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Component verification using X-ray Computed Tomography and CAD comparison

Tristan Lowe, PhD

Senior Experimental Officer in X-ray imaging,

Henry Moseley X-ray Imaging Facility,

The University of Manchester

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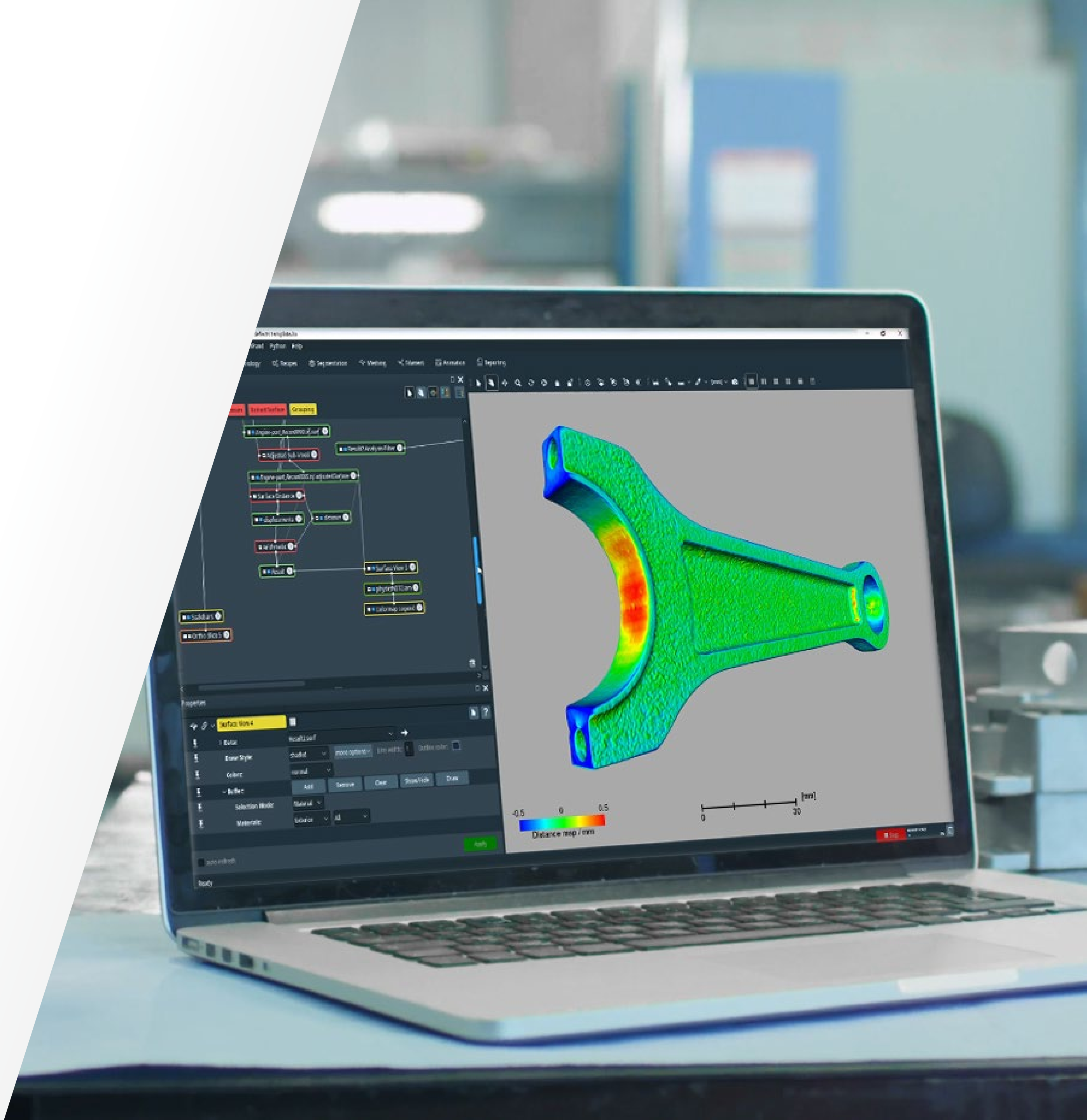

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Training materials

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Non-destructive testing (NDT) of engineering components is a critical aspect of modern high performance engineering. Coordinate Measuring Machine (CMM) and X-ray Computer Tomography (CT) are two techniques that are commonly used to verify parts produced using traditional forging and additive manufacturing. When verifying a component there are two primary aspects to consider:

1. Does the component have any critical internal defects such as porosity, fractures or particulates?
2. How closely does the finished manufactured part reflect the original design?

X-ray CT provides high resolution internal defect and surface information for part verification while CMM is ideal for surface characterisation.

This first part of training material will use an additively manufactured con rod to demonstrate how the surface profile generated from X-ray CT data can be compared to the original component CAD design. This presentation will also show how information regarding internal defects can be combined with the surface profiling for reporting purposes.

In a second part of the training material (available soon from our Xtra Library), we will explain how CMM and X-ray CT data can be combined with a CAD model for a more complete component analysis. In this example an additively manufactured turbine blade will be used.

Outline

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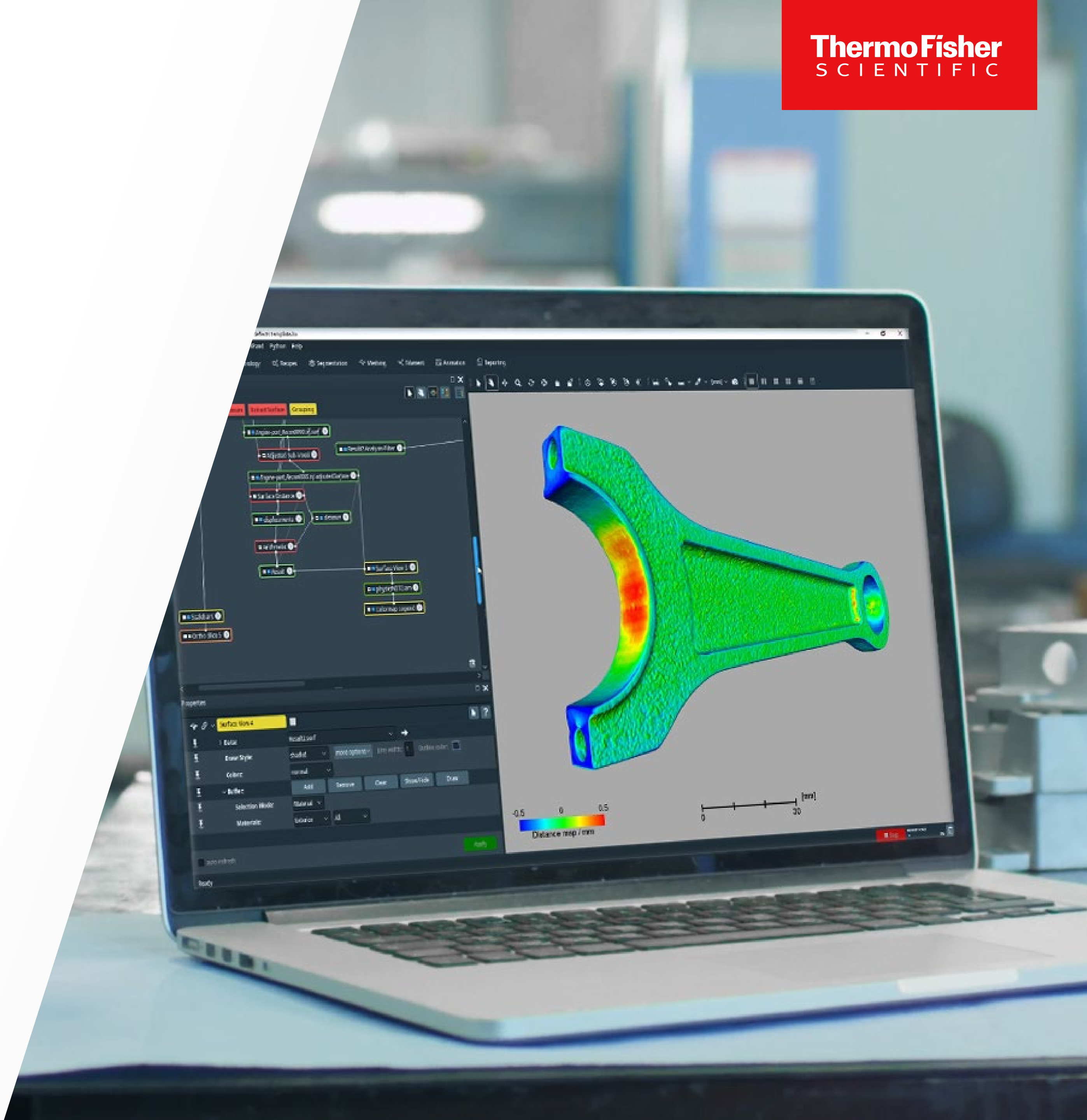
1. Useful Thermo Scientific™ Avizo™ Software tools
2. Loading data volumes
3. Data preparation
4. X-ray CT data and CAD registration
5. Surface analysis and measurement
6. Visualisation of surface comparison
7. Combining internal defect analysis



