

# Computation and Visualization of Fabrication Artifacts

Muhammad Muddassir Malik  
Vienna University of Technology,  
Austria  
mmm@cg.tuwien.ac.at

Christoph Heinzl  
Upper Austria University of Applied  
Sciences, Austria  
christoph.heinzl@fh-wels.at

M. Eduard Gröller  
Vienna University of Technology,  
Austria  
groeller@cg.tuwien.ac.at

## ABSTRACT

This paper proposes a novel technique to measure fabrication artifacts through direct comparison of a reference surface model with the corresponding industrial CT volume. Our technique uses the information from the surface model to locate corresponding points in the CT dataset. We then compute various comparison metrics to measure differences (fabrication artifacts) between the two datasets. The differences are presented to the user both visually as well as quantitatively. Our comparison techniques are divided into two groups, namely geometry-driven comparison techniques and visual-driven comparison techniques. The geometry-driven techniques provide an overview, while the visual-driven techniques can be used for a localized examination.

**Keywords:** Difference measurement; Surface model; Volume rendering.

## 1 INTRODUCTION

Comparison of two almost identical datasets is very important for the continuously rising demands of quality control in industrial engineering. Recently much work has been done in the area of mesh comparison. A high number of vertices and edges are hard to process in real time due to the limited processing power available in hardware. This initiated research to simplify mesh datasets in such a way that the rendering speed is increased while the mesh distortion is limited. Distortions introduced through mesh simplification led to research on mesh comparison.

In the manufacturing industry, it is necessary to produce industrial components as close as possible to the computer aided design model (CAD) of the part. Engineers use CAD tools like AutoCAD, Pro Engineering etc. for designing. The CAD model is considered to be the ground truth during the manufacturing process. To verify the accuracy of the production process, manufactured components are scanned with an industrial computed tomography (CT) machine. The volumetric dataset obtained from the CT scan is then compared to the CAD model of the part (called surface model henceforth). The comparison between the two datasets is supposed to clearly identify erroneous regions.

The comparison process uses various methods to measure differences between the two datasets. The differences present between the surface model and the volume data are the result of fabrication, measurement, and surface reconstruction artifacts. We are primarily

interested in detecting the fabrication artifacts as these are introduced in an industrial part during the production phase. The goal of the comparison process is to minimize all post-production artifacts so that the differences measured between the datasets mainly correspond to fabrication artifacts.

Datasets of industrial components, unlike medical datasets, mostly consist of materials with distinctive density values. There is a high signal to noise ratio and the interfaces in the volume data are easy to detect. For this reason the most common method for first part inspection is to generate an iso-surface mesh from the CT scan and to compare it with the surface model. In various cases this is not the ideal approach: First, the generation of a mesh from the CT dataset requires a surface extraction algorithm. Industrial components have sharp edges and corners and therefore a lot of surface reconstruction artifacts are introduced [6]. Second, mesh generation for a given iso-value is not interactively possible during the comparison process. Therefore, the need to do a comparison with a higher or lower resolution mesh will lead to a delay in the examination process. Third, a CT dataset goes beyond a surface model and has information about the interior of the mechanical part as well. Losing this information limits the examination possibilities of the CT dataset.

Figure 1 shows a CAD model in (a), direct volume rendering (DVR) of the industrial CT scan in (b) and an iso-surface mesh extracted from the CT scan in (c). In figure 1(c), all the internal information of the volumetric dataset is lost. Areas marked with black rectangles in figure 1(b) and 1(c) are shown as zoom-ins. We observe surface reconstruction artifacts in figure 1(c).

In this paper we present a novel approach to perform a comparison directly between the surface model (which is the ground truth) and the volumetric dataset obtained from the industrial CT scan. We calculate the difference between the surface model

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee.

Copyright UNION Agency – Science Press,  
Plzen, Czech Republic

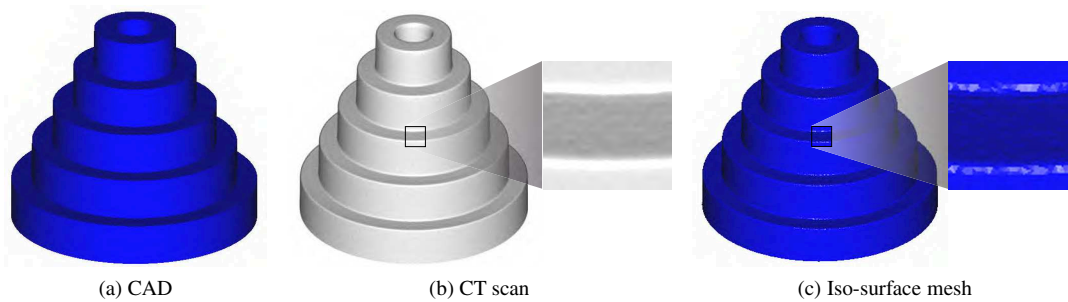


Figure 1: (a) CAD model of test-part-1 (surface model: 200,000 triangles, volumetric dataset: 561x559x436 voxels). (b) Direct volume rendering of the scan of test-part-1. (c) Iso-surface mesh extracted from the volumetric dataset in (b).

and an interface of the volume data and also compare the relative surface smoothness. We ensure that the differences we measure represent fabrication artifacts (section 4). The uncertainty of the measurement process is also evaluated and presented to the user.

