Computed Tomography enabling Virtual Assembly

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Abstract
Computed tomography (CT) is the only dimensional measurement technology that captures holistic geometric information of the complete object. The availability of equally and densely distributed measurement data gathered by CT enables the consideration of local form deviations of the object’s surface for the definition of a datum system. A datum system describes a coordinate system that is used for referencing geometrical tolerances. Therefore, the datum definition by an approximation of datum features is replaced by a fitting method called virtual assembly (VA), where the datum surfaces are registered in order to simulate the real, physical workpiece contact. Besides describing the theory, in this paper the method is evaluated using a linear guide assembly as an example that is compared to the real assembly of the object.

Keywords: virtual assembly, datum system definition, geometrical tolerancing, form deviations, deviations propagation

1 Integrating the concept of the virtual assembly in the current industrial production ecosystem

As products become more and more complex and requirements for the product performance increase continuously, a complete and function-oriented tolerance specification and verification of a part geometry is needed in order to fulfill the specified product quality with a sufficient process capability. The usual consequence is that design engineers assign smaller tolerance values to functions, resulting in more scrap parts or higher production costs. Modern manufacturing technologies like additive manufacturing in many cases suffer from a smaller process capability compared to more established manufacturing methods like subtractive manufacturing, because of much higher form deviations that are caused by the specific manufacturing processes. The advantages of additive methods such as freedom of geometry and the associated economic production of small lot sizes up to lot size one contradict the lower process capability due to higher form deviations. Besides the well-known shortcomings of additive technologies, this conflict also holds for many other manufacturing processes. Geometrical deviations originate from the production process, expressed by Srinivasan [20] as the axiom of manufacturing imprecision. Trends of an inherently increasing manufacturing precision are described by Nielsen [9]: Geometrical deviations, such as tolerances of size and location could be lowered through optimized manufacturing systems by significant numbers. As a rule of thumb, those tolerance types could be decreased by a factor of ten ever 50 years. Now, size and location tolerances can be manufactured in the dimension of form tolerances, so that the surface topology with its local form deviations becomes more and more significant [9]. Therefore, existing geometrical specification and verification methods have to be extended by form considerations using VA as a partial solution in the concept of the “geometrical variations management” (GVM). This concept describes the entirety of measures in all phases of the product life cycle dealing with the minimization of the impact of geometrical deviations on the function and perceived product quality [11]. The aim is to integrate the VA in the concept of the digital twin to enable a consistent geometrical process chain from the part design until the final assembly to further extent the possibilities of GVM. [1, 4]

Integration of the virtual assembly in the concept of the digital twin

The digital twin is a concept embedded in the field of industry 4.0. It is closely connected to the concept of cyber-physical systems that are systems to connect the physical world with the digital entities through its “[…] on-going processes, providing and using, at the same time, data-accessing and data-processing services […]” [8]. The digital twin in terms of production connects the theoretical model with actual data from production like geometrical deviations of a particular part. Data saved in the digital twin can be used to control processes during all phases of the product life cycle. For instance, data can be considered to optimize manufacturing or inspection processes in order to increase the product quality. Due to simplification, in this paper the digital twin is limited to considerations of geometrical nominal and actual data only. A proposition for the representation of the geometrical digital twin is given in ISO 17450-1:2011 [10]. The Skin Model hereby describes all allowed deviations of a part from its nominal shape. This is a theoretical concept, since there are infinite manifestations of that shape, defined by the physical limits between the part geometry and the environment. A Skin Model Shape furthermore is an actual manifestation of a certain combination of deviations. It can be gathered by capturing measurement data of a real, physical object in the observation stage or by applying deterministic and/or stochastic deviations to nominal geometries in the prediction stage. The latter concept is used to predict the effect of geometrical variation, when only a-priori knowledge of the manufacturing distribution is known, e.g. in the early design phase, when a physical product doesn’t exist yet. The former described observation stage approach is deployed.
in this paper. The deviations then are known for each particular part, which allows an individual part interpretation, whereas interpretations during the prediction stage can only be statistically significant. [4, 10, 11]

