Automated Geometry Measurement of Wheel Rims Based on Optical
3D Metrology

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ABSTRACT

One of the economically most important branches is the automotive industry with their component suppliers. The high degree of automation in manufacturing processes, requires automated control and quality assurance equally. In this scope, we present a complex 3D measuring device, consisting of multiple optical 3D sensors, which is designed to capture the geometry of wheel rims. The principal challenge for automated measurements is the variety of rims with respect to design, dimensions and the production flow. Together with connected conveyers, the system automatically sorts good rims without interrupting the manufacturing process. In this work we consider three major steps. At first we discuss the application of the used 3D sensors and the underlying measuring principles for the 3D geometry acquisition. Therefore, we examine the hardware architecture, which is needed to fulfill the requirements concerning to the variety of shapes and to the measuring conditions in industrial environments. In the second part we focus on the automated calibration procedure to integrate and combine the data from the set of sensors. Finally, we introduce the algorithms for the 3D geometry extraction and the mathematical methods which are used for the data preprocessing and interpretation.

Keywords: 3D measurement, geometry verification, wheel inspection

1. INTRODUCTION

Quality assurance in the manufacturing is of vital importance. New optical measuring technologies allow a 100\% control, which also applies to the production of wheel rims. For a high driving comfort and a maximal safety, the exact geometry of a wheel is very important. If the metal parts are manufactured exactly, the rubber tire runs round. Any deviation from the ideal shape leads to vibrations which are noticeable for the driver. Particularly, the wheel hub, the pilot bore and the lug bolt holes have a wide influence, since they represent the interface between the axes of the vehicle and the road. Important parameters are, for example, the radial and lateral run out, the absolute and relative positions of several bores as well as distances between inner/outer bead seat to each other and to the contact surface at the pilot bore. Actually, the quality of a wheel is tested by the manufactures with mechanical probes, moving along the wheel surface. This allows for the determination of dints or deformations, which move the probe in radial direction. This is a reliable and approved method but still has several disadvantages: the probe wears out and the parameters cannot be acquired correctly. Additionally, the surface must be digitized pointwise for capturing other or more complex geometry parameters, which becomes very time-consuming. Tactile methods often need air-conditioned rooms and, thus, are not suitable for online inspections in most cases.

In contrast to classical approaches, we present a system based on contact-free optical 3D metrology. An optical 3D sensor consists of a laser and a light-sensitive device, mostly a camera, which captures the 3D shape of the wheel. Therefore, a laser line is projected onto the wheel surface and the resulting light-section is observed by a camera (see fig. 1(b)). From the viewing angle of the camera, the wheel topology deforms this line to a curve. This effect allows, together with the known geometry
of the sensors, the 3D reconstruction of a radial profile on the wheel surface based on the triangulation concept (see fig. 1(a)). Within a continuous movement the sensors are rotated around the wheel and 360 three-dimensional profiles are computed and combined to one point cloud which is finally evaluated and compared against the given nominal geometry from CAD. Actually, this kind of 3D measurement is unique in the quality assurance for the wheel production.

2. RELATED WORK

Our work addresses the application of 3D measurement techniques for industrial usage as well as the application of several methods for the corresponding 3D evaluation. Thus, we have to consider well known problems in both fields to develop reliable and robust algorithms. Since 3D data acquisition has become a major tool for generating digital surface data in a variety of applications, the different scanning techniques have become more accurate. But most of these techniques still cause severe artifacts such as noise, outliers or holes. Therefore, a post-processing is usually applied to allow for robust measurements and sophisticated modeling operations on these data sets. In this scope, WEYRICH ET AL. discuss a variety of scanning artifacts that are created by common optical scanners and introduce methods for the processing of corrupted data sets, which include noise removal, outlier identification and hole-filling tools. Typically, such operations are applied to polygonal (triangular) meshes, which requires time consuming and often error-prone triangulations, particularly for automated processing. Methods for cleaning raw point clouds are also proposed, which base on the local approximation of geometric primitives, such as planes or spheres. For our procedures we use some modified versions of these procedures in our pre-processing step and discuss the optimization of the raw data as it is provided by the scanner in section 5.1.

The standard tool for fitting geometries is the least-squares approach, which minimizes the distance between the point cloud and the assumed geometry. Mathematical algorithms, particularly curve and surface fitting routines, are critical components of coordinate metrology systems. An important but difficult task is to assess the performance and the numerical stability of such routines. Therefore, general least-squares fitting algorithms are examined by SHAKARI, with respect to linear geometries (planes, lines) and the nonlinear geometry fitting. He introduces unconstrained optimization methods that require derivatives of the appropriate distance functions.