Useful Thermo Scientific™ Avizo™ Software tools

The wide range of tools in Avizo Software allow a wide range of data formats to be analysed and compared. This document demonstrates how Avizo Software can be used to compared measure geometries using X-ray CT to a CAD model.

In this example X-ray CT data of a 3D printed titanium engine con rod has been compared to the original CAD model in order to ascertain the reproduction quality of both the surface profile and internal defects.

A short list of the key tools used are as follows:

- **Open Inventor Scene to Surface**: to produce a surface for the CAD data
- **Scan Surface to Volume**: to compute a volumetric representation of the CAD data
- **Register Images**: to align the X-ray CT data to the CAD data
- **Auto Thresholding**: to segment the X-ray CT data in order to produce a surface profile
- **Generate Surface**: to compute the interface between different labels or materials
- **Surface Distance**: to calculate the distance between the X-ray CT and CAD surfaces
- **Arithmetic**: to quantify the difference in the X-ray CT data geometry relative to the CAD surface

Loading data volumes

For the comparison of X-ray CT data and CAD model for the part, two separate datasets must be loaded. It is generally easier to load the X-ray CT data first since an initial check of the image quality (see next slide) can be performed prior to loading the CAD model to determine if further analysis is required.

X-ray CT data can be loaded as either a .TIF stack (preferential for one off analysis) or .RAW (preferential for automated analysis) formats. In both cases it is better to crop the volume in the reconstruction stage to eliminate tediously large volumes and reduce the bit depth to reduce processing time. These can be performed in Avizo Software but result in an added data preparation step. In both formats it is critical that the voxel size is correct for the comparison.

A CAD model in .stp format (3D assembly file) can be imported directly into Avizo Software from the file dropdown menu (Fig.1). Once the CAD model is imported, the model can be visualised using **Display Open Inventor Scene** as shown in Fig.2 & Fig.3 by right clicking on the data.

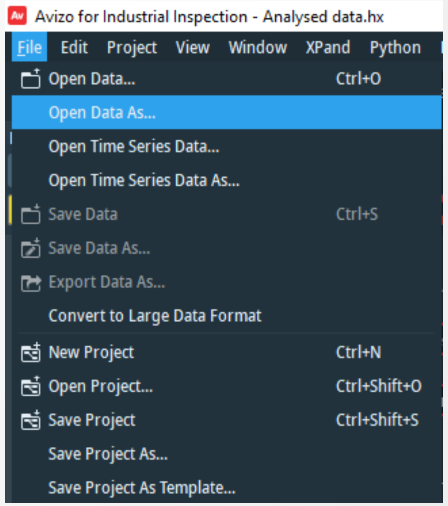


Fig.1

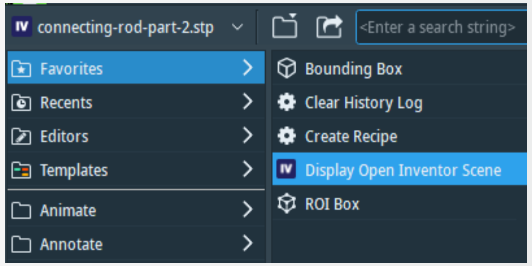


Fig.2

Fig.3

Data preparation

The comparison of component geometry to an original CAD design involves a number of steps. Therefore it is useful to carry out an initial check of the data using an **Ortho Slice**. This analysis can be useful to identify the following:

- major pores or defects within the component that render it inoperable (Fig.1)
- in the case of additive manufacturing, internal components may retain unprocessed powder (Fig.2)
- X-ray CT artefacts such as image noise, beam hardening, streaking, ring artefacts and cone beam distortion that would affect either the processing steps or distort the analysis
- identification of regions where surface roughness may be an issue as the surface comparison is required (Fig.1)
- incorrect scaling of the CAD model to the scanned data (Fig.3)

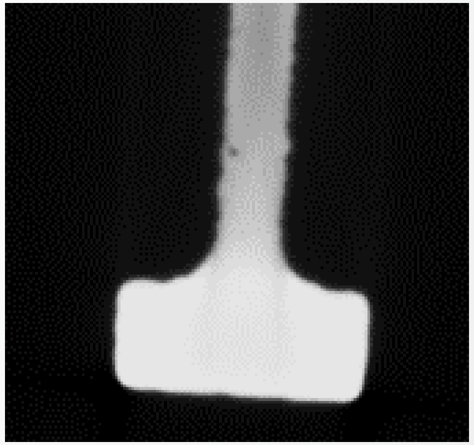


Fig.1: internal pore and surface roughness

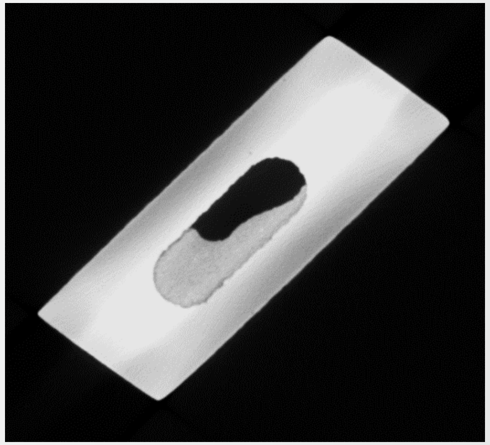


Fig.2: powder infill

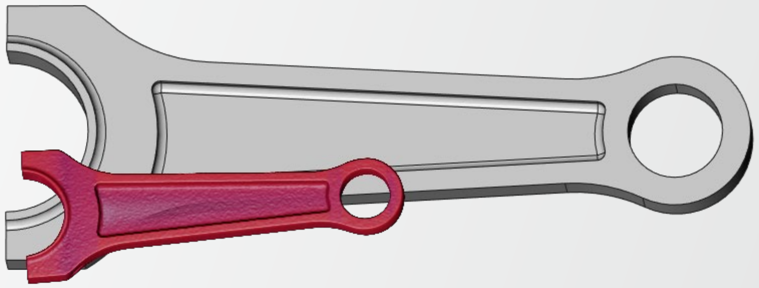


Fig.3: size discrepancy between CAD and X-ray CT data

X-ray CT data and CAD registration

Visualise both datasets

If the X-ray CT data for the component appears to conform well with the original model, the next step is registration in Avizo Software.

In the registration step the X-ray CT data will be aligned to the CAD data.

To accomplish the registration follow the these steps:

- ensure that both the CAD data and X-ray CT data are present in the Project View. It is useful to visualise both datasets as shown in Fig.1.
- it is also useful to leave a gap between the two data sets as shown in the Project View of Fig.2 in anticipation of the next processing steps.