Color coding, glyphs, ray profiles, and 3D box plots are provided for visualization and the results are also displayed quantitatively. The proposed method is implemented on the Graphics Processing Unit (GPU). It provides interactive comparison and visualization. We successfully avoid reconstruction artifacts by comparing the surface model directly with the volume data. Delays in the examination process are also avoided by embedding the complete comparison and visualization pipeline in a single system.

## 2 PREVIOUS WORK

Large numbers of triangles are inefficient to render and also hard to stream over a network. Subsequently, algorithms are proposed to simplify meshes [2]. Mesh simplification distorts the original shape, especially on sharp edges and therefore techniques are proposed to measure the differences between the two meshes.

Many public domain mesh comparison tools have been released in recent years [3, 9]. Metro [3] scan converts one of the surfaces into a set of points and then measures the Hausdorff distance between each point and the other surface. Aspert et al. [1] propose to use an approximation of the Hausdorff distance for measuring differences which is computationally and memory wise efficient. Pichon et al. [7] propose to use the gradient of the Laplacian equation to measure distances between the surfaces.

Weigle and Taylor [11] investigate visualization methods for distance and local shape comparison. Their study shows that glyphs are better in conveying deviation information between surfaces than color coding alone. They use intersecting surfaces with known alignment for their study.

There has been some recent work on the comparison between a surface model and an industrial CT dataset. These methods however introduce a pre-processing step to the comparison process, where an iso-surface mesh is

generated from the CT dataset. Heinzl et al. [5] propose a method for generating a feature preserving mesh from a CT dataset. They use filtering to suppress noise and a watershed segmentation to create a binary dataset. In the final step a surface model is created using elastic surface nets. The creation of a surface model is a time consuming and an error-prone process.

Geomagic Qualify [8] is a well-known software product, used for quality control in industrial engineering. A surface model and an iso-surface mesh of the volumetric dataset are inputs to this tool and it performs distance analysis between the two datasets. Methods for extracting an iso-surface mesh from a volumetric dataset [4, 5, 6, 10] have to be used in a pre-processing step for performing comparison using Geomagic Qualify. Geomagic Qualify works independently from the surface extraction process and therefore does not take into account surface reconstruction artifacts during the comparison process. However such errors are introduced in the pre-processing step.

## 3 COMPUTATION & VISUALIZATION

Our comparison system is divided into geometry-driven and visual-driven analysis techniques. Geometry-driven techniques provide an overall visualization of the differences between the surface model and the volumetric dataset. Visual-driven techniques are used on top of the geometry-driven comparison techniques for a user guided analysis and for obtaining precise quantitative information.

An overview of the system is shown in figure 2. The Iterated Closest Point (ICP) algorithm performs rigid registration and produces a transformation matrix as output. The output matrix transforms the surface model (moving dataset) through translation, and rotation to closely orient it to the CT dataset (fixed dataset). Registration is not the major scope of our work. We performed it with high accuracy (see section 4.1) using a well known algorithm in a semi-automatic way. Fully automatic registration techniques have not been investigated but might be applied.

Both types of comparison, i.e., geometry-driven and visual-driven comparison techniques (figure 2), query

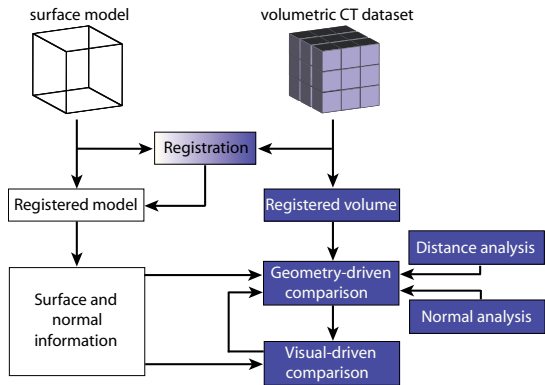


Figure 2: System overview. Geometry-driven comparison techniques color code the datasets and render glyphs. Visual-driven comparison techniques provide localized information about differences.

the registered surface model for the necessary information but work completely independent from each other. The results of the query, i.e., meta data from the CT dataset and the chosen visualization technique, are used to compute quantitative data and to produce images.