After having acquired 3D data an evaluation step with a geometry comparison against nominal data usually follows. Therefore, local sets of 3D coordinates must be represented by the same geometry as the given is. Primitives can be approximated by fitting algorithms as mentioned above. More complex shapes require the consideration of other kinds of shapes. Therefore, ZHANG ET AL. present a superquadrics based 3D object representation of automotive parts, which utilizes a part decomposition. They start from a 3D watertight surface model and apply a part decomposition as the first step to segment the original multi-part objects into their constituent single parts. Each single part is then represented by a superquadric. The need for watertight triangular meshes, limits these and similar approaches to non-automated measuring tasks. Since our sensors rotate around rotation-symmetric objects, we are able to determine a lot of measures directly from each captured profile. This enhances the processing speed and significantly increases the robustness. The following section gives an overview on the measuring machine and its hardware conception.

3. MEASURING MACHINE

The measuring machine was developed to support the quality assurance in the manufacturing of wheel rims. Therefore, each wheel is measured, instead of taking single samples. This section gives an overview on the system configuration, the used sensor technology and the basic measuring procedure.

3.1. Overview

The systems mainly consists of three different subsystems: a 2D part identification unit for “chaotic” part supply, a 3D measuring unit for capturing and evaluating the wheel geometry and an additional elevator/side shift unit for NOK/Rework classifications. The single subsystems are connected by conveyers (see fig. 2). In this work, we particularly focus on the 3D measuring unit.

The 3D system uses the principle of a fixed wheel and moving sensors. Actually, this unit consists of four triangulation based sensors. Three line based sensors are used to capture the inner and outer bead seats and the center bore area with the contact patch and the lug bolt holes. The fourth sensor measures ranges to the bolt holes pointwise from the outside. Therefore, the sensors are mounted on two rotation axes (inner and outer sensors) with additional lateral axes for the optimal horizontal and vertical orientation. From the given nominal values of the CAD geometry, the corresponding axial
positions are adaptively computed. The measuring system is designed for supporting all types of passenger car, SUV and truck wheels without mechanical re-setting. Therefore, all necessary information (geometry parameters, parameters for custom specific data evaluation) are stored in a database, which additionally allows for an easy parameter modification and the insertion of new wheel types.

![Diagram](image)

(a) 2D identification 3D measuring classification
(b) material flow
(c) 3D measuring

Figure 2. Schematic illustration of the wheel measuring machine (a), the real machine (b) and a closer view on the sensor technology (c).

Our measuring concept requires a triggered data acquisition. Otherwise, no angular relationship between the set of data from one sensor (and between the others) can be found, since each sensor initially yields raw 2D data only. The basis for an equidistant (related to rotation angles) data capturing are the rotary encoders. They generate signals for a trigger unit, which again generates impulses for all connected devices. This principle assures the real-time and synchronous generation of trigger signals. The basic idea behind the hardware concept is the decoupled arrangement of data measuring and hardware controlling functions. This allows for the minimization of the digital i/o signals between these systems. Finally, the measured data is transferred to a standard PC via Firewire (IEEE 1394 standard) bus, which then performs the 3D data reconstruction, feature extraction and evaluation.

3.2. Measuring Procedure

The wheel is automatically transported to the measuring system on a conveyer, which is connected to the manufacturing process. Once the wheel enters the machine, it is pre-centered and arrested. The measuring arms and axes, on which the sensors are mounted, are automatically moved to the optimal measuring position. Within 3.6 seconds, the sensors rotate around the wheel and capture data of all relevant parts. After one complete rotation, 360 profiles were generated. Each profile initially contains 1024 2D coordinates, which are finally merged to more than 1.1 mio. 3D coordinates for precise geometric measurements. On the basis of the given CAD data of the wheels, a geometric matching compares the actual against the nominal shape. Depending of the result and the computed deviations, the system sorts good wheels from the bad ones. The entire process takes about 12 sec, including wheel transportation.

The computation of absolute geometric measures requires an object coordinate systems, which usually exists within a world coordinate system, that is defined by the machine and its axes. Therefore, the raw data of each of the different sensors is transformed to one world coordinate system by applying the following calibration procedure.

