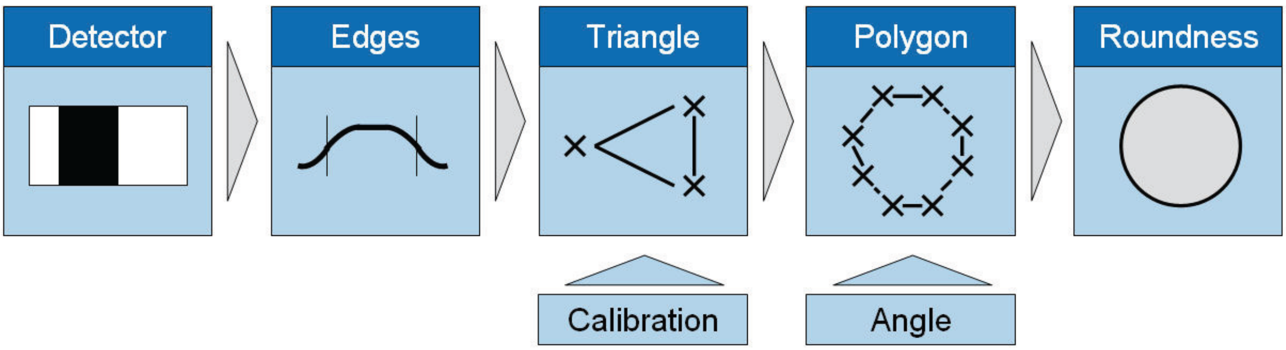

Fig. 4: Chain of information processing [5].

As the edge detection algorithms are the first steps of information abstraction towards the profile errors made in this sequential chain it is vital for this first step to be as precise as possible. The deviation of the edge detection algorithms directly affects the precision (variance of measurements) of the whole measurement system and will at least be as high as the number divided by the factor of the magnification. As the magnification can only be in the range of two due to the measurement of the pin bearings and the relatively high needed measurement volume, this means that the size of the shadow on the detector is roughly twice as large as the measured object itself. The accuracy (mean of measurements) of the measurement device will be mainly characterized by the quality of the calibration that sets a relation between shadow on the detector and certain value of diameter.

4.2 Edge detection

The edge detection algorithm is the important task to determine the shadows width on the detector. Errors of the edge detection on the detector have a direct effect on the measurement. As the pixel size of the detector is 26 µm the edge detection has to reach sub-pixel accuracy in a range from under one µm, which means a sub-pixel accuracy of less than 1/25th of one pixel. One main influence on the edge detection is the quality of the edge signal itself. When testing the edge detection algorithms on an ideal cylinder, lines on the detector can be averaged to get a better signal, which also means that the diameter of the measured cylinder is averaged over a certain height [5].

Different edge detection methods like spline interpolation and quintic polynominals as well as FWHM-detection and the fit of a sigmoid function have been tested on simulated detector images [6]. As the sigmoid function (eq. 1) is close to the edge definition of the real system it has a theoretical advantage compared to other edge detection algorithms because the Gaussian (or double-Gaussian) distributed source is transformed to a sigmoidal edge spread on the detector [7].

4.3 Contaminated edges

As one major goal of the XUV-System is to extract the diameter of shafts highly precise even in the presence of contamination two major different strategies can be discussed. Fig. 5 shows two pictures of the detector on the left hand side where only the left edge is shown. On the upper image the cylinder is without contamination and therefore shows the typical sigmoidal edge spread on the detector (blue curve). The lower detector image shows a contaminated test cylinder edge which directly affects the sigmoidal edge spread.

The contamination of the edge does not only affect the function in the upper region of the gray values but also affects the edge position on the detector shown as the red arrow in Fig. 5.

Based on a set of 26 experiments on the XUV-System (Fig. 3) with different test cylinders made of steel and ceramic and a diameter range of 1 mm up to 8 mm and a tolerance of the diameters of an average of below 0.5 µm this XUV System was compared with the tactile measurement of the test cylinders, adapted from the whole information processing step chain and the diameter.

The XUV system was set up with a source to detector distance of 600 mm, a magnification of 2 and an acceleration voltage of 45 kV. Also, on the basis of 17 experiments with contaminated test cylinders and the same XUV setup which had different contaminations like parylene, wax and oil in the approximate range of 10 µm to 120 µm on the surface a first estimation of the edge detection performance in the presence of contamination was conducted (Tab. 1).