Concept of the virtual assembly

Up to now, the virtual process chain of actual geometrical data, expressed through the digital twin, is interrupted, since all processes along the product life cycle cannot be consistently modeled virtually. The missing link visualized in Figure 1 is the assembly procedure that affects most of the geometrical inspections, since many products consist of two or more parts. At the moment, actual data of an assembly either has to be estimated from the propagation of deviations of the parts by assuming certain mathematical models, or has to be acquired by scanning the final, physical assembly. Due to an abstract mathematical formulation of the propagation of derived features of the parts (sizes, angles and tolerances), the uncertainty of interpretations on assembly level is usually higher compared to interpretations based on the scanned physical assembly, where only the measurement uncertainty has to be considered. Such mathematical models are among others Vectorial Tolerancing, Tolerance-Maps, Deviation Domain, Small Displacement Torsor (SDT), Technologically and Topologically related surfaces (TTRS) and the Direct Linearization Method (DLM) [11]. Although interpretations based on the scanned physical assembly are considered as the benchmark, it needs to be avoided due to economic reasons. Scans of physical assemblies are cost- and time-consuming and often not necessary, because the actual geometrical data of the particular parts is in most cases already available due to quality control. Moreover, the parts have to be physically assembled first, which causes additional effort. A virtual method such as the VA overcomes the imprecision and complexity of mathematical models for deviation propagation as well as the need for an additional scan of the physical assembly. The VA concept allows simulating numerous assembly configurations in a minimum of time. With the VA, the digital twin of the assembly is enabled without having to perform a physical assembly. Therefore, the physical mechanisms that affect the real assembly are translated into a mathematical description, expressed by a registration operation, where the measurement data is transformed, so that the relative position afterwards corresponds to the part positions of the physical assembly at the best possible rate.

Computed Tomography as key enabler for the Virtual Assembly

In the early days of coordinate measurement machines, mainly tactile sensors were used to capture the measurement data. Each point on the part’s surface had to be probed sequentially, leading to long probing times in order to acquire large numbers of points and dense point clouds, respectively. By using approximation methods, regular geometries were fitted to those sparse point sets, so that characteristics of those geometric features like the diameter of a cylinder could have been evaluated. Generally speaking, local form deviations were neglected. Optical measurement systems like industrial CT which emerged lately and still increase, offer the possibility to overcome the disadvantage of tactile measurements by capturing and considering complete, dense measurement point clouds. An overview on the measurement time dependency of different tactile probing strategies is given in Weißgerber et al. [12] and Petró [13]. For the computed tomography and generally speaking optical scanning methods, the number of points depends on system properties like the magnification, the sensor resolution and the evaluation strategy.

By performing measurement data acquisition using CT, the entire geometrical information of the object can be digitized in a single scan. Thus, indentations and inner geometric structures of parts being involved in the assembly can be acquired as well. Most of the part geometries include concave regions like occlusions and indentations, as shown in Figure 2. Therefore, the CT is in many cases essential to capture the geometrical information. To implement an entire virtual assembly of an individual physical assembly, all the surfaces of the parts, namely the Skin Model Shapes, have to be acquired. Figure 2 shows a case study of a typical technical assembly, a linear guide consisting of a rail and a slider that is mounted on the rail. The acquisition parameters for the CT scan are described in Section 4. If other optical systems for surface scanning are used instead, like methods based on triangulation, distinct concave regions cannot be captured.
2 Development of the method for virtual assembly

As described before, approximation methods historically were established to reconstruct the geometrical information from sparse data. This, for instance, allows deriving the diameter of a shaft by approximating a cylinder to measurement points acquired on the physical workpiece. The geometric primitives used are points, lines, circles, planes, cylinders, spheres, tori, cones, and cone sections [10]. Freeform surfaces are not considered there. Operations applied to geometrical data according to ISO 17450-1 are partition, extraction, filtering, association, collection, construction and reconstruction [10, 12]. Figure 3 shows the procedure for the association of geometric features using the example of a Gaussian plane fitting on the rail of the case study.

![Figure 3: Operations applied to the rail of the case study](image)

Figure 3: Operations applied to the rail of the case study: The measurement data was acquired using CT scanning. In the next steps, measurement points corresponding to a plane were partitioned (Partition), further extracted (Extraction) and filtered (Filtration) and then a nominal plane is associated (Association).

