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Continuous updating of the Geometrical Digital Shadow for additively manufactured products along the process chain

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Abstract

The industrialization of additive manufacturing requires a holistic understanding of the whole process chain to exploit its full potential as a sustainable and resilient production technology. The necessary resources, in terms of process and measurement data, to generate this knowledge are theoretically available, but in most cases not in a form that facilitates automated processing and interpretation. Instead, the acquired data is often only stored locally and in heterogeneous formats that necessitate expert knowledge and customized software for interpretation and utilization.
The “Geometrical Digital Shadow (GDS)” framework was previously introduced as a means to merge metrologically acquired geometrical data of a product along its lifecycle into a single source of truth. Boolean operations were proposed as a tool to track the geometrical changes of the products, which thereafter can be used analogously to diffs in version control systems. While a general proof of concept was provided for synthetic data, the tested methods resulted in large file sizes for real measurement data. Due to the measurement uncertainty of the used fringe light projection process, the diffing methods registered small deviations even in regions where the physical specimens were not altered between measurements.
In this work, an improvement to the previously presented computation of geometric diffs in digital meshes is proposed and integrated into the Geometrical Digital Shadow framework. By combining Boolean operations with an implicit-distance-function-based masking method, a threshold can be set for the minimum deviation that is registered as a change in the generated diffs.

Automation, Geometric modelling, Metrology, Quality assurance

1. Introduction

The use of additively manufactured components is steadily increasing in the production industry. One of the main advantages of additive manufacturing is the high degree of geometrical freedom in the design of the products. But this complexity poses a major challenge for the entire process chain. Even for established processes, such as surface machining with machine tools, previously unknown problems emerge [1]. Additionally, many new questions arise for the integration of measurement technology along the entire additive process chain [2].

For quality assurance purposes, optical measurement systems, e.g., fringe light projection scanners, can be used to digitize the geometries of complex parts with a high level of detail while minimizing measurement time [2, 3]. These generate three-dimensional (3D) point clouds, which are then polygonised by connecting the captured points to form triangular meshes. If such a mesh is acquired before and after a modification of the geometry of a physical component, the changes that took place can be determined. By comparing the generated 3D meshes to each other, the detected changes can be checked against the planned changes [4].

However, these measurements are in most cases individual processes, which generate a large amount of separated data. Management of this measurement data can quickly become convoluted and hamper the knowledge gain that could be generated from the acquired data. As a structured approach to this data management problem for 3D measurement data, the Geometrical Digital Shadow (GDS) framework, as summarized in Figure 1, was introduced in previous work by the authors [4]. Reminiscent of a version control system (VCS) for geometric 3D measurement data, it was proposed to only store changes made to the geometry of the physical products along the production chain, instead of multiple full-scale 3D meshes.

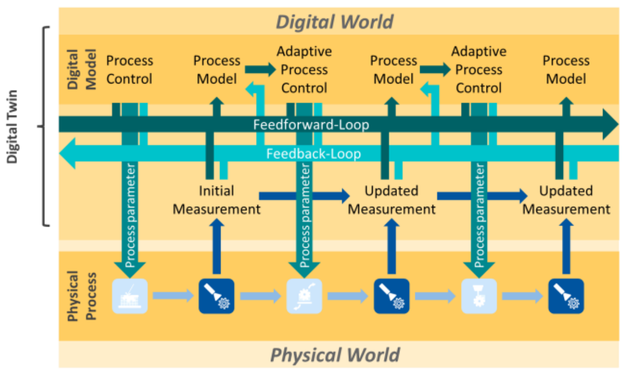

Figure 1. The Geometrical Digital Shadow (GDS) framework as presented in [4]. Arrows indicate the information flow inside of and between the physical world and the different components of the Digital Twin of the Product, i.e., the Digital Shadow and the Digital Model.