Geometry-driven comparison techniques consist of a distance analysis and a normal analysis. The distance analysis calculates the differences between the surface model and an interface in the volumetric dataset as Euclidean distances. It also measures the uncertainty of the measurement process. The normal analysis precisely locates differences in curvature and compares the surface smoothness of the two datasets.

We provide a ray-profile analysis and a magic lens as building blocks of the visual-driven comparison. The ray-profile analysis visually presents the data and differences at a user specified location and also displays the information quantitatively. The magic lens extracts the differences between datasets at a user specified neighborhood and displays them using glyphs, i.e., box plots.

### 3.1 Geometry-Driven Comparison

Distance and normal analysis methods require the specification of a corresponding point in the CT dataset for each surface point on the surface model. Starting from a surface point we have to locate the corresponding point in the volumetric data. The search direction is approximately along the surface normal. In high curvature areas the search should be extended to nearby directions as well to ensure robustness.

Consider the blue rectangle and the gray object in figure 3(a) to be a surface model and a volumetric dataset respectively. Black spheres represent surface points. A pair of red and green lines originating from each surface point indicates the conical space in which we search for a corresponding point in the volume data. The space is larger for surface points in high curvature regions (see the surface point at the corner in figure 3(a)).

For each triangle of the surface model we evaluate the facet normal and the three vertex normals. The angle between the facet normal and each of the vertex normals is computed and the maximum of the three angles (called search-angle henceforth) is stored. The search-angle indicates the local curvature of the surface model. In areas of high curvature, a large search-angle will be calculated whereas the search-angle will approach zero in planar areas of the surface model.

In figure 3(b) we indicate the search-angle as a red arc between the facet normal (black arrow) and one of the vertex normals (green arrow) of the blue triangle. Using the search-angle we can construct a double cone with the opening angle set to twice the search-angle. The double cone is depicted in figure 3(b) with the apex placed on the surface of the triangle. We then extract the spatial locations and the normal vectors for a set of uniformly distributed surface points on the triangles of the surface model. At each surface point the apex of a double cone is placed and the cone axis is oriented along the surface normal. A triangle therefore bisects the double cone at its apex (figure 3(b)). We call the nappe of the double cone that lies on the front face of the triangle as outside nappe, while the nappe on the back face of the triangle is called inside nappe. The double cone defines a region in which we can search for an interface point in the volumetric dataset. An appropriate interface point found inside the double cone will be associated with the surface point of the triangle for further computations.

In order to search for an interface point in the volume data, we start from the surface point and traverse the volume data along several rays distributed inside the double cone. The rays originate from the surface

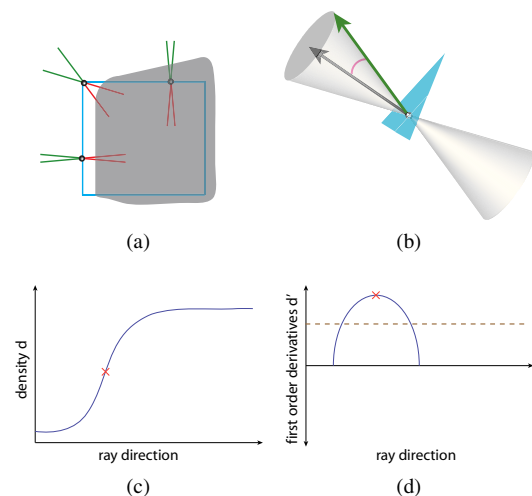


Figure 3: (a) Pairs of red and green lines depict the space in which we search for a corresponding point in the volume data (gray object) for each surface point (black sphere) on the surface model (blue rectangle). (b) Double cone representing the search space in 3D. A density profile and the first order derivative of a density profile are illustrated in (c) and (d) respectively.