Datum definition according to recent normative standards

The purpose of a datum system is to define a coordinate system for the workpiece, in which the measurement results are given, and to define location and orientation of tolerance zones derived from the tolerances [15]. A datum system is specified as shown in Figure 4 according to ISO 5459 for instance by three perpendicular datums [19]. Those datums are described by the invariance classes of their geometric elements like the normal vectors of planes as shown in Figure 4. They lock the six degrees of freedom (DOF) of the workpiece in 3D space. This sequential approach is often called the 3-2-1-alignment, thus constraining each 3, 2 and 1 degrees of freedom one after another. [5, 16, 19]

![Figure 4: Datum system according to ISO 5459:1982](image)

Figure 4: Datum system according to ISO 5459:1982 (image based on [19]).
Problem formulation

Ideal geometric features simulate the physical contact of the workpiece by defining the contact between real and ideal surfaces. According to ISO 5459, the default association criterion is an ideal geometry outside of the material. According to the draft ISO/DIS 5459.2:2017, the concept of reconstructing the physical workpiece is intensified [5]. When there is no unique solution for the optimization problem, a minimax (Chebychev) association should be used, that minimizes the maximum distance between the associated feature and the filtered feature, which has been used for association. There are two main deficits in this approach according to Weißgerber and Keller [16]: The Chebychev association requires also to capture the inner extremal points of the surface, that are hard to acquire e.g. with tactile methods. The associated feature coincides with only one up to three measurement points of the acquired data, so that the robustness is low due to a high sensitivity concerning outliers. In practice, mainly a comparatively robust Gaussian approximation is used, showing the deficit of non-reproducible results. [12, 16]

Figure 5 shows two datum definitions using approximated best fit planes (left) and tangential planes (middle) and in contrast the VA approach (right), where no approximation is performed. By best fit-approximation, the surfaces interpenetrate. By outer tangential plane approximation, the alignment is calculated in such way, that in most cases the surfaces hover. Extrinsic tolerances are constituted with respect to a datum system, contrary to intrinsic tolerances such as a diameter that is not further dependent. The qualitatively highlighted variation of the datum system definition causes greatly varying extrinsic tolerances, depending on the strategy of datum definition. This causes potential misinterpretations, when either tolerances are evaluated too small or too large compared to the real quantitative compliance with the associated product function. On the one hand non-detected functional failure and on the other hand scrap parts could occur [3, 12, 15].

Challenges of the datum definition by Virtual Assembly

Using the concept of the VA, the local form deviations of the surfaces are considered for assembly. The aim is to increase the accuracy of the alignment in order to improve the interpretation accuracy of extrinsic tolerances. A major problem of VA is the possible ambiguity of contact solutions. These can be overcome by constraints considering assembly forces as well as elastic and plastic deformation of the assembly zone [14]. Since the contact situation can change strongly even between two neighboring contact states, an established sequential approach as mentioned above cannot be further used [3]. In Section 3, the VA is described as a nonlinear optimization problem. Next to the mentioned challenges, the computational effort to solve the problem is higher than the effort for a conventional 3-2-1 registration. The implemented algorithm is described in Section 3.

3 Algorithm for the virtual assembly

Mathematically, the registration corresponds to an optimization problem. This problem includes the minimization of an objective function that is derived from a specific distance metric and therefore describes the minimization of the average distance between the surfaces to be registered. One surface A is fixed and therefore not moved, while another surface B is transformed relatively to surface A. Both surfaces are represented by triangulation meshes, which are described by faces and vertices. The vertices from a surface triangulation constitute the point cloud of the particular surface. In the following, the fixed point cloud of surface A is called the reference point cloud (A) and the point cloud of surface B, that is registered against surface A, is called the moving point cloud (B). The optimization variables are the six DOF of the moving point cloud. The aim of the optimization is to determine the transformation of the coordinate system of the moving point cloud into the coordinate system of the reference point cloud, so that it is subsequently possible to perform evaluations in a common coordinate system. A well-known implementation of the registration problem is the Gaussian Best Fit, where the sum of the squared distances is minimized by iteratively determining optimal parameters of a model function. Distances are computed between corresponding points that are possible candidates for a surface contact. Therefore, sets of corresponding points are determined, using the criterion of a minimal distance between corresponding points in surface A and surface B. These point sets are identified by a nearest-neighbor search utilizing a knn-search with the L2 norm (Euclidean distance) as distance metric, as described by Friedman et al. in [23]. A number of k nearest neighbors in B is determined for each point in A, where in this paper k = 1 neighbor is searched. The knn-search algorithm is based on a k-d tree algorithm, so that the data is represented in a tree structure in a sorted order. The advantage is a shorter computation time compared to the exhaustive search method, because the number of calculations needed to determine best matches for nearest neighbors is smaller than in an unstructured data set [23]. Thus, to each point P_i of surface A one corresponding point S_j of surface B is found with minimal distance. The distance d_i of point P_i (x_{P_i}, y_{P_i}, z_{P_i}) of point set P to point S_j (x_{S_j}, y_{S_j}, z_{S_j}) of point set S is defined in Equation (Eq.) (1) [17].
\[ d_i = \sqrt{(x_{p_i} - x_{S_i})^2 + (y_{p_i} - y_{S_i})^2 + (z_{p_i} - z_{S_i})^2} \]  

