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Smart Centering for Rotation-Symmetric Parts in Multi-Stage Production Systems for Zero-Defect Manufacturing

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Abstract

During manufacturing, geometrical deviations occur, e.g. due to heating processes. In multi-stage production systems, these errors propagate and lead to expensive rework or, even, to unusable products. In this paper, a method for smart centering of rotation-symmetric parts is introduced. The method is used in the scope of achieving zero-defect manufacturing processes. For this purpose, the products are measured and automatically compared with the required specifications. Based on the identified deviations, process parameters can be adapted and thus, defects can be compensated in downstream production steps. The method is exemplified in the context of an industrial use case.

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Keywords: Manufacturing Process; Machining; Compensation; Measurement; Quality assurance

1. Introduction

In the course of globalization and the associated increasing competition between low-wage countries and the European manufacturing industry, product quality, the resulting customer satisfaction and economic efficiency as well as resource efficiency of production play a decisive role in highly dynamic markets [1]. In order to improve these factors and thereby aim for Zero-Defect Manufacturing (ZDM), the existing processes must be extensively analyzed and optimized. The EU project ForZDM, which is part of the Horizon 2020 cluster, deals precisely with this topic in multi-stage production systems [2]. Given the complexity of modern production processes, a significantly higher process quality cannot be achieved without the development of data-driven and learning-based methods. In order to exploit the available potentials of the networking and central data acquisition used in the course of digitalization of production, it is important to consider the holistic character of multi-stage production systems. The aim is to prevent the occurrence of defects or to compensate already occurred deviations in downstream production steps. This allows to avoid cost-intensive and time-intensive rework or even scrap through dynamic production and process planning [3]. Next to comprehensive measurement and recording of machine, process and product data, an essential component of this approach is the evaluation in form of correlation analysis and comparison of actual and target state of the part (called Part Variation Modeling in the geometrical context) [4]. On the basis of identified deviations or other defects, compensation strategies can be derived and implemented. In addition to the extensive acquisition, processing and evaluation of measurement data, the basis of the actual and target comparison are the exact modeling of the nominal state and the applicable requirements for the parts in order to make them accessible for

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automated machine processing. In order to demonstrate the possibilities of the approach for ZDM within a multi-stage production system in the context of an industrial use case, this paper presents a strategy for optimizing the production of rotation-symmetric parts. However, the developed procedure and the underlying methodology can be applied to a large number of manufacturing processes and components independently of their geometrical character.

The paper is structured as follows: Section 2 describes the fundamentals of the concept as well as the production of rotation-symmetric parts and the resulting problems in the context of the industrial use case. Section 3 presents the methodology developed for optimizing the system using a smart centering strategy. Section 4 summarizes and critically examines the results and describes the future work.

2. Fundamentals

In the case that a defect occurs in an early phase of a multi-stage production system, it can propagate over the following processes and lead to scrap or extensive rework. Additionally, in some cases the identification of an occurring defect is not possible due to the complex character of the multi-stage production systems or the high amount of requirements on the part. Therefore, the moment of detection of a defect is essential and influences the possibilities to compensate it. The earlier this happens, the easier it is to react to the defect. Consequently, it is very important to measure key parameters of the part and processes to identify deviations from the nominal geometry at an early stage [5].

In addition, human capabilities, such as the rapid detection of defects, must be taken into account for later analysis and planning of downstream compensation strategies, especially in the context of increasing automation. To use the gathered data efficiently, an automated analysis and comparison with the nominal data is needed. This is of decisive importance, if the process of generation and the specific parameters are unknown or if it is not possible to improve the process generating the defects. This makes it possible to adapt process parameters of downstream production steps to the actual geometry of the part or in the worst case, to stop the production of the specific part in order to save resources. Fig. 1 shows a multi-stage production system without an early stage measurement and an analysis to identify defects, which can lead to scrap or rework (a) and the improved concept with the adaption of the parameters (b) in following processes.