The purpose of a VCS is to track changes, also referred to as diffs (short for differences), made to files by multiple users to facilitate collaboration by reducing redundancy as well as contradictions between different versions of the same file. However, few works are bringing the idea of VCS into the field of geometric measurements. The open-source tool 3D Diff [5] provides an interactive approach to determine differences and resolve conflicts between meshes. But, as the calculation of differences is based on a precisely defined scene graph, the software is limited to assembly applications. Denning *et al.* developed MeshGit [6] as a practical software for diffing and merging polygonal meshes, typically used in subdivision modelling workflows. While the algorithm has been tested successfully on a variety of mesh edits, it fails when the geometry changes are significant. Park *et al.* introduced the Meshchain [7]platform, which provides decentralized mesh data storage and cooperative modelling. However, their difference determination method is targeted at design models with simple geometry configuration, and the data footprint of the diffs will grow larger than expected if the number of triangles is very high. Though the authors have adopted a mesh compressing algorithm to solve this issue, it may lead to a loss of surface details in the measurement domain.

After this short introduction to the topic, current developments of the GDS framework are presented, focussing on an improved difference determination. Next, the methodology to validate the proposed procedure is presented, followed by a practical evaluation. Finally, a summary of the work and an outlook on future improvements are given.

2. The Geometrical Digital Shadow framework

The purpose of the GDS framework is to provide a single source of truth, which facilitates the storage and access of 3D geometric measurement data along the lifecycle of a product. Especially during the manufacturing of high-value products with small lot sizes, deviations from the ideal geometry can lead to large losses in resources and time in the downstream process chain. If these deviations are noticed early in the process chain, however, it might be possible to correct these by adapting upcoming processes accordingly or to save resources by removing the faulty part from production early [1]. The decision on how to proceed with a part is dependent on the current state of each individual part, which can only be captured through metrological means. Accordingly, the physical part should be digitized after every change to its geometry and the created measurement data should be made available to the decision-making entity. In addition to the raw measurement data, the changes made, and thereby the geometrical history of the part, can be of value, when evaluating the quality of a part and the processes, which led to its current state. Moreover, to save storage, it is sufficient to only keep the data containing the changes in the geometry, as the data of the unchanged geometry is already available from previous measurements.

Previously, it was demonstrated how 3D Boolean operations can be used to determine the differences between two optical 3D scans of the same part, before and after a change to the geometry of the physical specimen [4]. Furthermore, by applying these changes to one of the meshes through additional Boolean operations, the respective other mesh can be reconstructed. While this approach is sufficient for synthetic meshes without any measurement artifacts, it was shown to be inadequate for real measurement data. Due to the measurement uncertainty of the sensors and other influences during the data acquisition, 3D meshes created through measurements will rarely overlap, even in regions where the physical specimen was not affected by any geometrical changes. In return, the calculated differences include all these small deviations, and as a result, the generated meshes increase the data footprint instead of reducing it.

As metrology systems should ideally be chosen in a way that variations on the scale of the measurement uncertainty are insignificant, a new method is proposed, in which changes in the meshes, which are smaller than a predefined threshold, are ignored. For this method, two diffs are calculated, one using the above-mentioned Boolean operations, the second one utilizing an implicit distance function representation of the meshes. While the latter is not as accurate as the first, it can be used to quickly filter out distances smaller than a selected threshold. The filtered difference is then used to create a 3D mask, which is applied to the more accurate Boolean difference. The steps of the proposed data processing pipeline are summarized in Figure 2. The details of the most relevant processing steps are covered in the next section.

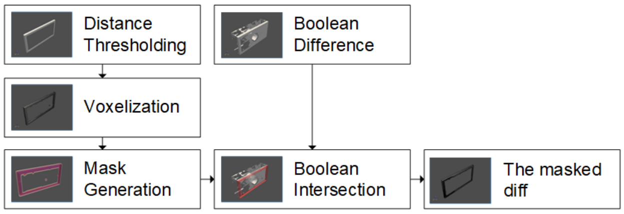

Figure 2. Overview of the processing steps for a threshold-based determination of geometrical differences in 3D meshes. An implicit distance function is used to calculate the distances between the two input meshes. Then, distances smaller than a preselected threshold are removed. The resulting mesh is voxelized and used as a mask for a more accurate difference determined by Boolean operations.