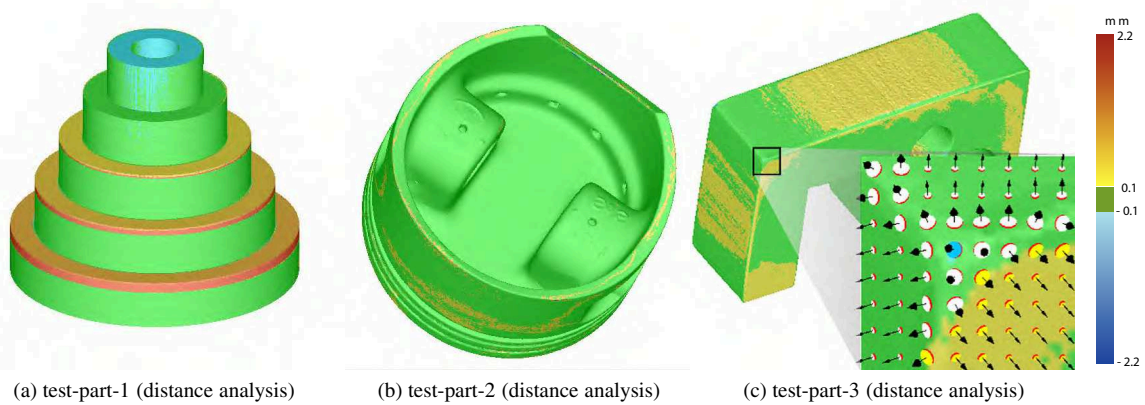


Figure 4: (a) test-part-1, (b) test-part-2 (surface model: 152,054 triangles, volumetric dataset: 408x351x355 voxels), and (c) test-part-3 (surface model: 25,880 triangles, volumetric dataset: 329x527x181 voxels) rendered using distance analysis. The image resolution is 512x512.

point and are directed towards the two bases of the double cone. The density profile of each ray is used to identify the interface point as the position with highest/lowest gradient magnitude (first order derivative is a maximum/minimum and the second order derivative is zero). The gradient magnitude at a spatial location must be greater than a user specified threshold for that location to be considered an interface point. Thresholding is necessary to filter out small changes in gradient magnitude which do not represent an interface. We also apply a median filter to the density values to reduce noise. Among all the considered rays the interface point with minimum distance to the surface point is stored for further processing. The rays are distributed in concentric circles inside the double cone. The density of the rays is kept almost constant by taking more rays on the outer circles compared to inner circles.

A density profile of a ray is illustrated in figure 3(c). The graph of the first order derivative of such a density profile is drawn as the blue curve in figure 3(d). The dashed brown line shows a threshold for the first order derivative. The first peak or valley with absolute derivative above the threshold is considered an interface point in the volumetric dataset. The interface point is indicated by a red cross in figures 3(c) and (d).

As we find an interface point in the volumetric dataset, we store its spatial location, the nappe (inside or outside) in which the interface point was found, and the gradient. The information extracted from the surface model and the CT dataset provides all the required parameters to evaluate the metrics for distance analysis and normal analysis.

**Distance Analysis:** The computationally intensive step of finding for each point on the surface model a corresponding interface point in the volume data has already been done. The distance analysis shows the difference between the datasets as Euclidean distances. We compute the differences between the spatial locations on the surface model and their corresponding interface points

in the CT dataset. We also have information about the nappe of the double cone in which the interface point was found. Using this information we color code the dataset for distance analysis.

Figures 4(a) and (b) show test-part-1 and test-part-2 respectively. The test-parts are rendered using the distance analysis with distances measured in millimeters. The color scale used for color coding is shown on the right of figure 4. The distance has positive sign if the interface point is found in the inside nappe of the double cone.

Figure 4(c) shows test-part-3 rendered using our distance analysis technique. We render distance glyphs on the zoom-in of the user specified area (black rectangle). The arrow of the distance glyph is aligned with the normal vector of the surface and the diameter of the disc is proportional to the diameter of the base of the double cone. The color of the disc indicates if the difference was found in the inside nappe (yellow), outside nappe (blue) or no difference was recorded (white).

So far we only consider the minimum distance between the surface model and the interface of the volumetric dataset for distance analysis. The technique does not take the interface shape into consideration. The results have uncertainty in high curvature regions which needs to be highlighted. For a double cone the difference between the minimum and maximum distance from the surface model to the volume data will be larger in high curvature regions compared to planar areas. Therefore the difference between the minimum and the maximum distance serves as the uncertainty value of the measurement process.

To determine uncertainty we look for the maximum distance from the surface point to the interface in the volume data. The search for the maximum distance is conducted in the neighborhood of the ray along which the minimum distance was found. The neighborhood for searching the maximum distance has a radius of one voxel. We choose this radius, as the search space should



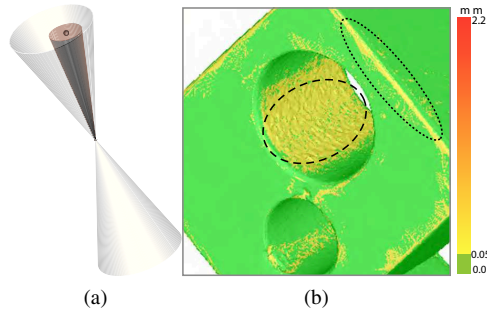


Figure 5: The maximum distance to the interface point is searched in the neighborhood (brown cone) of the ray (cone vertex to black sphere) along which the interface point was recorded. (b) Uncertainty rendering for a zoom-in of test-part-3. A dotted and a dashed oval highlight areas of high curvature and rough surface respectively.

be smaller than the smallest feature in the dataset. Any feature less than the size of a voxel is not detectable in the volumetric dataset anyway.