The measuring of the test cylinders with low-viscosity grease coat demonstrates that the accuracy of the measured cylinder diameter lies between the area 1-2 µm around the calibrated value of the normal. The bigger the measured normal becomes, the closer the measured value lies to the tactile calibrated value.

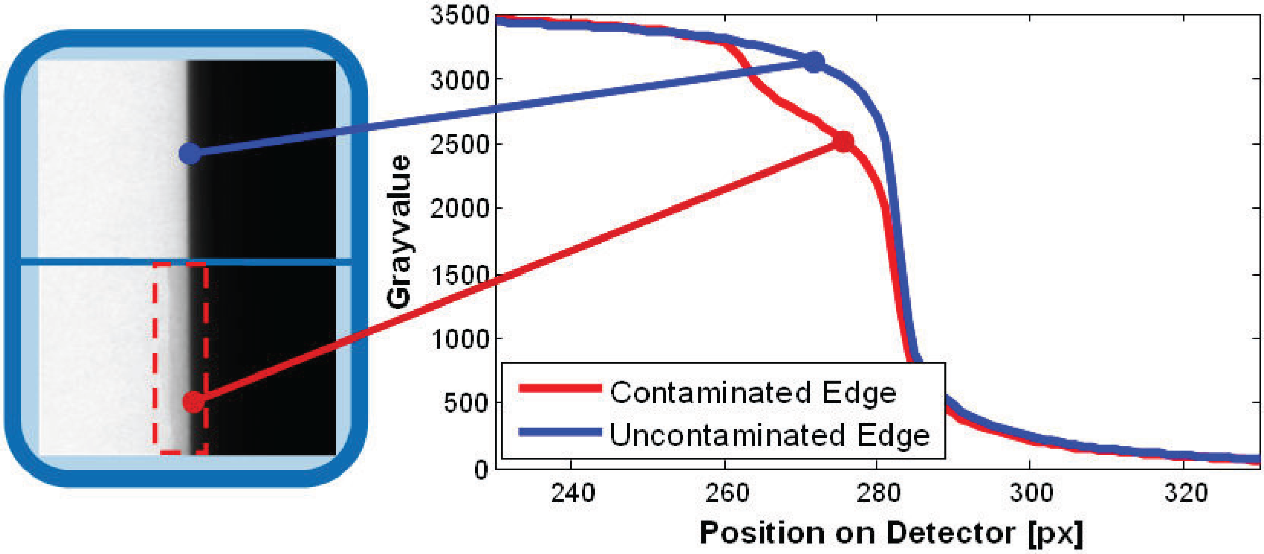

Fig. 5: Measured left edge of a test cylinder with and without contamination.

S3	non	thin	middle	thick
Measured value y [mm]	2.9971	2.9978	2.9971	2.9970
Calibrated value u_{cal} [mm]	2.995	2.995	2.995	2.995
Deviation e_y [µm]	2.1	2.8	2.1	2.0

S7	non	thin	middle	thick
Measured value y [mm]	6.9996	7.0018	7.0014	7.0015
Calibrated value u_{cal} [mm]	7.0001	7.0001	7.0001	7.0001
Deviation e_y [µm]	-0.5	1.7	1.3	1.4

S8	non	thin	middle	thick
Measured value y [mm]	8.0002	8.0012	8.0008	8.0007
Calibrated value u_{cal} [mm]	8.0002	8.0002	8.0002	8.0002
Deviation e_y [µm]	0.0	1.0	0.6	0.5

Tab. 1: Diameter deviation between the measured and the calibrated value of 3 different contaminated cylinders. Low-viscosity grease was coated in 3 different thicknesses (thin, middle, thick).

The polynomial fit edge detection has a good overall performance but still does not reach the targeted precision which should be below 1 µm.
Two strategies can be pointed out to reach the goal of a robust cylinder diameter measurement system which is invariant in the presence of contamination (Fig. 6). One way is to define the system in the region of high kV-values, probably in combination with a filter to get the hard radiation of the spectrum, and have a minimum change of the edge function on the detector which leads to the assumption that any state of the art edge detection algorithm can be precise and accurate. The other strategy is to analyse different features of the edge function and relate the movement of the edge gradient in the presence of contamination to those features which have to be invariant to the substance of the contamination.