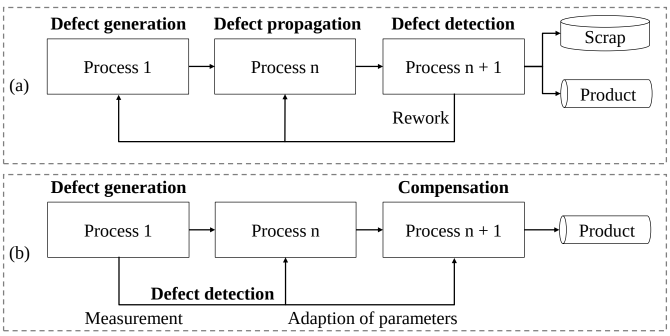

Fig. 1. Multi-stage production: (a) Classic architecture, (b) Downstream compensation based on measurement data and smart strategies.

Multi-Stage Production System for the Manufacturing of Rotation-Symmetric Parts

Rotation-symmetric parts are used in a variety of applications in a wide range of industries. Within the EU project ForZDM, there are two use cases. One of them is the production of turbine shafts for the use in aerospace industry and the other one is the production of wheelset axles for the railway transportation sector. Since these components are safety-relevant and strongly stressed, high quality and safety requirements must be met. In this paper, the manufacturing process of wheelset axles is used to exemplify the possibilities of ZDM strategies in multi-stage production systems. The relevant part for the presented methodology of the manufacturing process of wheelset axles is divided into the production steps shown in Fig. 2. At the beginning of the manufacturing process, a raw material is heated and formed during several forging processes. This process brings the raw material into the coarse form of the nominal geometry of the final part. Further heat treatments are carried out to reduce the internal stresses caused by the forging process and to improve the material properties. After that, the forged part is machined. The ends are cut off and the workpiece is thus brought to the required length. The planar surfaces serve as the basis for the subsequent turning process. For this purpose, reference bores are drilled on both end faces in a further machining step (called centering). The bores determine the rotation axis of the part during turning. Those center points are placed in the geometric center of the clamping system on the end surfaces of the part.

However, forging, heat treatment and storing of the part in the hot state have a side effect on the downstream processes, especially on turning, resulting in a non-rectilinear body. The longitudinal axis describes an arcuate shape that is not taken into account when determining the reference bore position. Regarding the part dimensions with a length of about 2400 mm and a diameter between 130 and 220 mm, a manual identification of the deviations and an adaption of the position of the reference bores is not possible for the operator. As a result, the target geometry of the final part may not be achieved in the following processes, as there is the possibility, that there is not enough material in some areas due to the deformation [6]. This circumstance is often only recognized towards the end of production and cannot be reworked. Furthermore, a consequence is a non-uniform material removal during the turning process, which leads to heavy wear of the used tools due to the fluctuating forces.

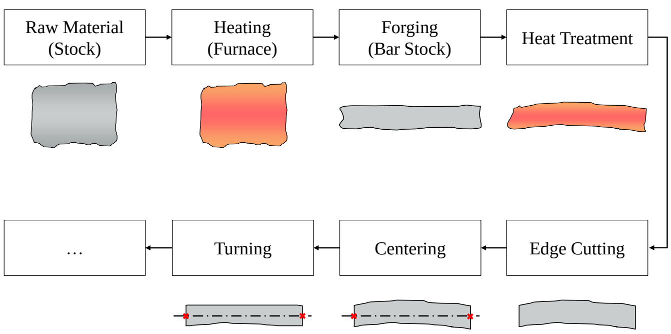

Fig. 2. Schematic representation of the manufacturing process from the raw material to the semi-finished product.

Fig. 3 shows the arcuate shape of the part and the resulting defects on the final geometry due to the deformation. This situation is currently wasting precious time and expensive resources. To counteract this problem, the current way of prevention is to forge the semi-finished part with higher tolerances in order to compensate deformations. Besides the fact that this procedure extends the processing time and increases the use of resources, it is uncertain wheter the production of the part is possible. Fig. 4 shows the effect of missing material detected in a late manufacturing step. In order to proactively prevent this problem and to achieve the goal of ZDM, the optimal positioning of the reference points on the part must be determined based on the actual geometry with respect to the target geometry. The project provides a newly developed measuring system that enables the recording of the actual geometry of the part. The presented strategy for smart centering takes into account the target geometry of the final product at an early stage of the manufacturing process. This makes it possible to predict whether a part can be manufactured and, if possible, to adapt the position of the reference bores. The aim is to reduce scrap, the amount of required material and also to achieve a homogenous machining and in the end a longer tool life.