Figure 5(a) illustrates the uncertainty measurement process. Let us assume that the closest interface point was found along the ray which starts from the surface point (cone vertex) and extends towards the black sphere depicted on the base of the cone. In the neighborhood around that ray (brown cone), we search for an interface point with maximum distance to the surface point. The difference between the minimum and the maximum distance from the surface point to the interface in the volume data is considered the uncertainty of the measurement process.

The uncertainty in the case of test-part-3 is shown in figure 5(b). It becomes apparent that areas of high curvature or high surface roughness, which are highlighted using a dotted and a dashed oval respectively, have higher uncertainty.

**Normal Analysis:** Normal analysis is proposed as an efficient method to compare surface smoothness. Normal analysis compares the orientation of the normal vectors extracted from the surface model with the gradients obtained from the CT dataset. The angle between the normal vector and the gradient indicates the difference in the curvature of the surface model and the interface of the CT dataset. Normal analysis is easy and efficient to compute given that the surface points and the corresponding interface points are already evaluated.

The type of difference shown by normal analysis may pass undetected by distance analysis. Consider the black plane in figure 6(a) to be part of the surface model with the normal vector indicated by a black arrow. The interface of the volume data (blue plane) overlaps the surface model in the area marked with a red oval. The distance analysis will report no difference in such a case. However, there is a difference in the orientation of the two datasets as the normal vector and the gradient do not point in the same direction. Such differences can be emphasized using normal analysis.

Normal analysis will report a constant difference along the entire surface in this example.

Figure 6(b) shows test-part-1 rendered using normal analysis. Normal analysis detects differences at edges and rough surfaces. As the volumetric dataset is generated from an industrial process, it does not match the smoothness and exactness of the surface model, especially at the edges. The zoom-in in figure 6(b) shows that the top of test-part-1 is quite rough. The color scale can be changed dynamically by the user.

### 3.2 Visual-Driven Comparison

Visual-driven comparison techniques are grouped into ray profile analysis and magic lens displays. Ray profile analysis displays the differences between the datasets both as 2D plots and as quantitative numbers. A magic lens is used to zoom-in/out of the dataset and to view the differences graphically.

A ray profile display (figure 7) is generated by plotting the first derivative of the density values encountered along the ray in the volume data. The peaks and valleys in the graph show the interface points. The location of the surface point is marked on top of the graph. The horizontal difference between the interface point and the surface point in the plot shows the local difference. This provides precise information about the differences in the datasets.

Figure 7 shows two ray profiles generated for positions on test-part-3 marked with black crosses. The vertical red lines depict the points on the surface model. The blue graph shows the first derivatives of the density values encountered by the ray, along which the interface point in the volume data was found. The peaks in the blue graphs are the edges detected in the volume data.

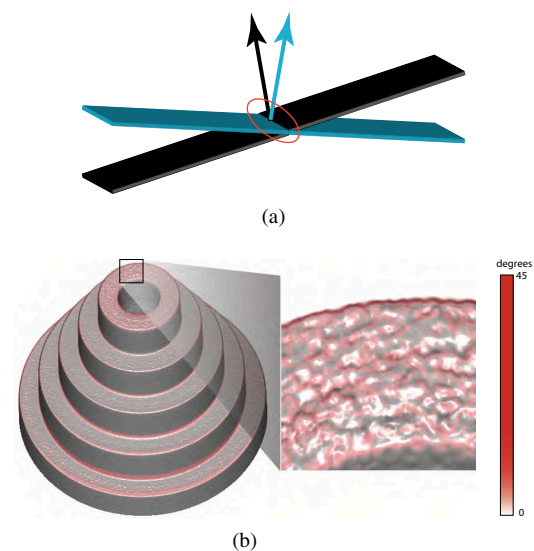


Figure 6: (a) Normal analysis emphasizes differences in orientation. (b) test-part-1 rendered using normal analysis. The zoom-in shows roughness at the top of test-part-1.

The horizontal distance between a peak and a red line indicates the local difference between the datasets.

In the ray profile on the left in figure 7, we observe that the surface point (red line) and the interface point (peak) overlap and thus there is very little difference between the two datasets. The ray profile on the right in figure 7 however shows a difference between the surface model and the volumetric dataset as there is a horizontal difference between the red line and the nearest peak. Our system reported a difference of  $0.2\text{ mm}$ .

A ray profile shows the distance at one specific position. The next approach shows differences in a small local neighborhood. A magic lens can provide a precise graphical view of the differences by means of 3D or 2D box plots (figure 8). The box plots are rendered in a user specified area. Each box plot shows the minimum, the maximum, the mean, and the standard deviation of the differences between the two datasets at each local neighborhood. Additionally, 3D box plots are oriented along the normal vectors of the surface model. The diameter of a 3D box plot is directly proportional to the base of the double cone in which the interface point was searched. 3D box plots therefore encode distance values, uncertainty, and the dependent variables (normal vector and the base of the double cone) whereas 2D box plots only encode the distance values and the uncertainty of the measurement process (figure 8(a) and (b)).