4. 3D CALIBRATION PROCEDURE

The computation of 3D coordinates from the raw 2D profiles of the laser sensors requires a mathematical model of the machine and a calibration procedure to calculate its parameters. For that we use a setting master, which global shape is similar to a wheel rim but with several revolving reference areas forming cylinders and planes (see fig. 3(a)). Their dimensions are determined precisely using a tactile coordinate measuring machine. Because of machining limitations, only selected contours, finally visible to the sensors, are manufactured and measured this way. For simplification we only store the nominal parameters of the setting master contour, which allows for a variable calibration and an easy maintenance of the machine database.

For the adjustment of the sensors we have specified, that the plane spanned by the laser has to coincide with its rotation axis. The most attention is thereby turned to the orthogonality between the plane normal and the direction of the axis. With
the center axis of our setting master, running nearly parallel to the rotation axes, we are able to reduce the complexity to a 2D problem. Additionally, the translation axes are parallel to the rotation axes too.

The automated calibration procedure starts a regular measuring cycle for the setting master. At each angular position \( \varphi \) and for each sensor, a multi-stage alignment process starts. At first, a variant of the Iterative-End-Point-Fit algorithm (IEPF)\(^{10,11} \) is used to cluster the measured points into sets of collinear points. Starting with a line from the first to the last point of the ordered dataset, all distances to points in between are computed, and the point with the maximum distance specifies the intersection of two new lines. This is done recursively until a specified minimum distance is reached and the clusters are returned. After fitting lines to the point clusters\(^5 \) we reduced the complexity from 1024 points to typically up to 10 line segments (see fig. 3(b)), which makes the following calculations more efficient.

The setting master with its measured faces defines only two or three reference lines in the two-dimensional space for one sensor. All detected line segments are matched to the reference structure, a quality coefficient is computed and, at last, there are up to four possibilities for aligning the measured data to its reference. With the a-priori knowledge that the sensors for the bead seats have to be outside of the rim and the sensor for the pilot bore has to be inside, the correct transformation \([\alpha, dX, dY] \) is chosen (see fig. 3(c)).

The parameter \( \alpha \) is the inclination of the sensor and \([dX, dY] \) its projection center referring to the coordinate system of the setting master. A subsequent fitting process\(^{12,13} \) ensures the computation of transformation parameters for minimal deviation. The raw sensor data \([x_s, y_s] \) is transformed with the following equation.

\[
\begin{align*}
x_t &= x_s \cdot \cos \alpha - y_s \cdot \sin \alpha + dX \\
y_t &= x_s \cdot \sin \alpha - y_s \cdot \cos \alpha + dY
\end{align*}
\]

The last step determines the transformation parameters for the rotary movement separately for each sensor. Because the setting masters center axis is not identical to the rotation axis, the parameters change during the movement. These changes follow a circular path using the rotation angle \( \varphi \) and the corresponding \( \alpha, dX \) and \( dY \), respectively. For example fitting a circle for \( dX \) results in three new parameters \( dX_u, dX_v, dX_r \) (see fig. 3(d)). For small displacements between the axes we can use the current rotation angle \( \varphi \) for the back transformation too instead of using \( \varphi' \):

\[
dX = \sqrt{dX^2 + 2dX_u(dX \cos \varphi + dX_v \sin \varphi) + dX_u^2 + dX_v^2}
\]

Figure 3. The reference shape of the setting master (a), its 2D representation in the laser sensor (b), the transformed shape after fitting to the reference (c) and the coordinate system for the calibration with its transformation parameters (d).

The back transformation of all 2D profiles results in a 3D point cloud in the world coordinate system. For the 3D data processing we determine an object coordinate system, which is defined by the pilot bore with its theoretical rotation axis and the outer contact patch.

5. 3D DATA PROCESSING

All the data interpretation and geometry comparison is done in 3D space. Thus, this section introduces the algorithmic approaches for the 3D data processing. This includes feature extraction methods and the final geometry evaluation, which is needed for the OK/NOK classification at the end of the processing pipeline. Here, we discuss the basic approaches to extract a set of more than 80 different measures from the wheel shape.
5.1. Preprocessing

Typically, the acquired 3D data contains some high-frequent noise within a certain tolerance. The reason can be found in the discrete sampling of the optical sensor on the one hand and in the different reflection properties of the surfaces on the other. Therefore, an additional smoothing option can be activated. The software system provides different algorithms, which were defined by different customers: moving average (usually applied for tactile methods) and b-spline approximations. Since the point cloud consists of single profiles, we use this data structure to process the profiles independently from each other. These methods also allow for the fast and robust identification and removal of outliers. Interrelationships between multiple scans are considered afterwards in the feature extraction and geometry evaluation steps.