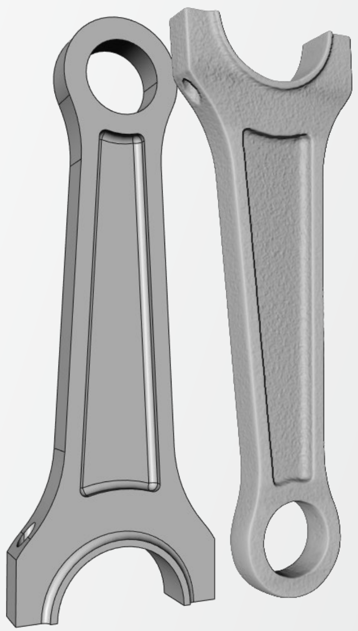


Fig.1

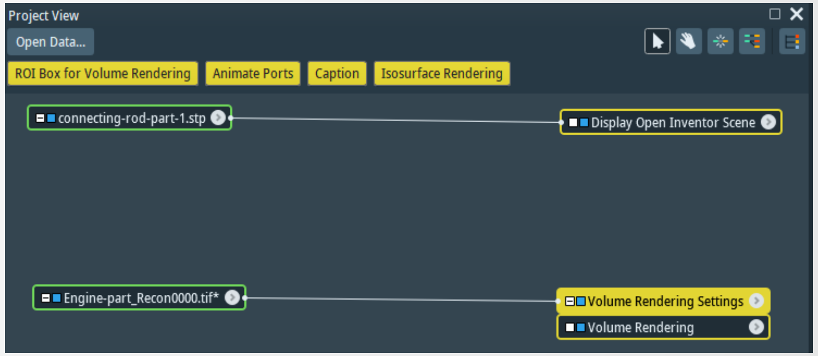


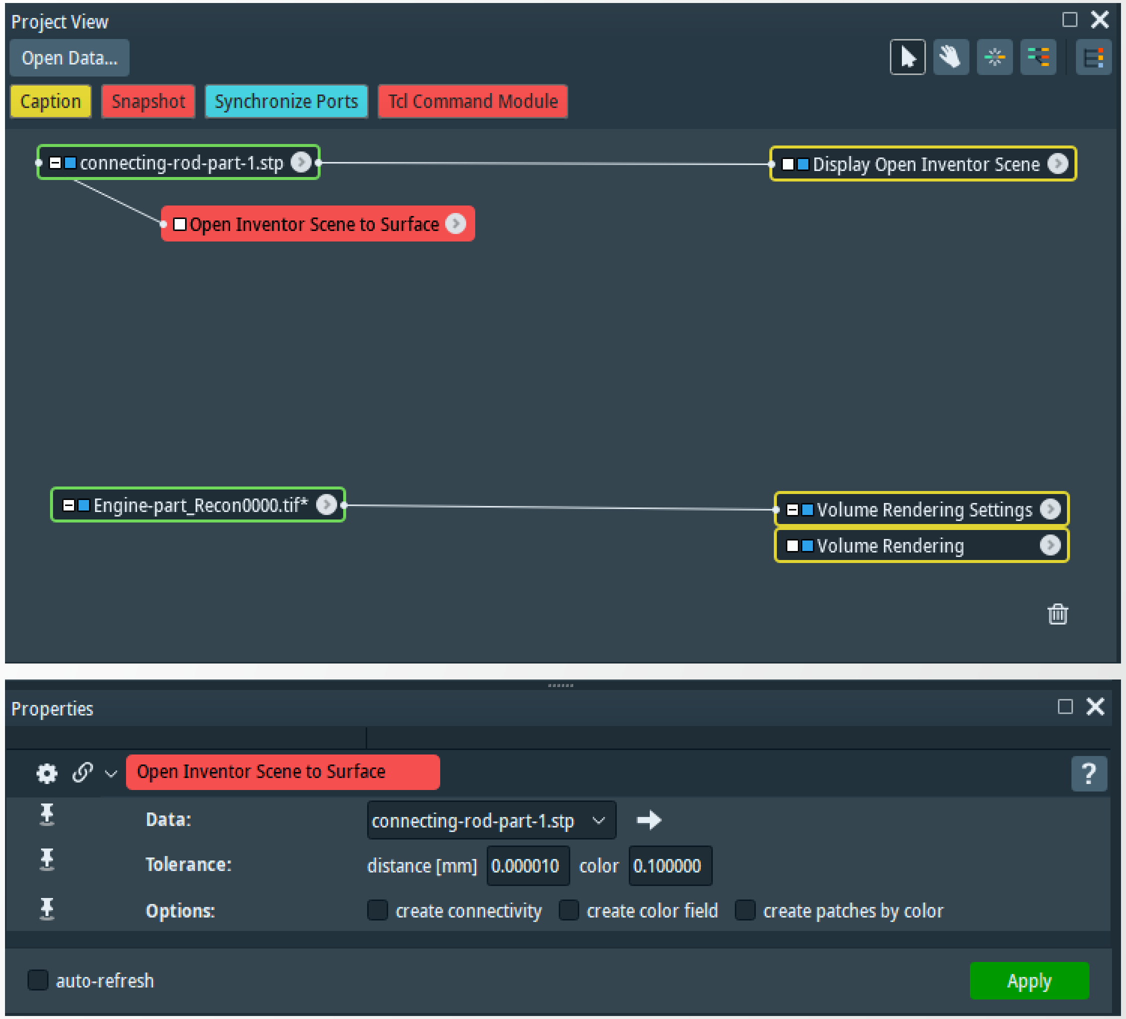
Fig.2

X-ray CT data and CAD registration

Convert the CAD data to a surface

To align the X-ray CT data to the CAD model, a surface for CAD must be generated. This is accomplished by right clicking on the CAD data and searching for **Open Inventor Scene to Surface**. This module converts the .stp data for the model into a surface format for the next step.

When applying the Open Inventor Scene to Surface module, press apply and a new dataset named *GeometrySurface* is created.



X-ray CT data and CAD registration

Create a volumetric representation of the CAD model

The resulting *GeometrySurface* surface can be viewed using **Surface View** for checking the output if desired.

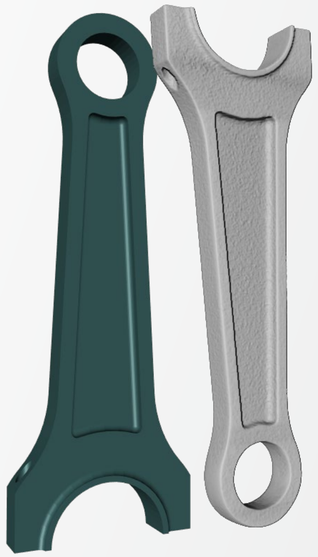
The CAD model now has a generated surface but no volumetric representation which is required for the registration of the two datasets.

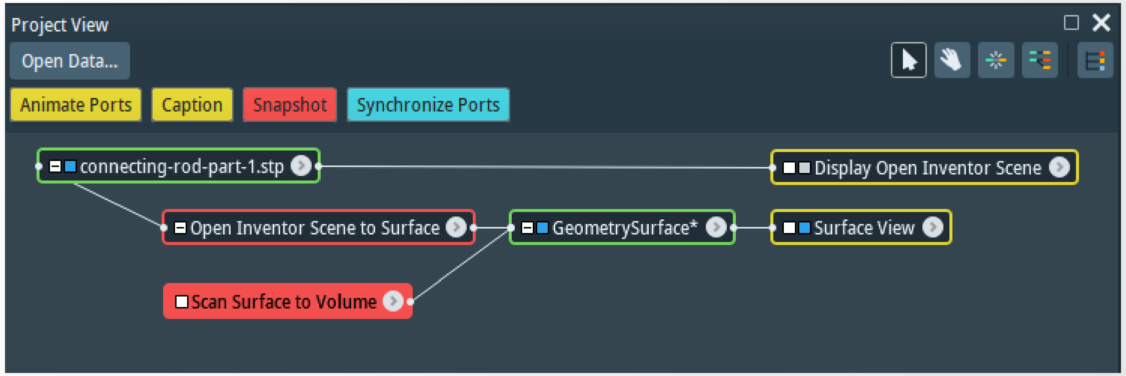
To create the required volumetric data for the CAD model surfaces right click on the *GeometrySurface* data and search for **Scan Surface to Volume**.