Figure 8(c) shows 3D box plots over a user specified area (black rectangle) on test-part-3. 3D box plots similar to white planar discs indicate no difference in the minimum, maximum, and the mean distances recorded between the two datasets. The measurement is most certain in areas where “flat” 3D box plots are rendered.

3D box plots are less suited for a relative comparison as they are differently oriented along surface normals. 2D box plots make a relative comparison in a user specified area easier (figure 8(d)).

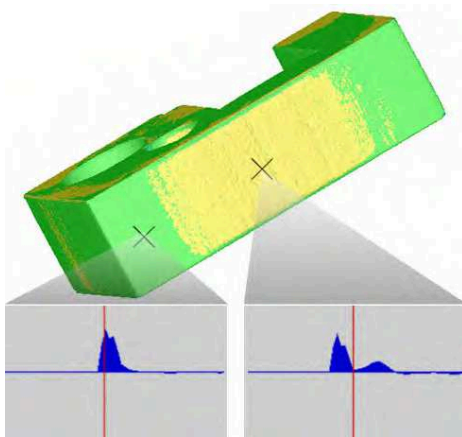


Figure 7: Two ray profiles are extracted for the locations marked with crosses on test-part-3. The horizontal differences between the red line (surface point) and the peaks in the graph (interface points) depict the dataset differences.

## 4 RESULTS

We implemented a prototype on a Pentium 4, 3.4 GHz CPU and an NVidia GeForce 8800 graphics board. We used C++ and OpenGL/GLSL as programming language. The system renders the volumetric data and the surface model side by side in a volume view and a surface view. We maintain a central queue for the events performed in all views. An operation initiated in one view also pushes an event into the central event queue and releases a signal. The other view pops the event from the queue and executes it. We implement first-come, first-serve scheduling for the central queue.

### 4.1 Artifacts and Errors

An industrial computed tomography includes fabrication artifacts and measurement errors. Fabrication artifacts are introduced during each step of the manufacturing process whereas measurement errors are caused by the CT machine. Additionally, two kinds of errors are generated by the software that is used to process the CT scan. Surface reconstruction artifacts are introduced while extracting an iso-surface mesh from the volumetric dataset. Registration errors are caused by the registration algorithm.

Quality assurance engineers are primarily interested in measuring the fabrication artifacts. To accurately compute the fabrication artifacts, errors caused by software should be minimized. We perform registration with high accuracy and unlike other contemporary techniques avoid surface reconstruction artifacts.

We evaluate the ICP registration algorithm by performing registration 20 times between test-part-3 and a feature preserving mesh [5] of test-part-3. We use a feature preserving mesh for testing purposes so that the fabrication artifacts and the measurement errors are minimized and we can monitor just the registration error. We measure the mean square error between the mesh and the test-part-3 (see figure 9) and record an average registration error of  $0.0152\text{ mm}$ . The registration algorithm converged in 3.5 iterations on average.

Experiment number 18 produced a high error compared to the rest of the experiments. The ICP registration algorithm requires user interaction and the large error in experiment 18 is due to a bad specification of control points. The maximum fabrication and measurement artifact found in test-part-3 is  $1.93\text{ mm}$  and the mean difference recorded is  $0.27\text{ mm}$ . Thus the average registration error introduced by the ICP algorithm is considerably lower than the mean and the maximum fabrication artifacts in the dataset.

Reconstruction artifacts are introduced while extracting a mesh from a volumetric dataset. We use a synthetic dataset with known fabrication artifacts to evaluate our technique. Measurement and registration errors are not present in a synthetic dataset. This provides a good opportunity to analyze just the effect of