3. Methodology of Smart Centering

The Smart Centering strategy is based on the comparison of the actual geometry of the semi-finished part and the nominal geometry of the final product. Fig. 5 shows the underlying architecture of the methodology of Smart Centering for rotation-symmetric parts. A mobile measuring station is used to measure the actual geometry. On the basis of the gathered data, the contour of the part is modeled. The nominal geometry is derived from technical drawings and CAD models and transferred to a parametric model. Algorithms are developed to calculate the optimal position of the part in relation to the coordinate system of the measurement station. These algorithms are implemented and executed in MATLAB®, whereby the position of the target geometry can be optimized under different aspects.

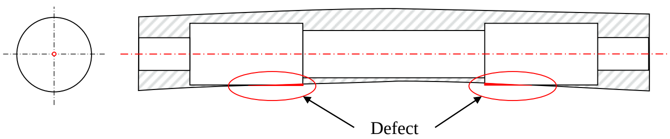

Fig 3. Present positioning of the reference bore and the resulting defect.

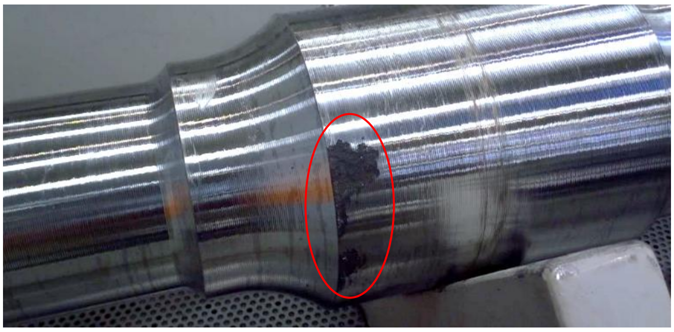

Fig. 4. Identification of missing material in a late process step.

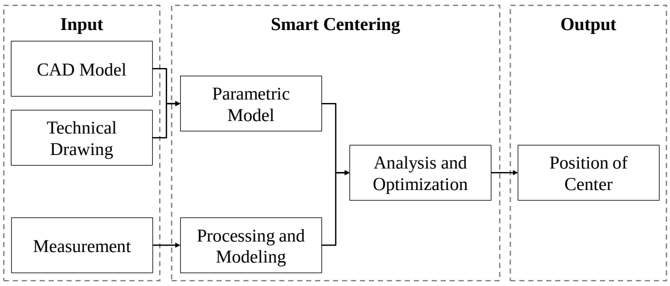

Fig. 5. Methodology of Smart Centering.

Chapter 3.1 presents the measurement system, the gathered data, the processing and the modeling of the actual geometry. The parametric modeling of the target geometry is explained in Chapter 3.2. The analysis and optimization of the position are shown in Chapter 3.3.

3.1. Measurement and Modeling

The mobile measuring station consists of a frame in the form of a U-profile, on which four measuring heads are mounted at an angle of 90 degrees. The measuring heads are laser-based distance measurement sensors. It is assumed that the sensors are exactly aligned and centered.

For the measurement, the part is positioned on supporting jaws and the frame is moved along the longitudinal axis of the part, parallel to the supporting frame. The position of the measurement station is calculated using the encoder signal of the motor for longitudinal movement. This design allows a flexible number of measurements or even continuous measurements along the longitudinal axis to be carried out in order to capture the contour of the part. As the number of measurements increases, the actual geometry of the part can be reproduced more precisely. The measured values are collected in a central database to provide a fast access from various systems. Fig. 6 shows the schematic structure of the measurement station. Due to the limited number of measuring points on the part contour for each section, an extended modeling is required to estimate the actual geometry and achieve a closed contour for the following analysis and optimization.