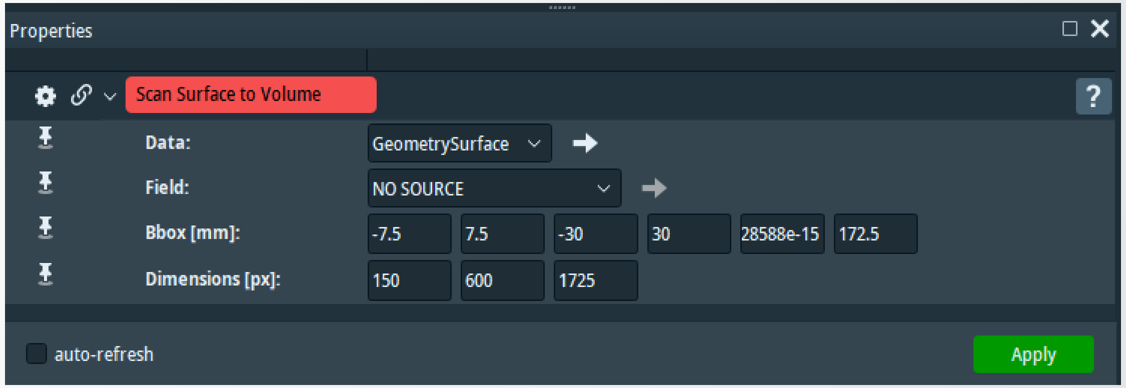
Click “Apply” for the Scan Surface to Volume module - there is no need to change any of the settings.

Once the *GeometrySurface.scanConverted* data is produced, visualise the volume using a **Volume Rendering**.

Next visualise the X-ray CT data using another Volume Rendering.







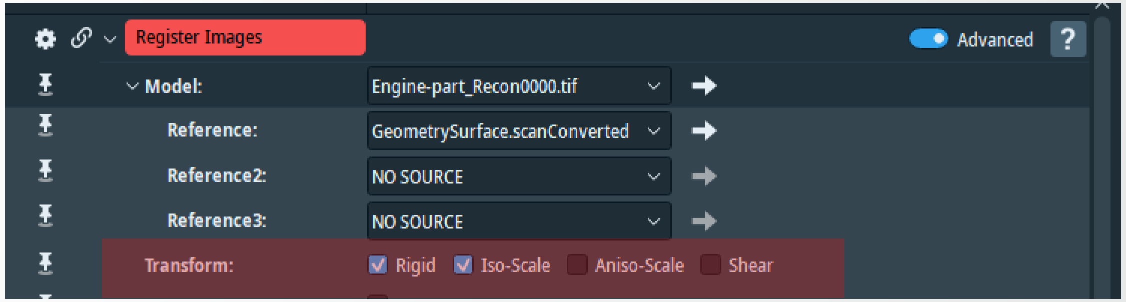
X-ray CT data and CAD registration

The Register Images module

The **Register Images** module computes an affine transformation for the co-registration of two image data sets, using an iterative optimization algorithm. A hierarchical strategy is applied, starting at a coarse resampling of the data set, and proceeding to finer resolutions later on.

From the "Transform" port, one can select the number of transformation parameters to be optimized. The number is 6 for "Rigid" (3 translations and 3 rotations), 7 for "Iso-Scale" (adding uniform scaling in all directions), 9 for "Aniso-Scale" (non-uniform scaling) and 12 for "Shear".

More information can be found in the information tab.



***Important note:** Usually, and in most industrial applications, scaling in addition to the affine transformation should not be allowed because the CAD model and the X-ray CT data should have the same scaling domain. Therefore the "Iso-scale" port of Register Images should be left disabled.*

In the special case studied in this tutorial, the 3D printed part has been scaled down before printing in order to reduce production cost. For the sake of transparency this little flaw has not been "corrected" prior to creating this tutorial. As a consequence, the "Iso-scale" port is enabled in what follows.

X-ray CT data and CAD registration

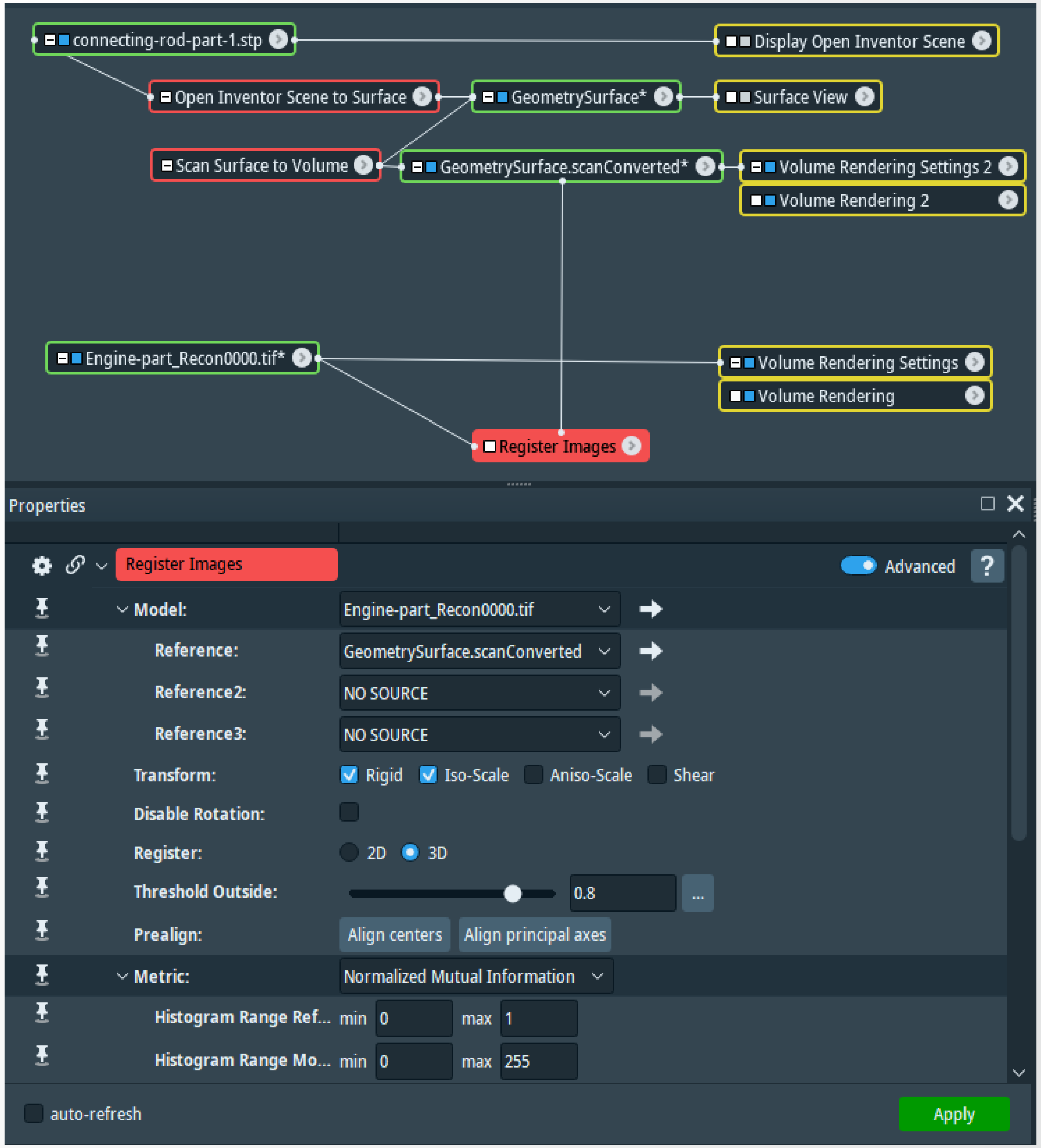
Aligning the CAD model and the X-ray CT data

To apply the Register Images module, right click on the X-ray CT data and search for the module.
When the module opens, allocate the *GeometrySurface.scanConverted* data to the reference.

Registration of the two datasets can be tricky if the two volumes are very miss-matched as shown in Fig.1 next slide. The X-ray CT data can be manually re-orientated to aid the registration step as a first step, however this is not required. Pre-alignment can also be performed with the "Align centers" and "Align principal axes" options.

Select "Rigid" transform option and click on "Apply". In this example we also use the "Iso-Scale" transform option to improve the alignment, as explained in the previous slide.

Once applied, the X-ray CT data will be aligned as shown in Fig.2 next slide.