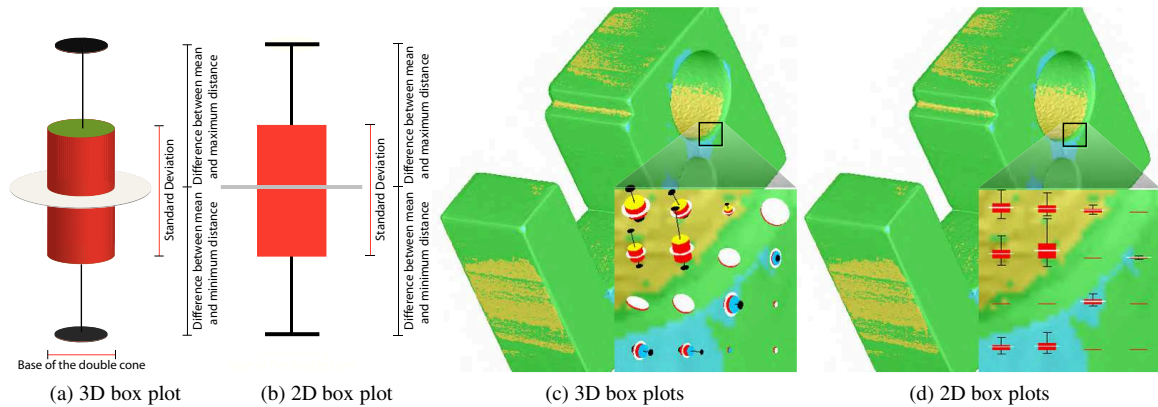


Figure 8: (a) 3D box plot. (b) 2D box plot. (c) and (d) show box plots over a user selected area. The user can interactively switch between 3D box plots and 2D box plots.

surface reconstruction artifacts. Figure 10(a) shows a surface model of a cube dataset and 10(b) shows a volume dataset with known fabrication artifacts. Fabrication artifacts are marked with an oval. The surface model consists of 12,288 triangles and the volume data has a resolution of  $256 \times 256 \times 256$ .

We generated a feature preserving mesh [5] of the volumetric dataset and compared it with the surface model using Geomagic Qualify (figure 10(c)). Surface reconstruction artifacts are visible in the differences shown by both zoom-ins. A difference is also reported at the vertical edge of the mesh (lower zoom-in) even though there should be no difference. The differences at vertical edges is purely caused by surface reconstruction artifacts and is not present in the dataset (see figure 10(b)). Figure 10(d) shows the comparison using our system. Our system correctly calculates no difference on vertical edges (lower zoom-in). The fabrication artifacts in the volumetric dataset are also reported correctly (upper zoom-in). The color coding is smooth and we do not observe any reconstruction artifacts.

The comparison of the maximum and average difference evaluated by Geomagic Qualify and our technique is given in table 1. Our method calculates the difference very close to the ground truth. Geomagic Qualify reports the maximum difference close to the ground truth but the average difference has a large error. Reconstructing a mesh from the volume data introduces artifacts distributed over the entire mesh. This is why the average error reported by Geomagic Qualify is very

small compared to the ground truth. As we avoid reconstruction artifacts, our calculations are more accurate.

Table 1: Maximum and average voxel difference reported by Geomagic Qualify and our system.

	Ground truth	Geomagic	Our technique
Maximum	8.485	7.95	8.91
Average	3.42	0.195	3.51

## 4.2 Performance and Evaluation

The earlier solutions proposed for comparison are divided into two major steps. For instance, Heinzl et al. [5] propose a robust surface detection pipeline for effective comparison. First, they extract a feature preserving mesh from the volume dataset. The mesh extraction part consists of a four step pipeline. In the first three steps, an anisotropic diffusion filter, a gradient filter and, a watershed segmentation are in turn applied to the volume dataset. In the final step constrained elastic nets are used. The mesh is then compared to the surface model using some existing tool like Geomagic. We combine the entire comparison and visualization process into a single, interactive system. Table 2 shows the runtime performance of our system, in comparison to the robust surface detection pipeline [5] and Geomagic.

The bottle neck in earlier methods has been the surface extraction process. Due to parameter tweaking the surface extraction took very long as opposed to the actual comparison process. Our method is more automated and requires much less user interaction.

Distance glyphs and the 3D box plots are additional visualization techniques for showing differences and

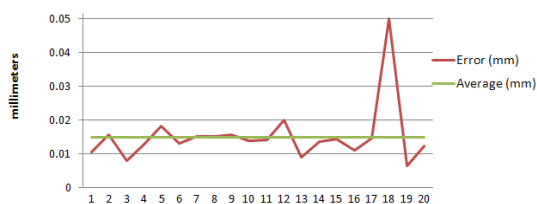
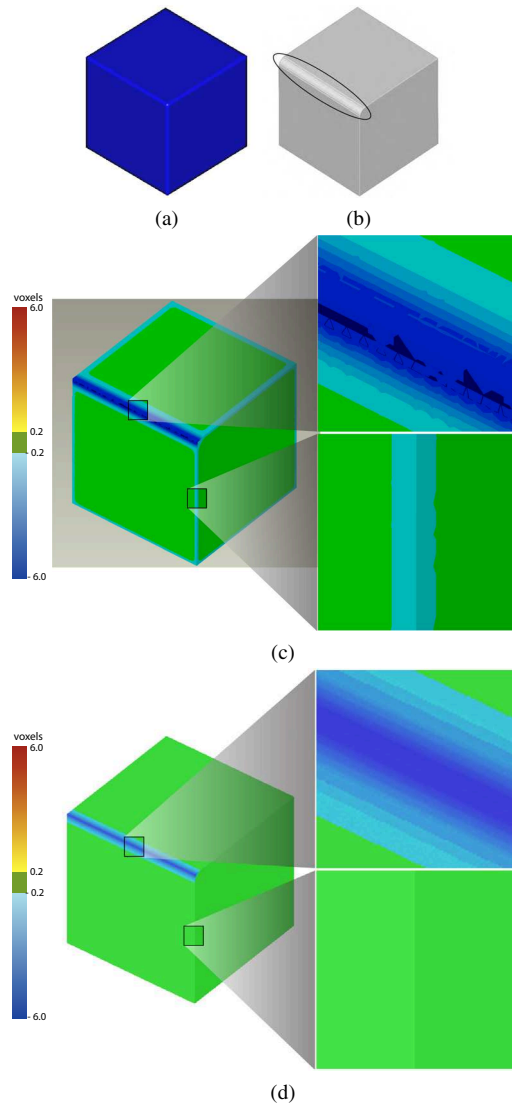