For analyzing a set of points on a curve, B-splines are helpful. They are used to obtain a mathematical description from which features can be easily extracted. In addition, they can be used to close small gaps between neighboring, disconnected sublines. Interpolating these gaps keeps the precision of measurements if the distance between the corresponding sublines is less than a certain threshold (e.g., 0.5 mm; this depends on the accepted inaccuracy for the closing segment). Otherwise, the interpolated spline would follow the assumed geometry insufficiently.

A B-spline curve \(x(t)\) of order \(k\) (degree \(k - 1\)) is defined over an ordered knot vector \(T\) as vectorial polynomial:

\[
x(t) = \sum_{i=0}^{n} d_i N_{i,k,T}(t), \quad t \in [t_{k-1}, t_{n+1}]
\]

with the basis functions \(N_{i,k,T}(t)\) and the control points \(d_i\). These B-spline curves offer \(C^{k-2}\) continuity at the segment transitions. To ensure that a B-spline curve approximates given points in an optimal way, control points have to be generated from the measured points. Therefore, the distance between the points on the curve \(X_i\) and the measured points \(M_i\) has to be minimized. A well-known and fast method is the minimization of the quadratic (Euclidean) distance:

\[
\sum_{i=1}^{n} \|X_i - M_i\|^2 = \text{min}.
\]

Control points \(D\) are computed depending on the values of the basis functions \(N\) and the measured points \(M\):

\[
D = (\left(N^T \cdot N\right)^{-1} \cdot N^T) \cdot M.
\]

The mentioned smoothing and interpolation operations work in a user-defined tolerance range, which do not allow large displacements. This is very important to steadily assure correct, undistorted measuring data. After having applied preprocessing operations, the next section discusses the feature extraction, which is used to identify the necessary measures.

5.2. Feature extraction

The lateral and the radial run out determine the quality of the manufactured wheel as well as the position of the bolt holes. Therefore, we need to consider the set of single radii over all measured features at defined positions along each profile and within the entire point cloud. There are three important areas, which must be analyzed: the inner and the outer bead seat and the area at and around the pilot bore (see fig. 4). The bead seat is the edge of the rim that creates a seal between the tire bead and the wheel. At the bead seat, there are three features, the rim flange, the shoulder (rim taper) and the hump. The rim flange is the edge of the wheel and the shoulder is the outer edge of the tire tread where it meets the sidewall. The small hump is for safety reasons and ensures the optimal seat of the tire to the inner wheel. The area at the pilot bore consists of a contact surface, a cylindrical area at the hub and the lug bolt holes for mounting the wheel at the vehicle axes.

For the feature extraction from the point clouds, we use a-priori geometry information, since the wheel type is always known. Thus, we define expectation ranges, which limit the possibilities, where a single feature can be found. In case of the bead seat features, we want to determine the lateral run out, which describe the planarity and the radial run out, that represents the roundness. The planarity or conicity of the contact surface at the pilot bore is a direct quality measure, which also applies to the spatial position and diameters of the pilot bore and the lug bolt holes.
Figure 4. Schematic wheel construction (a) with marked regions of interest: outer and inner bead seat (A,B) and the area around the pilot bore (C). Enlarged regions at the bead seats (b),(c) and the reconstructed 3D point cloud (d).

5.3. Measures at the bead seat

The shape of the bead seat and its measures with respect to the pilot bore are important parameters that significantly determine the runnability. If all radii to the rotation axis are the same, the wheel was manufactured optimally. This also applies to the distances of the bead seats to the outer contact plane at the pilot bore. The corresponding measures are found at the slope heading up to the rim flange and at the shoulder (see fig. 5(a)). Therefore, a circle with a fixed radius of 8 mm must be placed at the bead seat, touching, but not intersecting, rim flange and shoulder. This is achieved by fitting lines to the slopes in these regions. A parallel translation of these lines by 8 mm yields an intersection point, which is the center of the circle we have been looking for. The distances of the circle to the outer contact patch of the pilot bore and to the rotation axis are the measures for the run out. This procedure is applied to all profiles of the inner and outer bead seat. As a result we have a curve showing the development over the perimeter (see fig. 5(b)). The run of the resulting curves is evaluated by computing its Fourier series (6). After decomposing the complex signal into its frequencies, we are able to rate the contained shapes (see fig. 5(c)). For example, the maximum of the first harmonic yields a direct measure of the deviation from a circle, the second considers ellipses and so on. In the manufacturing, the first four harmonics are analyzed, since the influence of four spokes on the run out can still be measured.

