Condition monitoring of a computed tomography system without dedicated master workpiece

M. Fleßner†, T. Schönfeld, M. Bartscher and S. Gondrom-Linke

†Volume Graphics GmbH, Speyerer Straße 4-6, 69115 Heidelberg, Germany.
†E-mail: flessner@volumegraphics.com

Abstract

The condition of a computed tomography (CT) system must be monitored on a regular basis to continuously ensure the validity of the measurement results. The challenge is to minimize undetected and unwanted error sources with reasonable effort. The presented approach is to statistically evaluate the raw data of the measurements performed in normal operation mode for anomalies. This allows to save valuable machine time as fewer or even no measurements of a dedicated master workpiece are needed, but also introduces new requirements for the evaluation algorithm: as there is no prior knowledge about the exact geometry of the measured parts in normal operation mode, it is difficult to differentiate whether a detected anomaly is induced by a change of the CT systems condition or merely by variations of the geometrical properties of the parts examined. To address this issue, statistical measures that are mostly not affected by the geometry of the scanned part are used to monitor the condition of the CT system. Sophisticated quality measures, which analyze the volume date at the surface of the measured part, are particularly suitable for this. First examinations of this approach for dimensional measurements show promising results regarding the ability to separate the effects of CT system changes from those induced by variations of the measured objects, potentially enabling a time- and cost-efficient monitoring scheme.

Keywords: Radiographic Testing (RT), Computed Tomography, condition monitoring, quality measures, in-line CT, quality assurance

1 Introduction

Computed tomography (CT) has proven that it is capable to perform dimensional measurements and a large variety of non-destructive analyses with high accuracy and reliability. This is one of the main reasons why the number of CT systems used in an in-line setup, where a large quantity of parts is scanned and evaluated automatically to monitor a manufacturing process, is continually increasing.

For in-line CT, the supervision of the operator is minimized: the evaluation of the CT scans is usually fully automated because comprehensive analyses of all scans by human operators would be too time-consuming to match in-line requirements. While the automatization helps to reduce costs, some errors of the CT system, which could be identified by an experienced user examining the raw data in detail, may remain undetected. Additionally, even a short downtime of the CT system may impact the whole manufacturing chain and can therefore induce large costs. This shows that it is important to monitor the condition – i.e. the metrological properties for dimensional measurements – of an in-line CT system.
continuously to ensure a fully functional condition of the CT system even between the maintenance services of the manufacturer. Therefore, the challenge is to detect failure states (malfunctions of X-ray source or detector, geometric misalignments or other errors) which may decrease the accuracy of the measurement results as soon as possible with reasonable effort.

Currently, the most common method for condition monitoring of a CT system is to perform scans of a dedicated master workpiece on a regular basis. With the master workpiece emulating typical measurement tasks, the information about the condition of the CT system is deduced from a comparison of the measurement results of these scans with a reference measurement: if the results match (i.e. the measurement deviations are small), the CT system is assumed to be in a functional state. Discrepancies in the measurement results, however, may indicate failure states of the CT system. On the downside, this approach does not provide a 100% test as the state between the tests is unknown and the effort to perform the regular scans of the dedicated master workpiece decreases the throughput of the CT system. Additionally, some minor issues of the CT system might be visible in the raw data while not (yet) directly affecting the measurement of the master workpiece. This information, which could help to predict future failure states, remains undetected. To tackle this issue, in some cases an experienced and skilled expert additionally examines the data visually for anomalies that could indicate variations of the CT system’s condition. However, this approach is time-consuming, expensive and relies on the subjective perception of the operator.

Other approaches commonly used for condition monitoring of machines (e.g. analyzing acoustical emissions, wear or vibrations for monitoring of wind turbines [1], drilling tools [2] or other machinery [3]) are not directly transferable to high precision measurement technology such as modern dimensional metrology CT because there is no clear connection between the signals these approaches monitor and the reliability of the measurement results the CT system produces.

2 Method

The proposed method for condition monitoring of CT systems comprises two steps. The first step evaluates the quality of the measurement data, emulating the examination by an experienced operator. The second step performs a deeper statistical analysis of the data quality to identify failure states of the CT system.

2.1 Evaluation of data quality

As already mentioned, in many cases an experienced operator can see at a glance if there are problems with the state of a CT system just by examining the volume data. However, for a conventional automatic
evaluation of the measurement data, this information about the quality of a measurement is lost entirely in the step of the surface determination.