X-ray CT data and CAD registration

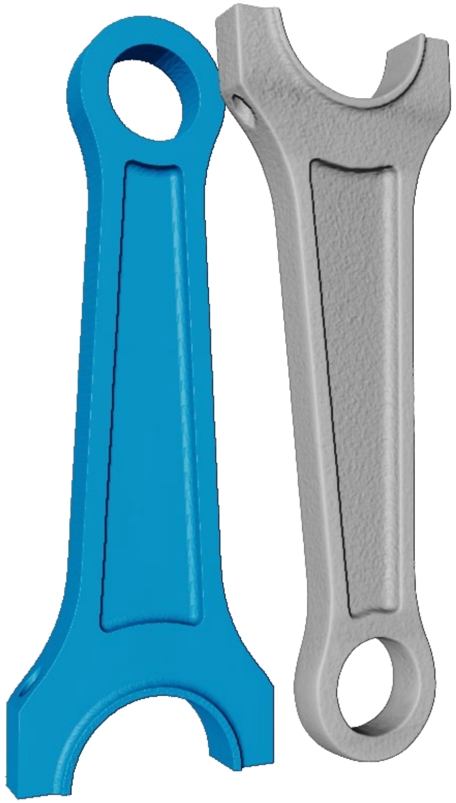


Fig.1: visualisation of the X-ray CT data and CAD volume. In this example the volumes are both displaced and rotated which can be challenging for registration.

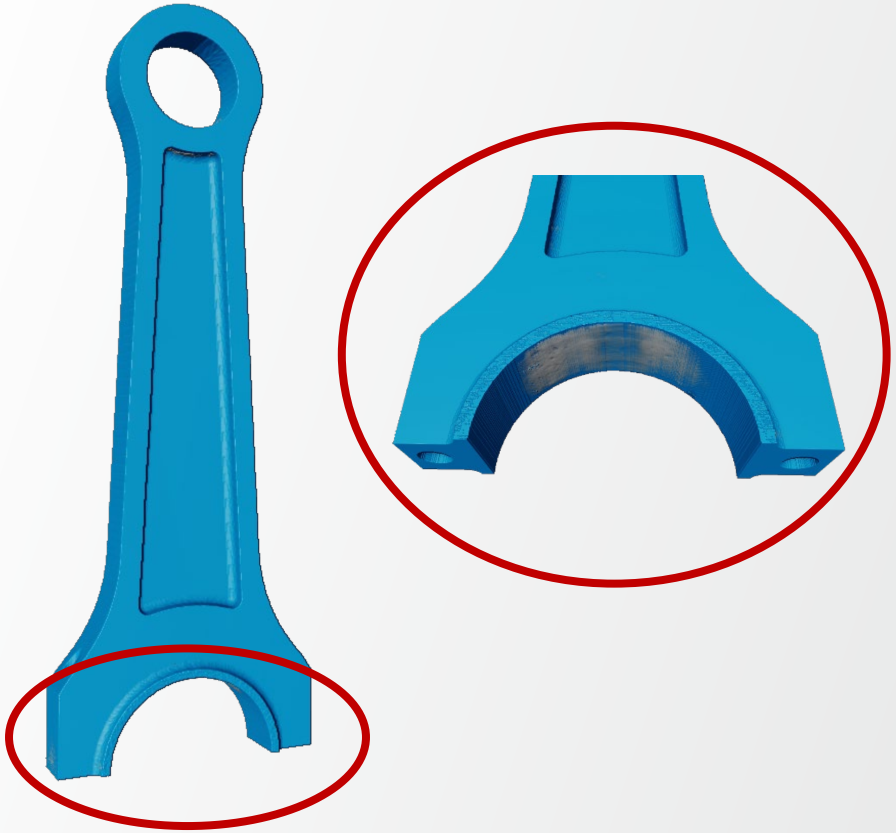


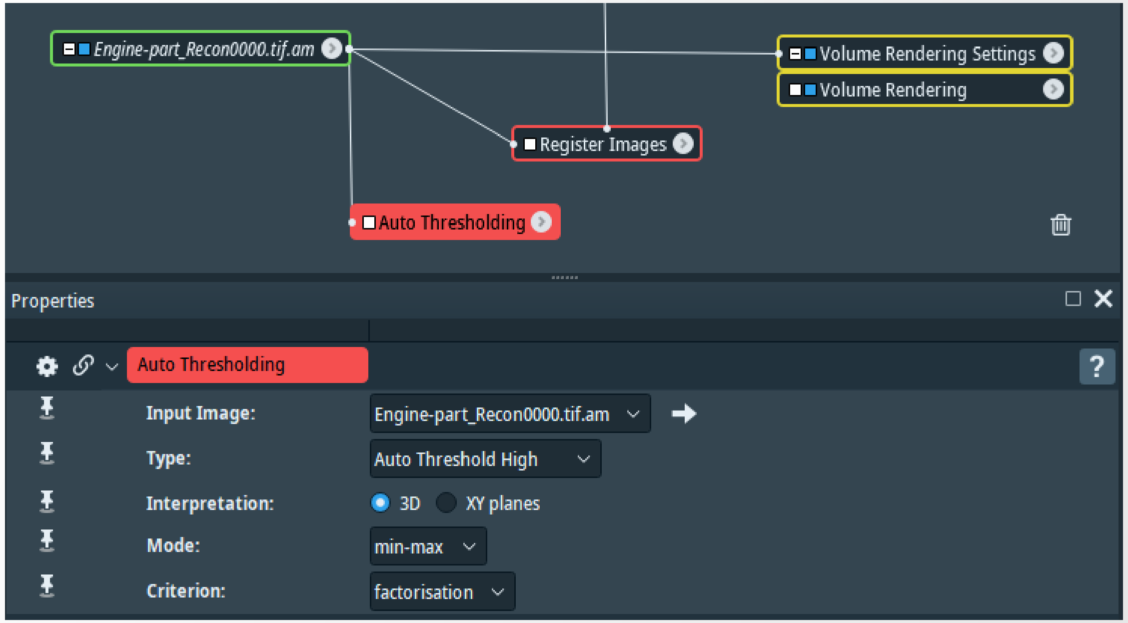
Fig.2: visualisation of the X-ray CT data aligned to the CAD volume. The circled section shows where the Scan data for the component does not match that of the CAD model.

Surface analysis and measurement

Segmenting the component as a first step for surface generation

Once the X-ray CT data is aligned with the CAD model a measurement of the differences in geometry can be performed. However to accomplish this, a number of steps must be taken first:

- to calculate the distances, the X-ray CT data must have a surface and this is achieved by segmenting the component. In the example **Auto Thresholding** was used since this most accurately replicated the component surface profile.
- when applying segmentation to a component for the first time it is good practice to compare the segmented surfaces to the raw data using ortho slices to ensure the surfaces match. Volume renderings are useful for detecting reconstruction artefacts such as those caused by scattering that will dramatically affect any surface measurement comparison in the following steps.