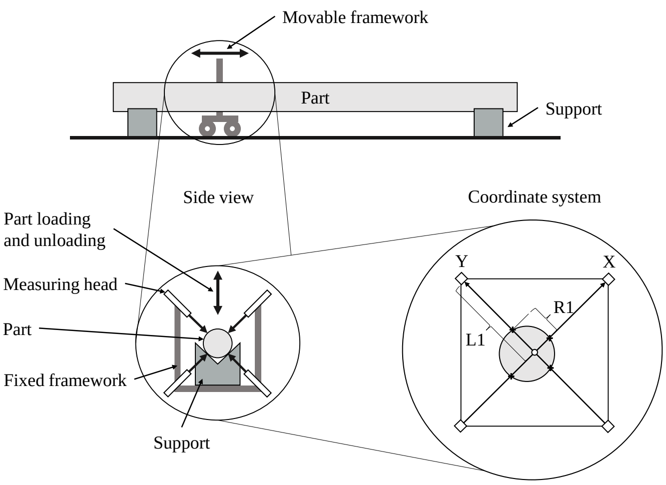

Fig. 6. Schematic architecture of the used measurement system.

Three basic approaches for modeling the cross-sectional contour of the actual part are developed and presented in this section. The aim of modeling is to reproduce the actual contour of the part as accurately as possible. The modeled contour is then used as boundary conditions for the analysis and positioning of the nominal part.

The first approach is based on the assumption that the contour of the part can be described by a circle. Therefore, the first method fits a circle to the measurement points using a Least Squares algorithm [7]. The method minimizes the sum of squares of the geometric (Euclidean) distances d_i to a given set of $n \geq 3$ points in $\mathbb{R}^2$, with $\{(x_i, y_i) \mid 0 \leq i \leq n\}$. The objective function $\mathcal{F}$ to be minimized is given by

$$\mathcal{F} = \sum_{i=1}^{n} d_i^2 \ . \tag{1}$$

With the general circle function including the center (a, b) and the radius R as

$$(x-a)^2 + (y-b)^2 = R^2 \ , \tag{2}$$

the geometric distance d_i can be described by

$$d_i = \sqrt{(x_i - a)^2 + (y_i - b)^2} - R \ . \tag{3}$$

This approach leads to a nonlinear Least Squares problem which can be solved with Newton step-based methods like trust-region-reflective or Levenberg-Marquardt [8]. These methods are not described in detail in this paper. Due to measurement inaccuracies, the measured contour cannot be a perfect circle. As such, measurement points may be inside the fitted circle shape which is equivalent to missing material. To avoid assuming material where there is none, a circle with the minimum fitted radius must be determined, too. This ensures all points lie on or outside the estimated contour. The literature describes a set of similar mathematical approaches like [9–13] for fitting circles or ellipses to data points.

The second approach calculates the centroid (geometric center) of a set with n points (x_i, y_i) in $\mathbb{R}^2$, with $\{(x_i, y_i) \mid 0 \leq i \leq n\}$. The arithmetic mean position in the form of $(\bar{x}, \bar{y})$ is given by

$$(\bar{x}, \bar{y}) = \left(\frac{1}{n} \sum_{i=1}^{n} x_i \, , \frac{1}{n} \sum_{i=1}^{n} y_i \right) \ . \tag{4}$$

The calculated center point is also used to create a circle with the radius of the distance to the next measuring point and is similar to the first approach, but less computationally intensive, which reduces the calculating time and the resources required. The method can be used to calculate the geometric center independent of the number of measurement points. Whereas the first approach needs at least three measurement points.

The third approach is based on the assumption that the contour of the part is approximately a circle. Therefore different interpolation methods can be used to model the contour between the data points, e.g. linear interpolation and cubic spline interpolation [14–17]. In the following approach, a cubic spline interpolation, which is a third order polynomial, is used. The spline has the condition to be continuously differentiable twice. The method is described in detail in [18]. The cubic spline interpolation is used due to its property to obtain smooth results [19]. The aim is to ensure, that no false material is modeled, which leads to a false positioning. To achieve a closed modeling of the contour, the measurement points are converted from Cartesian coordinates to polar coordinates. After interpolation, the center of the calculated data points is determined using Eq. (4).