\[
F(x) = \frac{1}{2} a_0 + \sum_{n=1}^{\infty} a_n \cos nx + \sum_{n=1}^{\infty} b_n \sin nx
\]  

(6)

Usually, the resulting curve is smoothed in a preliminary step based on a very fast moving average approach. But in most cases this method is not able to smooth high frequencies sufficiently. A more sophisticated but slightly slower method is the Fourier interpolation. High frequencies, which are contained in the last harmonics, are removed by accumulating only the lower ones. The curve consists of 360 values, and with respect to the sampling theorem, only 180 harmonics can

Figure 5. Measures at the sampled bead seat (a),(b) and result of the 1.–4. harmonic analysis (c). Figure (d) compares the moving average method (top) and the Fourier smoothing (bottom) on the radial distances. The noise in the signal is additionally amplified for a better visualization.
be used to interpolate this curve without adding noise. We achieve a smooth curve by accumulating the first 90 harmonics (see fig. 5(d)).

5.4. Measures at the pilot bore
The spatial position and the orientation of the pilot bore define the object coordinate system on the one hand and the shape and the dimensions at the contact patch are geometric measures on the other. Each wheel has a cylindrical center bore, which must be detected. Due to the arrangement of the hardware, the rotation axes of the sensors and the wheel are nearly the same. This observation helps, to detect an area around these axes. The resulting point cloud represents a cylinder, which is limited in its length by the inner contact patch (see fig. 6(a)). Because of the varying wheel geometries, optimal data for robust cylinder fittings can’t be provided in every case. Therefore, we use the direction of the inner contact plane, which is determined by applying a plane fitting algorithm. All the data from the assumed cylinder are now projected to this plane. As a result, we have data that allows for very reliable circle fittings. Center and radius of the circle and the direction of the plane finally define the cylinder at the pilot bore. The bolt holes are found at locations parallel to the inner plane. Their shape is analyzed by laying spheres and cones into their bore. The center of the shape is the reference for further measurements, such as distances and radii.

Figure 6. Scheme of the area at the pilot bore (a) and resulting point cloud with colored inner/outer contact patch and the detected lug bolt holes.

Fitting standard geometries to incomplete data is a recurrent and difficult problem. Even if the curve is quite simple, such as a circle, it is still hard to reconstruct it from noisy data sampled along short arcs. Therefore, Chernov et al. study the least squares, geometric and algebraic fit of circular arcs to incomplete scattered data. We also apply geometric fittings, because they are more stable than the least-squares approaches and their computation speed is comparable to them, since the quality of our input data (after projecting it to the plane) is generally sufficient (~10 iterations). The application of fitting algorithms for our procedures is done iteratively. Therefore, an initial fit is computed and those points which have large distances to the approximation, are removed. This procedure is repeated while enough points are available (typically 70% of the initial point set).

Due to the fact, that the machine is used in industrial environments, the influence of temperature changes must also be considered. Thus, all measures $V$ (distances, radii), that have been computed directly, are corrected by a temperature compensation (7), which includes a temperature coefficient $T_c$ (e.g., aluminum $23.8 \cdot 10^{-6}$ per degree) and the difference $\Delta T$ between the actual temperature and the nominal 20°C.

$$V_c = V \cdot (1.0 + T_c \cdot \Delta T)$$ (7)

6. SUMMARY
We presented a wheel measuring machine based on fast optical 3D metrology. It consists of multiple laser sensors, which use the triangulation and light-section principle for the computation of 3D coordinates. The decoupled arrangement of machine controlling and geometry measurements allows for the fast and flexible application. Wheel diameters between 13 and 24.5 inches are measured within 12 seconds which enables us to integrate the machine directly into the production process while preserving the cycle times. The quality of the measurements is comparable to that of present tactile methods in the wheel manufacturing. In the second part, we proposed a calibration procedure that finds the transformations between
the coordinate systems of the machine and the sensors. This approach is based on an Iterative End Point Fit algorithm (IEPF) and aligns the captured data to the nominal data of a calibrated setting master. Finally, the last part has focused on the 3D data evaluation. At first, the acquired set of 3D data is corrected by interpolating single scan lines with b-spline curves, which have a smoothing character and are able to fill holes. In the next steps, geometry extraction approaches were presented that use the given CAD data to adaptively define expectation ranges for the feature detection. The extracted surface parts were analyzed and compared to the given ones by approximating the same geometric primitives, such as lines, circles and planes. Finally, a set of more than 80 measures and deviations are computed and stored in a database for process control and documentation.

REFERENCES