Due to the physical impossibility of penetration of surfaces, the intersection of the point clouds needs to be avoided by introducing a boundary condition as discussed in prior work in [2 - 4] and [16]. An intersection can be excluded, when the normal vector \( \vec{n}_i \) assigned to a specific point \( P_i \) on the surface A and the vector \( \vec{v}_i \) from \( P_i \) to its corresponding point \( S_i \) on the surface B point in the same half space of the plane through \( P_i \) with the normal vector \( \vec{n}_i \), as visualized in Figure 6.

![Figure 6: Intersection determination by assessment of vectors \( \vec{n}_i \) and \( \vec{v}_i \)](image)

The normal \( \vec{n}_i \) in \( P_i \) is estimated by the normal vector of a plane fitted to a certain number of neighboring points with respect to \( P_i \) considering the definition of a positive sign for a normal vector pointing away from the surface material side. If \( \vec{n}_i \) and \( \vec{v}_i \) point in a common half space, the included angle is smaller or equal to 90° and thus the dot product is greater or equal to zero. The formation of the dot product is described in Eq. (2). In this case, the point \( S_i \) does not interfere the surface described by point set \( P_i \), whereby an intersection is precluded. In the other case, an intersection occurs, stated by a negative sign of the signed distance \( d_{x,i} \), as described in Eq. (3).

\[
\vec{n}_i \cdot \vec{v}_i = \vec{n}_i^\top \cdot \vec{v}_i = |\vec{n}_i| \cdot |\vec{v}_i| \cdot \cos \theta (\vec{n}_i, \vec{v}_i)
\]

\[
d_{x,i} = \text{sign}(\vec{n}_i^\top \cdot \vec{v}_i) \cdot d_i
\]

The optimization variables represent the DOF of the surface to register by three translational degrees of freedom \( T_x, T_y \) and \( T_z \) and three Euler angles \( \phi, \theta \) and \( \psi \) with respect to the coordinate system of the reference point cloud. The objective function \( f \) is

\[
f (T_x, T_y, T_z, \phi, \theta, \psi) = \sum_{i=1}^{N} d_i^2
\]

The optimization problem is solved iteratively either using the MATLAB implementation of the Nelder-Mead simplex method that is used to compute nonlinear unconstrained problems, when a penalty function is used as described later, or by using the interior-points algorithm as a constrained problem [21]. In each iteration step, a rigid transformation of the moving point cloud is computed according to the temporary optimization values. The point cloud of the reference objects remains at its position. In order to preserve the dimensional accuracy, no shear or scaling may be applied to the transformation. The optimization problem is a nonlinear problem due to the mathematical formulation of the objective function \( f \). As a constrained problem, the optimization can be described according to the objective function \( f \) in Eq. (5) and the constraint function \( g \) in Eq. (7). In this approach the formulation of the constraint function \( g \), that all signed distances \( d_{x,i} \) should be greater than or equal to zero, is applied with a swapped sign due to the specific algorithm implementation. Here, the constraint postulating that \(-d_{x,i} \) being smaller than or equal to zero is set. The optimization problem is formulated as an unconstrained problem with the objective function \( f \), using the penalty term \( w \cdot q \) with \( w \geq 0 \) as penalty weight and \( q \) as the number of signed distances smaller zero according to Eq. (6). The higher the value for \( w \) is, the less likely an intersection of the surfaces occurs. By solving the constrained optimization, negative signed distances can be fully avoided, whereas by using the penalty approach, an intersection can occur. [17]
4 Experimental evaluation of the virtual assembly

The experimental evaluation is performed using the case study of a linear guide. This assembly contains a rail and a slider. The rail consists of a composite material made of resin and carbon fiber, the slider is completely made from plastic. The CT system used to scan the parts is a Werth TomoScope HV 500. The parameters listed in Table 1 were used to acquire the data of the physical assembly and of each part separately with the same settings.