Figure 9: Mean square error produced by point-set to point-set registration on test-part-3 ( $60 \times 100 \times 30$  mm).

Table 2: Comparison of the performance of our system.

	Test-part-1	Test-part-3
Distance analysis (our method)	0.051 sec	0.033 sec
Robust surface detection pipeline	10.23 min	4.58 min
Distance analysis (Geomagic)	9.31 sec	8.51 sec



**Figure 10:** (a) Surface model. (b) Volume data with known fabrication artifacts. Artifacts are highlighted with an oval. (c) Comparison between the surface model and a feature preserving mesh of (b). (d) Direct comparison between a surface model and the volume data (our approach).

uncertainties. Two domain experts who have used various mesh comparison systems in their professional capacity tested the usefulness of our visualization techniques. They were both quite interested in using distance glyphs and 3D box plots to visualize differences as compared to color coding alone.

They acknowledged that they acquired more valuable information about the surface (surface normal), the measurement process (base of the double cone), and the differences using distance glyphs and 3D box plots. The idea of showing glyphs in a user specified area was one of the issues which the users are missing in conventional tools. The experts also appreciated the idea of showing the uncertainty of the measurement process

along with the distance analysis. The robustness of the registration algorithm was satisfactory for them.

## 5 CONCLUSION

We have presented techniques that compare a reference surface model directly to the industrial CT scan of specimens, especially in the preproduction phase of the industrial products. We avoid intermediate steps of data enhancement and surface extraction. Two sets of tools, namely geometry-driven and visual-driven techniques, provide comprehensive comparison opportunities.

## ACKNOWLEDGMENTS

This work is partly funded by the SimCT project (FFG Bridge initiative). We are thankful to Torsen Möller from the Simon Fraser University for fruitful discussions and help in designing this method.

## REFERENCES

- [1] N. Aspert, D. Santa-Cruz, and T. Ebrahimi. Mesh: Measuring errors between surfaces using the Hausdorff distance. In *Proceedings of the IEEE International Conference on Multimedia and Expo*, volume I, pages 705–708, 2002.
- [2] P. Cignoni, C. Montani, and R. Scopigno. A comparison of mesh simplification algorithms. *Computers and Graphics*, 22(1):37–54, 1998.
- [3] P. Cignoni, C. Rocchini, and R. Scopigno. Metro: Measuring error on simplified surfaces. *Computer Graphics Forum*, 17(2):167–174, 1998.
- [4] C. Heinzl, J. Kastner, and E. Gröller. Surface extraction from multi-material components for metrology using dual energy CT. *IEEE Transactions on Visualization and Computer Graphics*, 13(6):1520–1527, 2007.
- [5] C. Heinzl, R. Klingsberger, J. Kastner, and M. E. Gröller. Robust surface detection for variance comparison and dimensional measurement. In *Proceedings of Eurographics / IEEE VGTC Symposium on Visualization*, pages 75–82, 2006.
- [6] L. P. Kobbelt and M. Botsch. Feature sensitive mesh processing. In *Proceedings of the 19th spring conference on Computer graphics*, pages 17–22, 2003.
- [7] E. Pichon, D. Nain, and M. Niethammer. A Laplace equation approach for shape comparison. In *Proceedings of SPIE Medical Imaging*, pages 373–382, 2006.
- [8] Raindrop. Raindrop: The magic of making it simple. March 2007. <http://www.geomagic.com>.
- [9] S. Silva, J. Madeira, and B. S. Santos. Polymeco - a polygonal mesh comparison tool. In *Proceedings of the 9th International Conference on Information Visualization (IV05)*, pages 842–847, 2005.
- [10] Volume-Graphics. *VGStudio Max 1.2 User Manual*. 2004. <http://www.volumegraphics.com>.
- [11] C. Weigle and R. M. Taylor. Visualizing intersecting surfaces with nested-surface techniques. *IEEE Visualization, 2005. (VIS'05)*, pages 503–510, 2005.