3. Implementation

In recent years, the distance function has arisen in scientific literature as a novel type of geometry representation [8]. The signed distance function (SDF) implicitly represents the model as a continuous function:

$$SDF(x) = s : x \in \mathbb{R}^3, s \in \mathbb{R} \tag{3.1}$$

which outputs the distance *s* of a given point *x* to the closest surface in space. The function describes the surface by indicating the relative position of a point to the surface by assigning the sign. The function outputs a negative value when the point lies inside the surface and a positive value when the point lies outside the surface. Thus, the surface can be implicitly represented by the isosurface of:

$$SDF(\cdot) = 0 \tag{3.2}$$

Similarly, the implicit distance function (IDF) can be used to describe the distance between two geometries. For each point *p* in a mesh, the function computes the distance to the nearest point *x* in the other mesh *M* as:

$$IDF(p, M) = \inf_{x \in M} \|p - x\| \tag{3.3}$$

To track only changes with a distance greater than a predefined threshold *T*, the meshes are filtered according to the calculated distance field. As the geometric difference between two meshes is not commutable, two diffs need to be determined for each set of meshes. Additionally, the implicit distance can be positive or negative and therefore, the threshold should act bidirectionally. Altogether, four filtered meshes need to be calculated:

$$A' = \{a \in A \mid IDF(a, B) > 0 + T\} \tag{3.4}$$
$$A'' = \{a \in A \mid IDF(a, B) < 0 - T\} \tag{3.5}$$
$$B' = \{b \in B \mid IDF(b, A) > 0 + T\} \tag{3.6}$$
$$B'' = \{b \in B \mid IDF(b, A) < 0 - T\} \tag{3.7}$$

Examples of these four filtered meshes are shown in the centre of Figure 3.

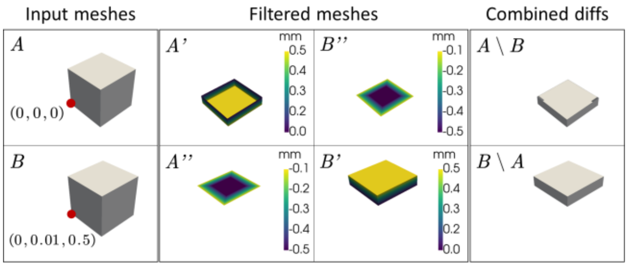

Figure 3. The implicit distance functions (centre) needed to create the threshold-filtered diffs (right) of two cuboids with offset origins (left).

To acquire the diffs, the filtered meshes are then combined. Where a volume is removed from mesh A, the faces belonging to both mesh A and the subtracted volume are removed from the resulting mesh, while the faces belonging to both mesh B and the subtracted volume are kept. And vice versa for the cases where volume is added. Therefore, the filtered meshes form the diffs $A\backslash B$ and $B\backslash A$ in the following way, respectively:

$$A\backslash B = A' + B'' \tag{3.8}$$
$$B\backslash A = A'' + B' \tag{3.9}$$

Examples of meshes generated by such combined diffs are shown on the right side of Figure 3.

However, some caveats limit the further application of the generated diffs. As distances smaller than the predefined threshold T are removed from the differences, points close to the intersection of the combined meshes with distances below the threshold are also filtered out, resulting in gaps in the diff meshes. This impairs the manifoldness of the meshes, which is an essential requirement for many Boolean solvers. Consequently, the diffs generated by the IDF method are only used to mask more accurate diffs acquired by a Boolean operation method, which ensures manifoldness.

The first step of the masking step is to close the gaps in the combined diffs. As surface meshes do not contain volume information, mesh voxelization is used to transform surface meshes into voxels. For the voxelization step, the bounding box of the input mesh is acquired and separated into evenly distributed cubic cells according to the required voxel size. Then, for each cell, a statistical method, based on ray casting and a voting strategy, is used to determine whether it is inside or outside of the input mesh [9].