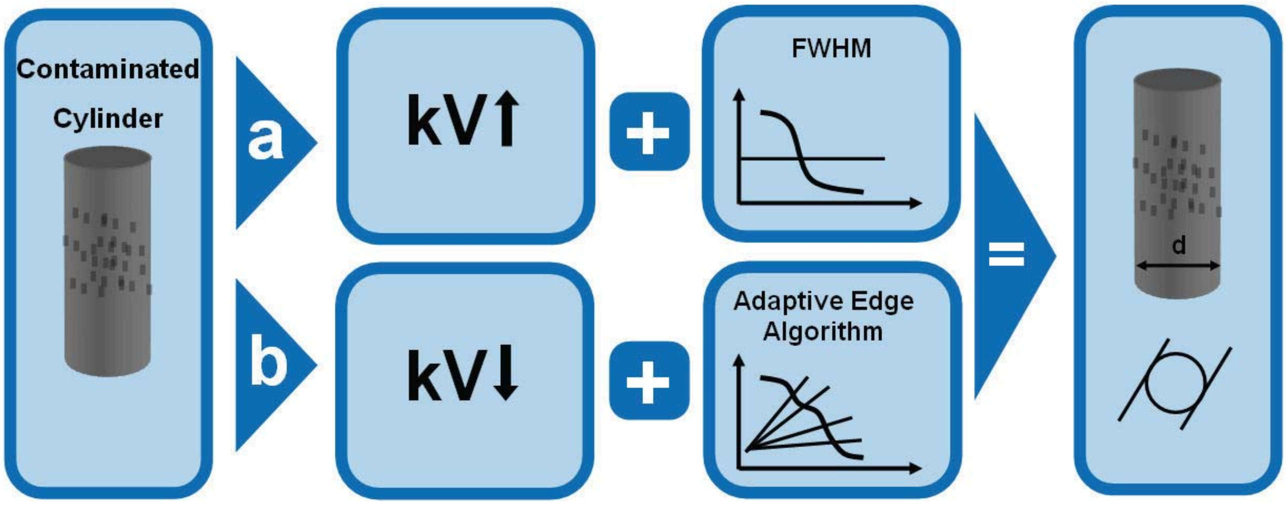

Fig. 6: Two strategies to gain a robust measurement result.

4.4 Measurement Uncertainty

A measurement result is incomplete without the measurement uncertainty.

In order to define the measurement uncertainty U with the coverage factor $k = 2$ (whereas 95% of the values are localised $y \pm U$) several methods are possible. In this demonstrated case it is reverted to the method of the prestandard DIN ISO/TS 15530-3. The standard describes the calculation of the geometric product specification (GPS) method for calculation of measurement uncertainty of coordinate measuring machines. In order to reach an accurate calculation of the measurement uncertainty at least twenty entire measuring cycles have to be analysed. Uncertainty is subdivided in a systematic error and a random error around this point. For the calculation of the always identical diameters, the systematic error can be deducted (substitution method).

The assignment of the measurement uncertainty of the contaminated test cylinder S5 (diameter 5 mm) had the result of

$U = 0.76$ µm.

The calculated measurement uncertainty simply refers to the measuring task, whereby it has been calculated (here: measuring of one concrete diameter). The measurement uncertainty U ensures as follows:

$$U = k\sqrt{u_{cal}^{2} + u_{p}^{2} + u_{w}^{2} + |b|^{2}}$$

u_{cal}: standard uncertainty of the calibrated measurement of the workpiece

u_p : standard uncertainty of the measurement process

u_w : standard uncertainty of material and production deviation

b : systematic error

The influence of an excentric and tilted object on the rotary disc effects an increase of measurement uncertainty. The measurement uncertainty values of the test cylinder S3 (diameter 3 mm) are generated by:

S3	*U*
Central and not tilted	1.698 µm
Excentric with 3.3 mm	1.591 µm
Tilt error 1°	3.086 µm
Excentric with 3.3 mm, Tilt error 1°	3.290 µm

Tab. 2: Measurement uncertainties for the S3 normal in excentric and tilted position

The measurements uncertainties of contaminated workpieces are localised depending on measuring normal or position of the measuring object in the area between 0.76 µm and 3.29 µm. Hence partly similar uncertainty values as in optical measuring are reached.

4.5 Roundness – Comparison XUV against coordinate measurement

A qualitative comparison of the roundness measurement between an XUV roundness plot and the DKD calibration plot ensures very consentient values. The XUV plot on the left side of fig. 7 denotes a roundness of 0.62 and the calibration plot on the right side denotes a roundness of 0.63. The peaks and valleys, consentient in both plots, of the measurement trace are in evidence.