Fig. 7 presents the results of the three approaches for an exemplified dataset in the first measurement section of the part. It can be seen that the centers of the introduced methods differ slightly. This is due to the fact that only four measurement points are available in the presented use case and that the contour resembles a circle. In the case of the used minimum circle, it can be seen, that comparatively much of possible material is not taken into account. For the fitted circle, using a Least Squares algorithm, areas are included where no material is available. The used cubic spline interpolation does not have this drawback, especially in the case of a more elliptical shape. It is expected, that the contour is described much more precisely by the interpolation. As a result there is more space for the positioning of the nominal part inside the actual geometry and the certainty that only a contour is modeled, which is also existing in reality, is increased.

In future work it has to be investigated, which of the presented approaches fits the reality the most and if the number of measurement points is sufficient to model the contour exactly enough. Furthermore, additional interpolation methods can be implemented and compared, in order to achieve a realistic modeling of the present part.

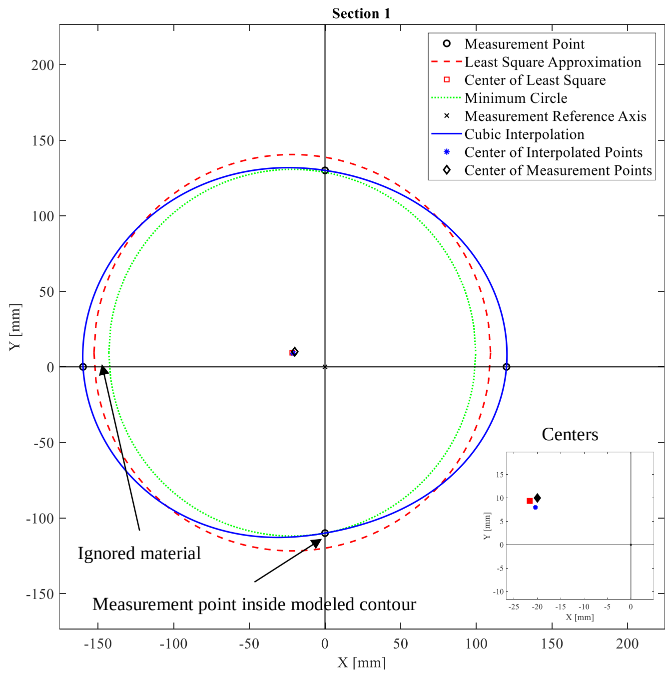

Fig. 7. Comparison of three approaches for modeling the contour of the actual part on basis of four measurement points.

3.2. Parametric Model

A new data model based on a CSV file is introduced as an example to map the target geometry of rotationally symmetric parts. Based on existing CAD models, technical drawings and requirement lists, the geometry of the component can be described by the data model. The structure of the input for creating the parametric model is shown in Table 1 using sample data. In the first two columns, the area on the longitudinal axis is defined by the start and end point. In the next column, the radius is defined in the individual areas. The next two columns contain the upper and lower tolerance limits of the specified radius. On basis of the table, algorithms create a parametric model that defines the nominal geometry of the final part and from then on serves as the basis for the analysis and optimization methods in relation to the Smart Center.

3.3. Analysis and Optimization

In order to analyze the position of the nominal part with regard to the actual geometry, the parametric model is placed with reference to the coordinate system of the measurement station as shown in Fig. 8. It can be seen that the nominal part overlaps the outer contour of the actual geometry, which will lead to a later defect due to missing material. This fact can be detected by the developed algorithms. To enable a successful manufacturing, the axis of the nominal part can be moved by $(\Delta x, \Delta y)$ perpendicular to the reference axis. The placement of the nominal part is calculated solving an optimization problem for which three cost functions are derived. Fig. 9 shows the nomenclature for the following equations.

Table 1: Transferred part requirements as input for the parametric model.