Due to noise and measurement uncertainty, as well as the existence of gaps in the meshes, unexpected voxels can be generated. These unwanted voxels must be removed to mask only the relevant regions of the meshes. Additionally, due to the loss of surface details in the process of voxelization, the mask should be slightly larger than the generated voxel volume, to fully encapsulate the regions of interest. To remove isolated voxels and thicken the main structure, morphological operations, i.e., an opening followed by a dilation, are applied to the generated voxels as a post-processing step. An example of such a post-processed mask can be seen in Figure 4.

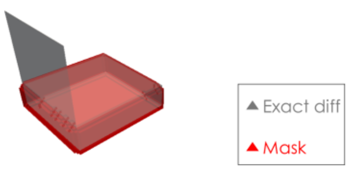

Figure 4. Post-processed voxel mask of the previous example in red enclosing the regions of the more accurate diff, created by an off-the-shelf Boolean solver, where the deviations are below the threshold.

Finally, the generated voxel masks are applied to the more accurate diffs, which were generated by a Boolean solver. By calculating the Boolean intersections, everything outside of the voxel masks is removed from the accurate diffs, while upholding the level of detail and the manifoldness.

For validation purposes, the new diff approach is implemented in the Python programming language with most of the applied methods being based on the PyVista module [9]. To obtain accurate Boolean-based diffs, the Python wrapper around the C++ library libigl, provided by the Python package PyMesh is used. PyMeshFix is used as a post-processing tool to fix defects on the resulting meshes [4].

4. Evaluation

In order to validate the new approach for the generation of geometrical diffs, the proposed method is applied to the same test geometries that were used to evaluate the previous method [4]. Mesh A is a cuboid of size $100 \times 50 \times 25$ mm³, created using an Ultimaker 3 extended fused deposition modelling (FDM) printer. Mesh B is the same cuboid with a cylindrical hole of 22.5 mm in diameter drilled through the top surface. For mesh C, chamfers are added at a 5 mm distance to the edges of its top surface. These modifications are created using a 5-axis Kolibri 500 MBE machine tool by Mitsubishi Electronic. After each step, a digitalized model is acquired using an ATOS Core 300 fringe light projection scanner by Carl Zeiss GOM Metrology GmbH. The generated meshes are shown in row a) of Figure 5.

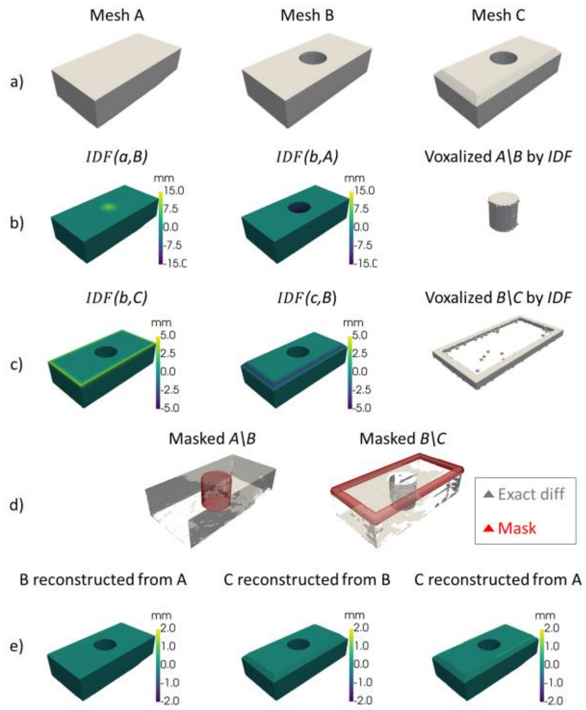

Figure 5. Overview of the practical evaluation, showing the whole diff generation and mesh reconstruction pipeline step-by-step. a) original meshes acquired by fringe light projection scanning. b) and c) mesh representation of the four implicit distance functions used for the threshold-based diff generation and resulting voxel masks before post-processing. d) diffs created by an off-the-shelf Boolean solver, overlayed by the voxel masks (red). e) reconstruction results of the different states of the product from applying the diffs to the mesh of the previous state.