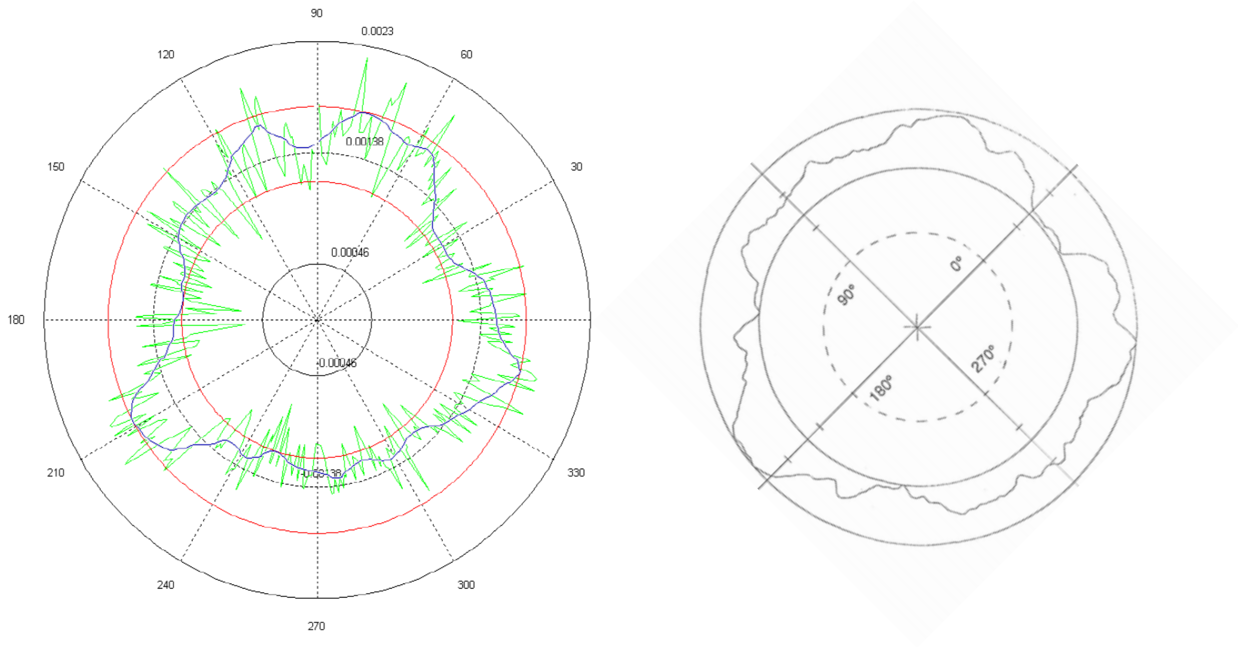

Fig. 7: Roundness XUV plot (with Gaussian filter, 360MP, 15UPR) (left) and DKD calibration plot (with Gaussian filter, 4000MP, 50UPR) (right) in one section.

Both roundness plots show a very high accordance in roundness profile and roundness value. Consequently measurement results comparable to tactile measuring can be generated by the use of XUV technique.

5. Conclusion

A new method for measuring contaminated parts in the industrial production process has been introduced. Results from a prototype experimental setup are presented.
Speed of the measurement, the dimension of the measured parts and the accuracy of the measurement can not separately optimized. The given setup was designed for the measurement of big metallic parts of a diameter up to about 300 mm. For that geometry the low resolution of the used X-ray camera and the weak radiation of the X-ray tube limits the accuracy as well as the measurement speed. The algorithm for the edge detection of contaminated parts gives a mean error

of the radius of 3 µm. The measurement uncertainty was estimated on the basis of calibrated cylinders and lies between 0.76 µm and 3.29 µm, depending on measuring normal or position of the measuring object. The estimated speed of a roundness measurement on the prototype experimental setup is comparable to the measurement speed of tactile instruments but with the benefit to be flexible due to the big distance between the workpiece and the parts of the measuring instrument.
To get a real measurement instrument which is suited for the industrial inspection of contaminated high precision metallic parts further improvement of the algorithms for the edge detection will be done. The robustness of the measurement is supposed to become higher by use of a moderatly rised acceleration voltage for the X-ray micro focus tube. The accuracy as well as the speed of the measurement is also supposed to scale directly with the availability of soft X-ray cameras with higher resolution and with the optical flux coming from the X-ray micro focus tubes.

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