Start [mm]	End [mm]	Radius [mm]	Upper Tolerance [mm]	Lower Tolerance [mm]
0	100	120	+1.0	+0.0
100	300	130	+1.2	+0.5
300	350	125	+1.0	-0.5
350	600	140	+1.3	+0.0

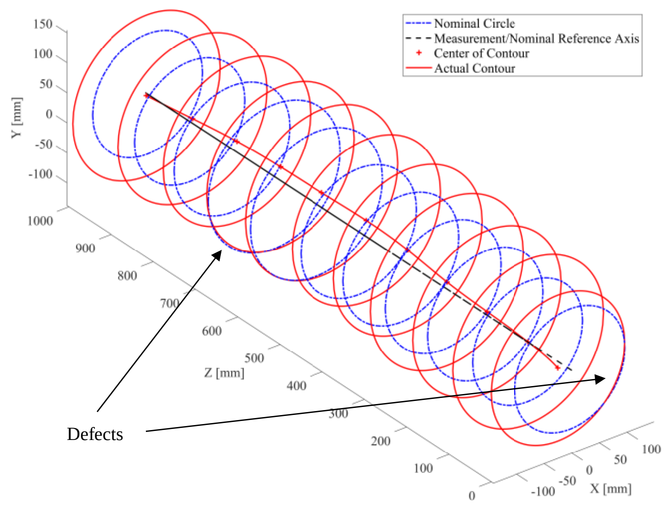

Fig. 8. Analysis of the position of the nominal part in reference to the actual contour.

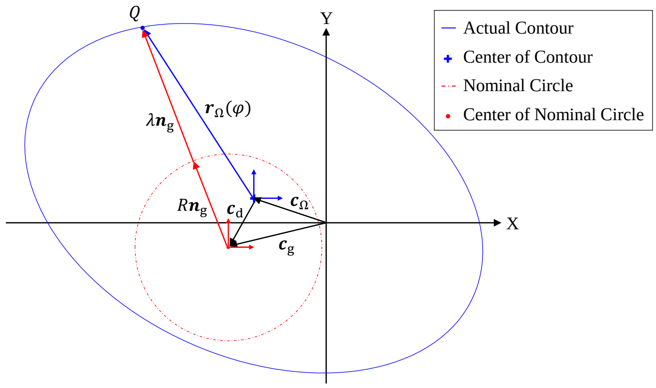

Fig. 9. Nomenclature used in the optimization equations.

The criteria and the subsequent optimization of the position of the nominal part can be carried out under various aspects. Let us look at one measurement section as shown in Fig. 9 from which we infer the vector loop for a point Q on the surface Ω of the measurement as

$$\boldsymbol{c}_\mathrm{g} + R\boldsymbol{n}_\mathrm{g} + \lambda\boldsymbol{n}_\mathrm{g} = \boldsymbol{c}_\Omega + \boldsymbol{r}_\Omega \quad . \tag{5}$$

Considering that $\|\boldsymbol{n}_\mathrm{G}\|_2 = 1$, we can solve Eq. (5) for λ yielding the distance of all points of the measurement surface to the center of the nominal part as

$$\lambda = \left\|\boldsymbol{c}_\Omega + \boldsymbol{r}_\Omega - \boldsymbol{c}_\mathrm{g}\right\| - R\,, \tag{6}$$

which must be calculated for every point $\boldsymbol{r}_\Omega$ on the surface. All three optimization problems are constraint such that the minimal distance $\lambda_{\mathrm{min},k}$ between the nominal and actual contour of the measurement section $k \in \mathbb{N}$ $(k = 1, \dots, m)$ must be greater than or equal to zero

$$\lambda_{\mathrm{min},k} = \min_{\boldsymbol{r}_{\Omega,\mathrm{k}}}\left(\|\boldsymbol{c}_{\Omega,\mathrm{k}} + \boldsymbol{r}_{\Omega,\mathrm{k}} - \boldsymbol{c}_\mathrm{g}\|\right) - R \geq 0 \quad . \tag{7}$$