Rows b) and c) show the results of the threshold-based difference determination, with the IDFs in the first two columns and the voxelized combined meshes before post-processing in the third column. Both masks exhibit unwanted voxels, especially at the edges where gaps are present in the combined IDFs. The denoised masks can be seen as a red overlay on top of the more accurate diffs, created by the Boolean solver, in row d). Finally, in row e), different meshes created by the reconstruction pipeline are presented. For the first column, the diff $A\backslash B$ was applied to the original mesh A through a Boolean difference, removing the cylindrical volume in the centre, and therefore mimicking the drilling process, which resulted in mesh B. By applying the diff $B\backslash C$ to mesh B, the chamfers are added, as can be seen in the second column of row e). The last column shows the result of applying $B\backslash C$ to the mesh in the first column to show a reconstruction over multiple states.

As can be seen from the colour grading, i.e., the deviation from the original meshes, most of the faces are highly consistent with the faces in the original meshes. However due to a misalignment errors, deviations occur at the corners and edges of the meshes. Since the mask is slightly enlarged to fully encapsulate the regions of interest, the faces around the boundaries of the changes are intersected and appear in the diffs consequently.

To evaluate the data footprint, the storage needed for saving the original mesh and all the needed diffs is compared to saving every measurement result individually. For the old method, i.e., just the Boolean solver, the stored data takes up 195.23 % of the original data for the full reconstruction pipeline from mesh A to mesh C and is therefore deemed unfeasible for data reduction. With the newly proposed method, however, the needed storage was reduced to 49.14 %. As small geometrical deviations are not tracked in the diffs anymore, the meshes consist of significantly fewer vertices and faces and therefore take up less storage space.

5. Conclusion and future work

In this work, improvements to the previously proposed Geometrical Digital Shadow framework [4] are shown. The new approach for calculating geometrical differences between 3D meshes uses an implicit distance function representation, which provides the option to filter small differences based on a user-defined threshold. By applying the results as a voxelized mask to Boolean differences, created by an off-the-shelf Boolean solver, manifold diffs can be generated. This approach is tested on optical 3D scans including measurement uncertainty. For these data sets, the previous method resulted in diffs with extensive unwanted data. With the new approach, regions where differences only occur due to measurement uncertainty or noise can be successfully filtered out, which in return, leads to a reduction of the data footprint to 49.14 % of the original meshes, when only storing one of the meshes and the necessary diffs.

Overall, the new threshold-based geometrical diff generation exceeds the capabilities of the previously presented approach. As intended, the introduction of a threshold to filter out small deviations significantly reduces the needed storage space and thereby renders the proposed geometrical diff method applicable for data fusion and reduction within the Geometrical Digital Shadow framework.

However, the major limitation of the proposed method is the large number of computational resources needed for the voxelization during the mask generation process. This is currently limiting the accuracy that can be achieved. Large voxels lead to a reconstruction error due to overlapping faces that occur at the edges in the resulting meshes, as the mask exceeds the actual regions of interest. This could be improved by using a strategy such as the k-d tree algorithm to further subdivide the voxel grid close to the outer surfaces that intersect with the original meshes, while keeping large and coarse voxels in the inner volume of the mesh.

For the practical evaluation presented in this work, various parameters, such as the voxel size during voxelization and the IDF threshold, are manually selected. To further advance the potential for automated data processing, these parameters should be set based on information that can be extracted from the input data. For example, the measurement uncertainty of the metrology system could be used as a basis.

While the focus in this work lies on the comparison of measurements of different physical states of the same part, the presented methodology could also be applied to evaluate the conformity of a part. For this, the tolerance limits could be used to create a hull around the nominal surface. Determining the IDS between this mesh and the measurement would indicate if the surface of the part lies within the specifications.

For either application, it is important to keep in mind that the result of the difference calculation is strongly dependent on the method used to align the input meshes into the same coordinate system. How to properly determine and document the uncertainty created during the alignment and the following processing steps is part of future work.

Acknowledgement

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