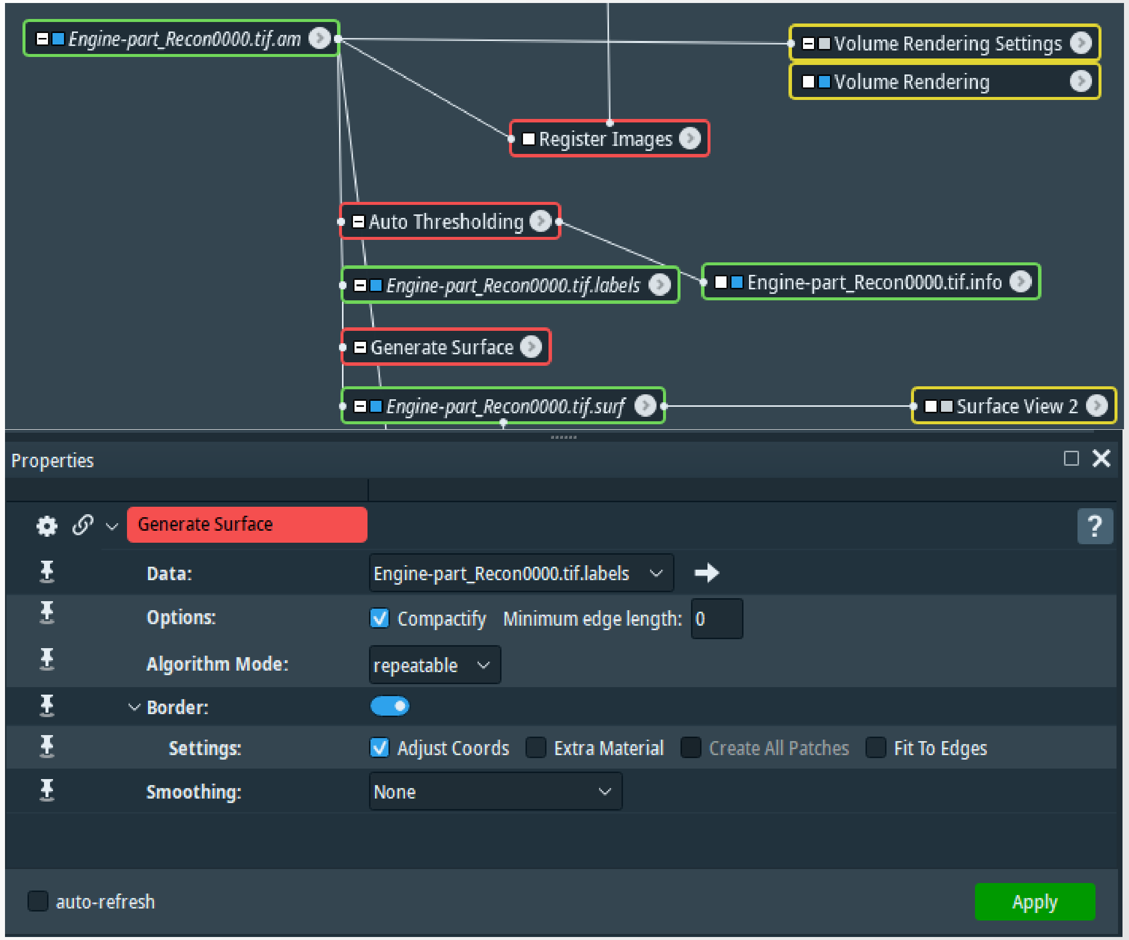
Surface analysis and measurement

Surface generation

A surface can now be generated from the segmented data. This is completed by applying **Generate Surface** (choose “Smoothing: None”).

The generated surface can then be visualised using Surface View.

The generated surface could be used to calculate the difference in geometry of the CAD model and the X-ray CT data. However there are some flaws relating to this that occur due to the inherent nature of X-ray CT data reconstruction. In X-ray CT the pixels on a detector are usually square in nature and the resultant voxel after data reconstruction is either a cube or cuboid*. Therefore any curved surfaces or surfaces that don’t perfectly align with the voxel orientation will result in small steps which will result in small inconsistences.



* This depends upon the X-ray instrument design where one axis can be elongated due to scanning speed and sample movement.

Surface analysis and measurement

About next step

The next slides explain how to use the **Adjusted Sub-Voxel** module to generate a more precise surface profile of the component than the one generated with Generate Surface.

The Adjusted Sub-Voxel module is only available in **Avizo Software for Industrial Inspection**, the Avizo application dedicated to industrial inspection, quality control and materials characterization.

Not having Avizo Software for Industrial Inspection doesn't prevent you from preforming this tutorial workflow till its end. However, you should be aware of the small inconsistencies caused in the CAD model to CT data distance measurement by data reconstruction issues. This has been mentioned in the previous slide, and is visually demonstrated on slide 18.

To pursue this training without Avizo Software for Industrial Inspection, please skip slides 16 to 18 and use the surface *Engine-part_ Recon0000.tif.surf* instead of *Engine-part_recon0000.tif.adjustedSurface* in what will follow.

Surface analysis and measurement

The Adjusted Sub-Voxel module*

Avizo Software for Industrial Inspection, the Avizo application dedicated to industrial inspection, quality control and materials characterization, features the **Adjusted Sub-Voxel** module that is available from the Metrology workroom. This module calculates a more precise surface profile that can take into account a profile that cuts across voxels producing a smoother and more accurate surface.

As said before, the module is available from the Metrology workroom, but it can also be used in the Project workroom. To do so, it has to be created *via* the Tcl console (see Fig.1), by typing in “create HxAdjustedSubvoxel”, and then pressing Enter.

A new red module will be displayed in the Project View area.

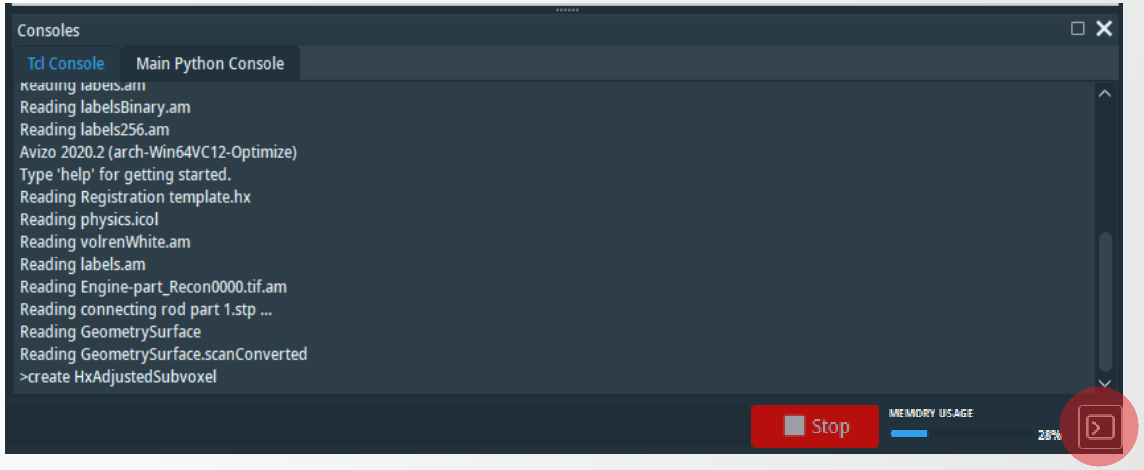


Fig.1: Consoles button highlighted in red and Tcl Console with Tcl command “create HxAdjustedSubvoxel”