For this reason, a method to automatically determine the quality of each surface point was developed [4] [5]. As the position of each surface point is determined by evaluating the volume data nearby, this very data is analyzed to calculate local quality measures. As depicted in figure 1, the properties of the local voxel volume near each surface point are evaluated along 1D gray value profiles perpendicular to the predetermined surface. A model function is fitted to the profile to divide it into three geometrical regions and to derive many quality parameters. These parameters can be utilized to calculate a dimensionless quality measure in the interval [0, 1] (as used in this publication) or even a prediction of the local deviation in the unit of voxel edge lengths or micrometers.

![Figure 1](image1.png)

**Figure 1.** Left: 2D slice of volume data with the location of gray value profiles perpendicular to the determined surface. Right: analysis of the profile to derive a quality measure for each surface point examined.

The result of an exemplary evaluation is depicted in figure 2. As can be seen in the 2D slice, regions of increased measurement deviations due to low data quality are reliably identified without the need for surveillance by an operator. This demonstrates that the surface quality measure is a helpful tool for automated identification of regions with low data quality.

![Figure 2](image2.png)

**Figure 2.** Color-coded visualization of the surface quality calculated for an exemplary simulated measurement of a pressure die-casting with severe artefacts. Left: 3D scene. Middle: 2D slice. Right: 2D slice with color-coding.

The tool aRTist was used to calculate the simulated measurements [6].
2.2 Monitoring of surface quality

To detect variations of the CT system’s condition, the surface quality of the executed measurements is monitored. To enable a comparison, a training phase consisting of multiple measurements of a typical workpiece using typical measurement settings is carried out in advance of the in-line measurements to be monitored. The surface quality is calculated for these training measurements and a typical distribution of the surface quality’s values is deduced. Likewise, the distribution of the surface quality is calculated for measurements of the monitoring phase and the mismatch to the distribution of the training phase is determined using an appropriate metric – e.g. the earth mover’s distance (EMD) [7]. This mathematical measure can be thought of as being comparable to the work which is required to transform (to shovel) one heap of material (earth as an example) into a second one of different shape.

In this context, a large EMD value implies a variation of the distribution of the monitored measurement (regarding the surface quality) compared with the distribution of the training phase. Therefore, this allows to detect whether a large quantity of surface points with unusual surface quality are present in the monitored measurement. As this might be an indicator for an unwanted, faulty state of the CT system, this measure is monitored to obtain valuable information about the CT system in use.

The described monitoring scheme is not restricted to the analysis of the surface quality, other measures can be used as well. However, for methods directly analyzing geometrical properties of the part (e.g. the results of a wall thickness analysis), it is difficult to differentiate whether a detected anomaly is induced by a change of the CT system’s condition or merely by variations of the geometrical properties of the parts examined (i.e. deviations caused by the manufacturing process). Therefore, a master piece with known geometry must be used.

However, the surface quality is, in a first approximation, independent from small geometrical variations of the part. In principle, this allows to separate the effect of the CT system from the effect of the measured part and no prior knowledge about the geometry of the part (obtained from a reference measurement) is needed. Therefore, especially for in-line setups, monitoring based on surface quality can be performed using only the measurement data of the parts that are scanned in normal operation mode.

3 Test series

3.1 Setup

In order to investigate the viability of the monitoring scheme proposed here, it is applied to data from an in-line CT system in an automotive cast aluminium production line. The analyses performed on each
part comprise multiple plane fits, a nominal/actual comparison, a wall thickness analysis and a porosity analysis.

To investigate the viability of the monitoring scheme proposed here, it is applied to the data in two stages: In the first stage, an arbitrarily selected part of the type shown in figure 3 is set aside and measured repeatedly. The training phase consists of 30 measurements performed on one day in June 2016, and the monitoring phase consists of 340 measurements of the same part performed roughly three times per day during March – December 2016. This first stage is meant to serve as the baseline from which any changes of the metrological behavior of the CT system can be recognized. The second stage then consists of measurements from February – November 2016 of distinct parts of the same nominal type as the selected one. The second stage is intended to allow investigating whether the proposed monitoring scheme can automatically distinguish workpiece changes from CT system changes.

In the time span during which the CT scans were performed, there were two noteworthy events relating to the CT system: In July 2016, the X-ray tube was exchanged – the previous X-ray tube reached the end of its expected lifetime and was therefore exchanged before noticeable errors occurred. A little while later, the experts noticed ring artefacts appearing in the voxel data. Their magnitude grew slowly over time, until in August 2016 the system was serviced and repaired by the system manufacturer – before the effect had a strong impact on the measurements. After the service the effect disappeared. The most likely cause seems to have been a slightly misadjusted X-ray detector cabling.