Table 1: Measurement settings of the evaluation setup

<table>
<thead>
<tr>
<th>X-ray voltage</th>
<th>Tube current</th>
<th>Integration time</th>
<th>Filter</th>
<th>Number of projections</th>
<th>Image averaging</th>
<th>Magnification</th>
<th>Voxel size</th>
</tr>
</thead>
<tbody>
<tr>
<td>180 kV</td>
<td>240 mA</td>
<td>500 ms</td>
<td>none</td>
<td>1000</td>
<td>2</td>
<td>4</td>
<td>200 µm</td>
</tr>
</tbody>
</table>

For the recreation of the physical workpiece contact, a datum system is defined as visualized in Figure 7. The primary datum A is the collection of the two top planes of the rail and of the four corresponding contact surfaces of the slider. The secondary datum B is defined by the side plane constituting the fixed bearing side and the corresponding two surfaces of the slider. The tertiary datum would lock the remaining translational DOF along the axis of the rail. This DOF, the translation along the z-axis, is here constrained to \( z = 0 \text{ mm} \) by a theoretical plane to avoid ambiguous results. As registration approaches, both the constrained optimization and the penalty approach described in Section 3 were implemented. Due to a faster convergence in the case study, the penalty approach has been further used. A penalty weight of \( w = 5 \) was used. The transformation result of the VA is compared to the registration approach using tangential geometrical elements (TA) and to the physical assembly (PA). In order to compare VA against TA, only the contact patches were considered. To compare against PA, the complete data sets were evaluated in an actual-actual comparison, because the surfaces of the contact zones are partially blurred due to low contrast material transitions and cannot be determined in the PA data set, as can be understood in Figure 12 on the left.

Comparison of VA against TA

In Figure 8, the differences between the registration approaches using VA and TA are visualized with color-coded signed deviations. No negative distances that indicate intersection of surfaces occur by the TA approach, instead of distances down to -0.021 mm by the VA approach. This is explained by the penalty approach that allows a small intersection of the surfaces depending on the penalty function formulation. If the penalty weight \( w \) would increase, the absolute frequency of deviations smaller 0 mm would decrease. According to Weißgerber et al. [16], the contact is not defined in practice by at most three points like in theory, but by contact zones with a higher spatial expansion, so a small permissible intersection would be a reasonable approach to increase the simulation accuracy of the physical workpiece contact.

The main visual difference between the approaches is the more equally distributed contact zones of the four top patches for the VA approach. Here, the left two patches also depict significant contact zones that are marked in green. Using TA, the contact zones are very small in comparison. An angular deviation about the z-axis (along the rail movement, compare to Figure 8) between the two approaches was determined about 0.1208° with the TA alignment as reference, outlining the most significant transformation component between the approaches. Summarizing, the translational displacements \( T_x, T_y \) and \( T_z \) and the Euler angles \( \phi, \theta \) and \( \psi \) between TA and VA with TA as reference are
Statistically, the histogram of signed deviations $d_s$ calculated according to [22], does not represent a Gaussian normal distribution. In the Anderson-Darling hypothesis test for normal distribution (significance level $\alpha = 0.05$), the null hypothesis of a normal distribution is rejected both for TA and VA. In Figure 9, the histograms of deviations calculated by both alignment approaches are shown. Thus, the mean value $\bar{x}$ and standard deviation $s$ of the distribution are calculated. The mean value $\bar{x}_{VA} = 0.127$ mm for VA is only about 0.003 mm smaller than $\bar{x}_{TA} = 0.130$ mm for TA. The standard deviation $s_{TA} = 0.05579$ mm for TA is about $s_{VA} - s_{TA} = 0.00598$ mm smaller than $s_{VA} = 0.06168$ mm for VA. This is caused by the significant amount of distances smaller or near zero that occur for VA, but not for TA, since the surface is shifted more towards the material contact for VA. By TA, very few values smaller than 0.02 mm occur, what leads to a hovering surface contact that is defined by only a few contact points.

**Comparison of VA against PA**

The accuracy of the virtual assembly approach described in this paper defined by its mathematical formulation should be quantitatively assessed by comparing towards the physical assembly (PA) as the “real world” problem. By using the case study of the linear guide, the assembly can be easily performed by just attaching the slider to the rail with a specific orientation and location. No assembly force was applied, so that only the gravitational force presses the slider onto the contact zones on the rail. The slider was aligned flush-mounted with the rail and was fixed in this position by tape. A valid point of criticism is this alignment so far, since it needs to be done manually, causing a potential manual influence on the accuracy of the alignment for the physical assembly. The PA is scanned in a ca. 45° shifted orientation in CT to avoid Feldkamp artifacts on beam-parallel surfaces with the CT parameters given in Table 1.