We can describe the cost function of our first optimization problem as minimizing the distance between the geometric center of the actual contour and the center of the nominal contour, yielding

$$\min_{\boldsymbol{c}_\mathrm{g}}\left(\sqrt{\sum_{k=1}^{m}\left\|\boldsymbol{c}_{\mathrm{d},k} = \boldsymbol{c}_\mathrm{g} - \boldsymbol{c}_{\Omega,k}\right\|^2}\right). \tag{8}$$

This approach leads to the center axis lying as closely as possible to the center of the actual contour. The second cost function maximizes the smallest distance $\lambda_{\mathrm{min},k}$ of all measurement sections m and increases the safety of the process, reading

$$\min_{\boldsymbol{c}_\mathrm{g}}\left(-\min_{k=1\dots m}\left(\lambda_{\mathrm{min},k}\right)\right). \tag{9}$$

The third cost function is the minimization of the difference between the smallest and largest distance from the nominal to the actual contour of all measurement sections, as

$$\min_{c_g}\left(\sqrt{\sum_{k=1}^{m}\left(\lambda_{\max,k}-\lambda_{\min,k}\right)^2}\right) , \tag{10}$$

where $\lambda_{\max,k}$ is calculated similarly to Eq. (7). The goal of this cost function is homogenizing machining i.e., the alteration of material to be removed in one section is as uniformly distributed as possible.

The constrained nonlinear multivariable optimization problems are minimized using methods such as interior-point or trust-region-reflective [20–21], providing the position of the center of nominal part in reference to the measurement coordinate system. Fig. 10 shows a sample measurement section with the initial and optimized position of the nominal geometry using the cost function according to Eq. (9).

4. Conclusion and Future Work

The presented Smart Centering strategy allows a more economical manufacturing and contributes to the aim of ZDM. In order to avoid defects due to incorrectly set centers, the nominal geometry as well as the actual geometry of the part are taken into account. For a comparison of both geometries, different modeling methods are presented and discussed. The developed algorithms optimize the position of the nominal part automatically, providing information on the feasibility of manufacturing. The identification of the optimized position of the reference bores proves Smart Centering can reduce defects, the wear of tools and resources (e.g. time and energy), and the necessity for high tolerances on the semi-finished part. Additionally, the amount of remaining material is calculated which helps to determine the estimated success of production of the actual component at an early stage of production.

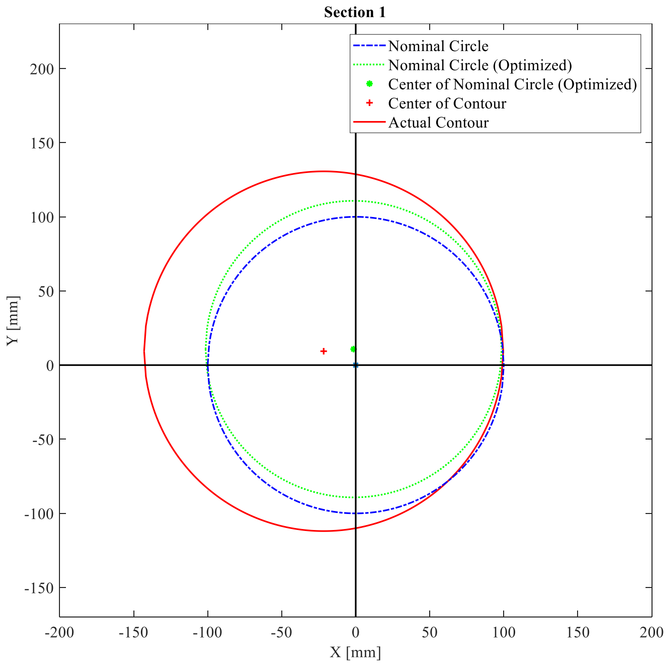

Fig. 10. Comparison of the initial and optimized position of the nominal geometry in dependency to the actual contour exemplified for one section.

Future work includes further verifications that the modeling corresponds to reality within the use case. As well as the validation of the optimization methods with regard to various criteria. Additionally, challenges, such as the transformation of the calculated center position into the machine coordinate system and the development of a more automated tool for the creation of a parametric model, need to be addressed.

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