### 3.2 Results

Figure 3 shows data from an unaffected (top) and an impaired measurement (bottom). The overall surface quality measure is slightly lower in the bottom image (more dark red and purple spots).
Figure 3. Slices through the voxel volume of two different CT measurements of the selected part, with color-coded surface quality measure. Top image: Measurement not affected by ring artefacts. Bottom image: Measurement impaired by ring artefacts.

As it can be seen in Figure 4, the artefacts (which are restricted to a small area) only have a small impact on the distribution of the surface quality. The distribution of a measurement unaffected by artefacts (right) resembles the distribution of the training phase (middle), while the ring artefacts cause a small variation of the distribution towards smaller values of the surface quality (left).
However, when applying the monitoring scheme to the measurements of the selected part from the first stage (measurements of the master workpiece), these small variations of the surface quality can be made visible. Figure 5 shows the EMD of these measurements compared to the training phase.

The first blue line indicates the exchange of the X-ray tube. This seems to have a small (but noticeable) effect on the surface quality. More importantly, the second blue line indicates the repair of the X-ray detector. As described above, prior to this, increasing ring artefacts were observed in the volume data. This is well reflected by the steady increase of the EMD in this time span and the sharp decrease after the repair.

As mentioned above, it is also possible to monitor different types of geometrical measurands. Figure 6 shows the results for monitoring wall thickness analyses as an example. In principle, the results are similar to those of the evaluation of the surface quality (increase prior to the repair of the X-ray detector and slightly increased level after the exchange of the X-ray source). However, the effects are weaker compared to the overall noise level and therefore harder to identify. Thus, using the surface quality seems to be the more suitable approach to monitor the state of the CT system.
Figure 6. EMD of the wall thickness for measurements of the master workpiece. Compared to the evaluation of the surface quality, the effects are weaker compared to the overall noise level.

So far, measurements of the master workpiece were analyzed, which means that the geometry of the part in the training phase and in the monitoring phase is identical. To test whether a timesaving monitoring during the normal operation mode is feasible, the measurements of the second stage (distinct parts of the same nominal geometry) were evaluated (see figure 7).

Figure 7. EMD of the surface quality for measurements of distinct parts in normal operation mode. After the first blue line (exchange of X-ray source) an increase of the EMD is noticeable. Please note that this figure covers a larger timespan than figures 6 and 7.

Unfortunately, no measurements were performed in the relevant period prior to the repair of the X-ray detector as measurements were only performed when parts of the particular geometry were manufactured. Therefore, it is not possible to assess the impact of the ring artefacts on the EMD for this test setup using the current data basis. However, the effect of the exchange of the X-ray tube, which represents a controlled alteration of the CT system’s state, is still noticeable (slightly increased EMD after the exchange), even though the geometry of the measured parts slightly varies.
4 Conclusion

The results from the test series show that (wanted and unwanted) changes of the CT system’s state show themselves in the dimensional measurement results and in the raw CT data. Therefore, deriving and monitoring suitable measures yields helpful information about the state of the CT system. As demonstrated in this paper, this can be implemented by plotting the variation of the measures over time (allowing an operator to detect trends over many measurements at a glance), but more complex monitoring schemes including an automated tolerancing of the measures are also thinkable.

Sophisticated surface quality measures, which analyze the volume data at the surface of the measured part, are particularly suitable for this monitoring task, as they are sensitive to changes of the CT system’s state. Additionally, the surface quality is approximately independent from the geometry of the part scanned. First results indicate that it might be possible to separate the effect of the CT system from the effect of the measured part using this approach. This would reduce the need to scan a dedicated master workpiece and therefore save machine time, as the monitoring scheme can be applied to the measurements of the parts scanned in normal operation mode.

The monitoring scheme allows new possibilities for the condition monitoring of CT systems, enabling a more reliable and more timely indication of a potential faulty state with less effort. It is particularly suitable for in-line setups, where downtime induces large costs and must therefore be minimized, while at the same time a large amount of measurement data is available for automated evaluation using the proposed monitoring scheme.

While prior investigation already demonstrated that it is possible to increase measurement accuracy by taking the surface quality into account when performing dimensional measurements [5], the presented results show that the surface quality is also well suited for condition monitoring. Further works concerning intelligent data analysis are planned, e.g. in the field of timesaving and task specific determination of measurement uncertainty.

Acknowledgements

Funding for the work described here was provided by the German Federal Ministry of Education and Research for a joint project of Volume Graphics GmbH and Physikalisch Technische Bundesanstalt in the framework of the program “KMU-innovativ” (code 01IS15039A-B).
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