In order to compare both VA and PA data sets, they have to be transformed into a common coordinate system by registration. Here, a sequential registration approach according to the 3-2-1 registration was implemented. The datums therefore were defined as shown in Figure 10, where the primary datum is the lower contact plane of the rail that was associated by Chebychev criterion,
exactly like all other planes were associated. The secondary datum is the theoretical symmetry plane of the flanks of the rail that is constructed from the collection of the planes marked in red according to Figure 10. Additionally, the tertiary datum is defined as a plane on the back side of the slider. By this registration approach, the data sets are merged for the rail component mainly, because the variations of the relative positioning of the slider towards the rail want to be assessed. Another suitable approach would be a Best Fit-alignment that considers the rail only.

Figure 10: Description of datum system applied for registration (left image) and color-coded visualization of deviations between virtual assembly and the physical assembly as reference (right image).

Figure 11 shows the histogram of the signed deviations according to (3. Here, three peaks can be determined. An assumed Gaussian normal distribution with a mean value of about 0 mm can be observed that is overlaid with two additional distributions left and right to the peak at 0 mm. These deviations describe a shift between VA and PA that can be observed as yellow-to-orange marked spots on the color-coded plot visualized in Figure 10 for the positive deviations, and as blue marked spots on the opposite side of the data set. As a conclusion from histogram and color-coded plot, there is a linear shift along the x-axis about 0.15 mm totally, that does not manifest in the physical assembly. In the optimal case, the side peaks would vanish and only a normal distribution symmetric to zero would remain, whose standard deviation corresponds to the measurement uncertainty of the measurement system. So, the histogram of signed distances towards the PA can be described as an optimization criterion. The optimization variables then have to be chosen in such a way that a nearly ideal normal distribution symmetric to zero results. Therefore, the slider has to be aligned carefully, comprehensible and reproducible to the rail for the scan of the PA with high precision. Also, the alignment procedure described in Figure 10 has to be further assessed regarding the robustness of the registration of the data sets in respect to the rail.

Figure 11: Histogram of signed distances of VA as well as TA with respect to PA (reference).

5 Outlook
The implementation of the VA shows smaller distances and fewer distances smaller zero, what indicates a more equal distribution of contact zones as it can be created by TA. The comparison of VA and TA to the physical assembly is complex due to various influences on the accuracy of the deviations histogram that is used to interpret the conformance of the virtual methods to the real-world assembly. Among other influence quantities, the algorithm implementation with e.g. its mathematical formulation and stopping criterion, the registration used to align the data sets and the method how to align slider to rail robustly in the physical assembly are aspects to consider when interpreting the comparisons for future evaluations.
In future work, also the measurement uncertainty of the CT system has to be considered quantitatively. The uncertainty budget of the measurement tasks can be assessed experimentally, as described in ISO/IEC Guide 98-3:2008 [6] by Type A assessment. Here, the budgets from the CT scan itself and from data processing algorithms like surface determination, tessellation and registration are acquired commonly. By establishing the measurement uncertainty chain, the budget caused by the virtual assembly can be further assessed. Galovska et al. [7] describe a mathematical model based on ISO/IEC 98-3 [6] that includes the uncertainty propagation caused by the registration. Another promising approach is the spatially resolved measurement uncertainty assessment described by Flessner et al. in [18] for CT scans by the single point uncertainty.

As shown by the case study and assured by problem settings from the industry, assemblies are usually geometrically complex and feature concave regions like indentations and occultations. Often features derived from the holistic data set of the assembly should be evaluated, such as the Euler angles of the slider, when the slider is moved along the rail in order to estimate the running smoothness of the linear guide. For this setting, the CT is the only measurement method to acquire holistic data and is therefore closely related to the concept of virtual assembly. In future work, the connection between CT and VA should be further worked out with the aim to increase the relevance and the task spectrum of the CT technology. One synergistic advantage of CT and VA is the enabling of the quantitative assessment of hidden, occluded contact zones as shown in Figure 12 that is not possible to assess up to now with CT or even other measurement systems. The deficit of CT, that only spatial frequencies up to a certain cutoff frequency can be acquired, leading to blurred contact zones, can be overcome by separately scanning the parts and performing the VA. This enables also the evaluation of assemblies from multi-material, where due to strong artifacts a scan of the physical assembly is not feasible. In the long run, the geometries gathered by VA can be used as specifying geometries in order to reduce artifacts or to improve surface determination methods specifically in the contact zones. Machine learning methods such as reinforcement learning could be used to improve those algorithmic implementations based on VA.

Figure 12: Comparison of physical (left image) and virtual assembly (right image).

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