*only available in Avizo Software for Industrial Inspection

Surface analysis and measurement

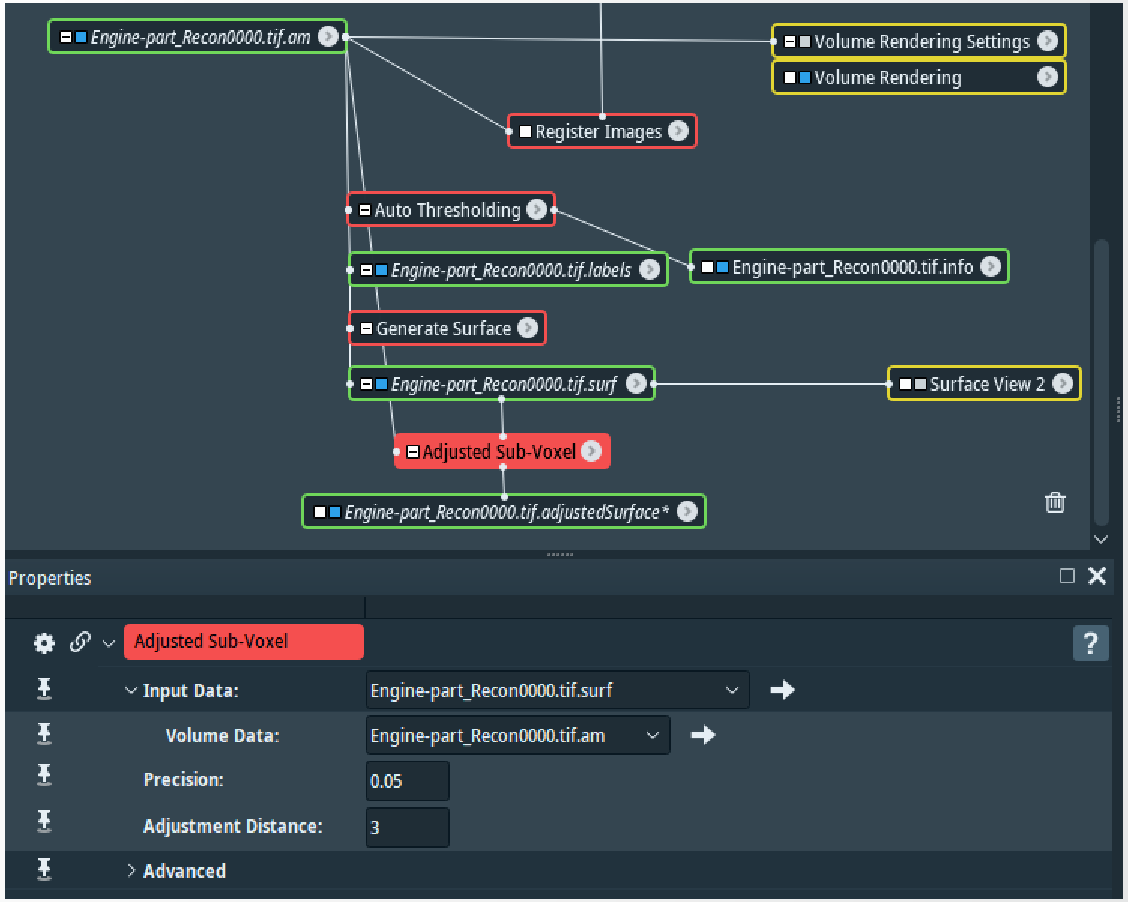
Adjusting the surface to the component

The Adjusted Sub-Voxel icon will not be attached to any field when it is first created. When opening Adjusted Sub-Voxel, perform the following steps:

- attach the “Input Data” field to the the *Engine-part_Recon0000.tif.surf* data
- use the drop down menu to add the “Volume Data” as the *Engine-part_Recon0000.tif.am* data

This allows the generated surface to be adjusted to the original data in order to calculate a more precise surface geometry.

Once the Adjusted Sub-Voxel module has been applied, a surface is created.



Surface analysis and measurement

Inspecting the adjusted surface accuracy

The new surface profile can be inspected using an Ortho Slice option and comparing directly to both the original .am or .surf files.

The adjusted surface gives a more accurate interpretation of what the true surface is compared to the surface obtained directly from the X-ray CT data segmentation.

The Ortho Views module can be a convenient tool to observe the differences at the same time in the 3D viewer and in three 2D viewers displaying xy, yz, and xz planes.

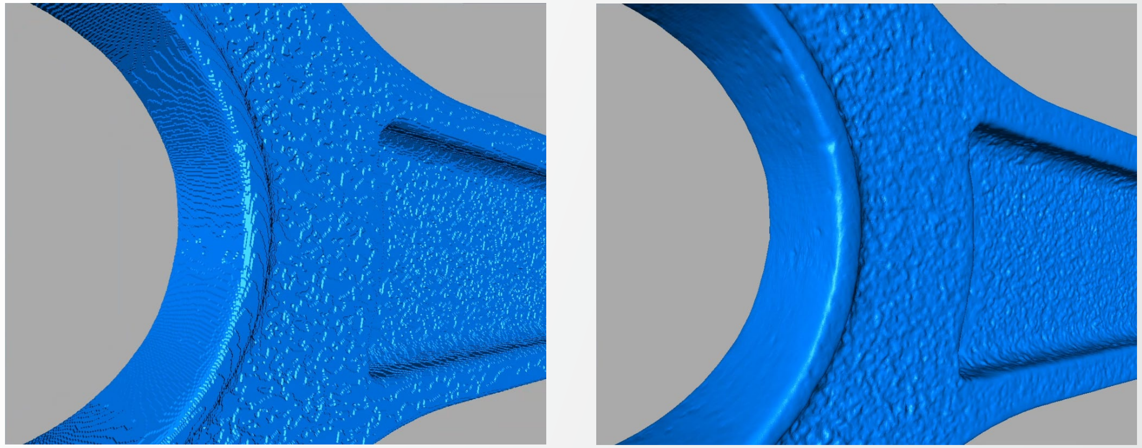


Fig.1: Small “steps” on the Generate Surface result (left) and smooth surface generated by Adjusted Sub-Voxel (right)

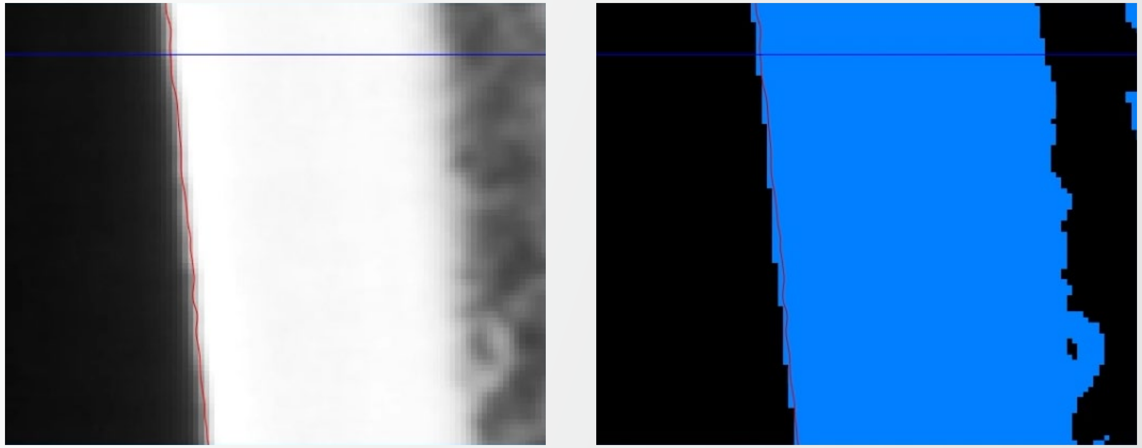


Fig.2: Orto Slices of the original data (left) and of the labelled image (right) and adjusted surface contour in red

Surface analysis and measurement

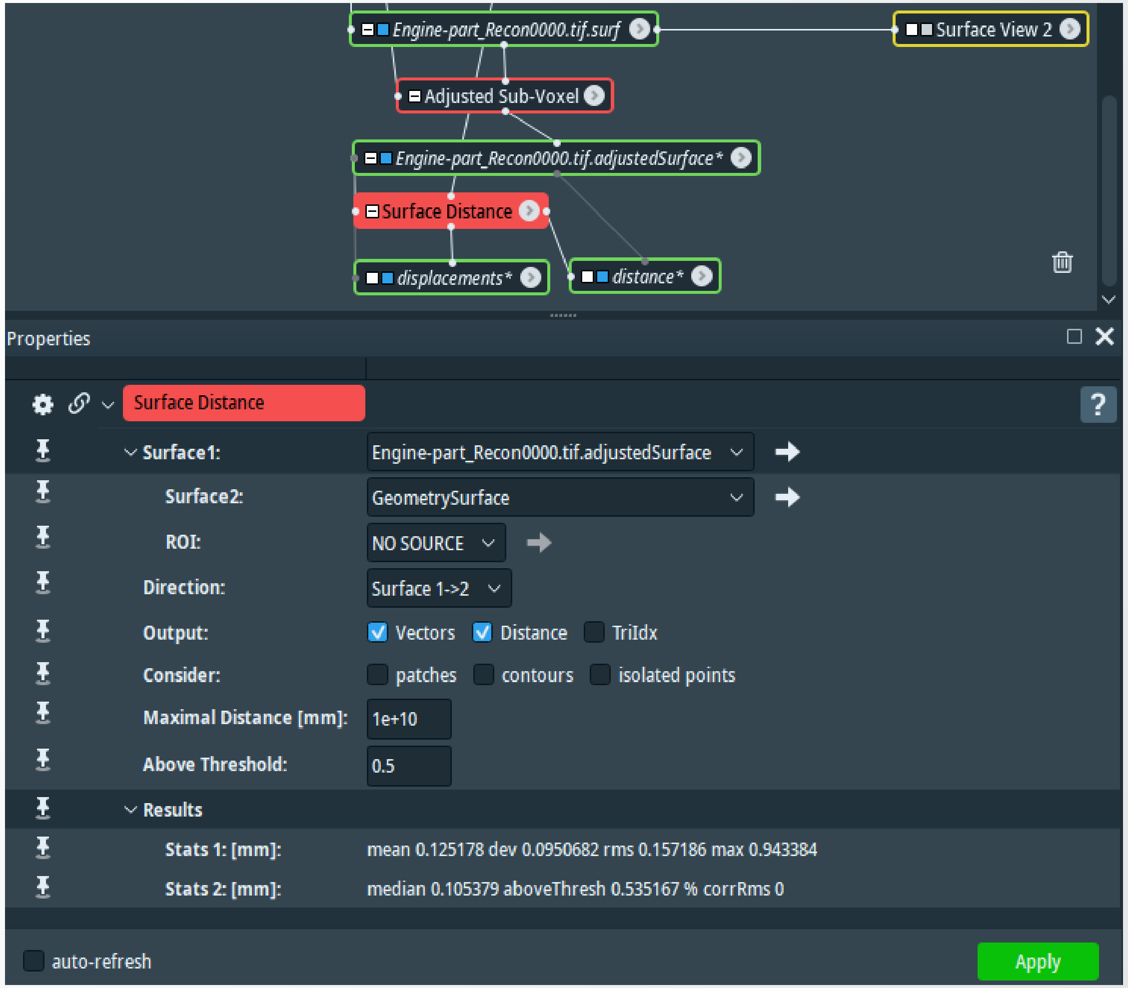
Surface distance computation

The **Surface Distance** module is used to calculate the distance from the CAD model surface to the surface adjusted to the X-ray CT data. The module can be accessed by right clicking on the surface object created by the Adjusted Sub-Voxel module. When applying the Surface Distance module, the following must be done:

- the “Surface1” input data field should be the Adjusted Sub-Voxel output, i.e. *Engine-part_recon0000.tif.adjustedSurface*
- “Surface2” should be the CAD model surface that was produced at the very beginning. In this example it is *GeometrySurface*
- for the output, “Distance” should be selected.

When applied, the Surface Distance module will output a data field labelled *distance,* a data object containing scalar values assigned to each vertex of Surface1.

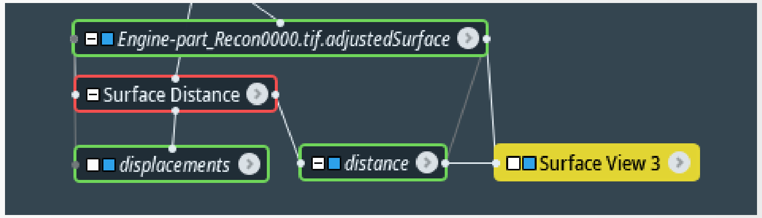
That data set can be used to display the difference in surface geometry as shown in the next section.



Visualisation of surface comparison

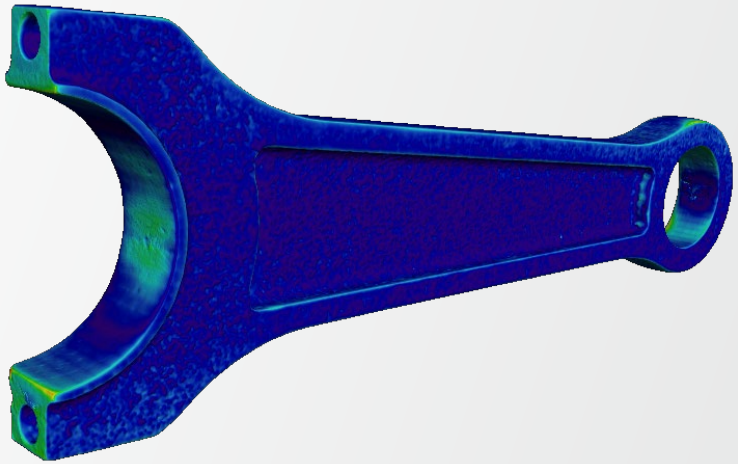
Introduction

The most useful method for showing the difference between the CAD design and the finished component is to visualise the calculated surface distance. The surface distance can be immediately visualised using a **Surface View** as shown here.



A number of colormaps can be used to visualise the surface distance and demonstrate divergences in the finished component vs the original CAD design. However this method does not necessarily give the direction of the deviation, and whether it is too small or too big compared to the nominal.

Indeed, Surface Distance returns for each vertex of Surface1 the distance to the closest point on Surface2. That distance value is the absolute value of the distance, i.e. there is no distinction between “outside” and “inside”.



To obtain the signed distance, one can use an **Arithmetic** module.

Visualisation of surface comparison

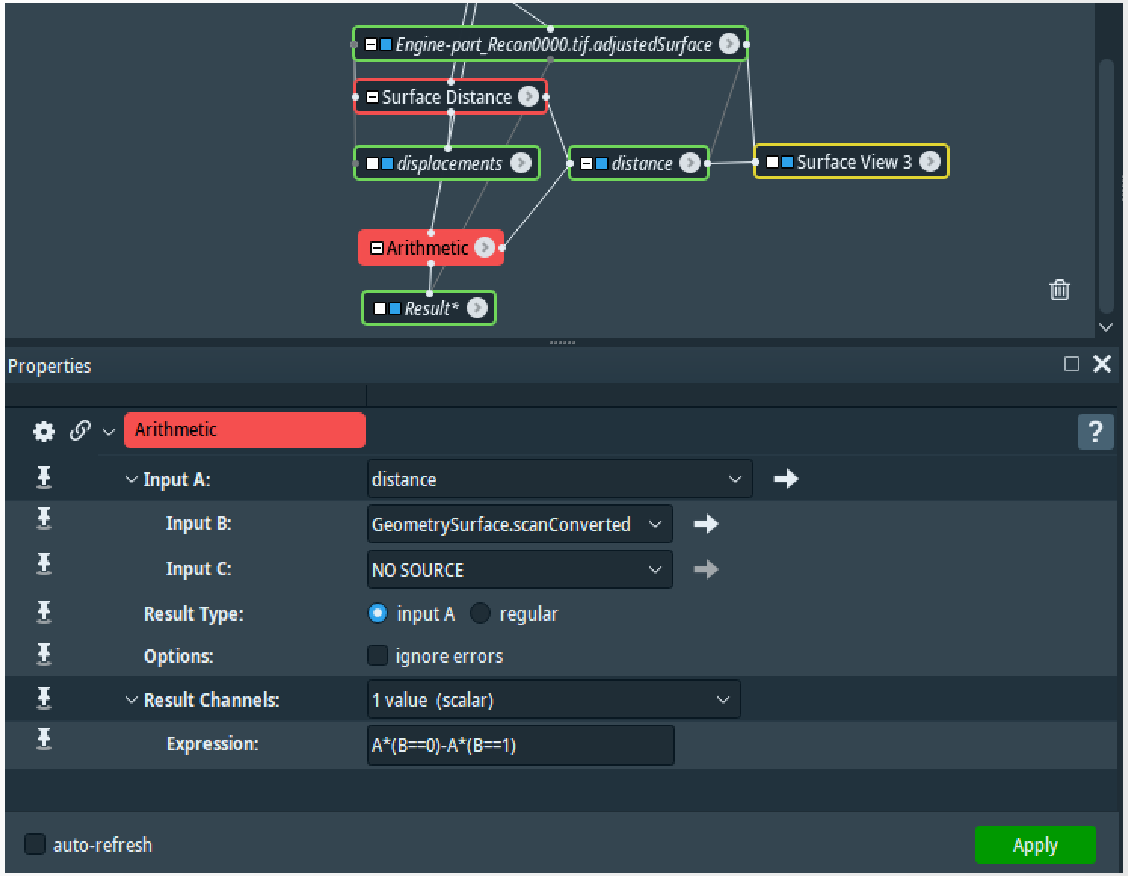
Signed distance computation

Connect the **Arithmetic** module to the *distance* object, and make sure that it is connected to “Input A”. With keeping “Result Type” as “input A” we are making sure that the result of Arithmetic will be of same data-type as the *distance* object.

“Result Channels” should be set to “1 value (scalar)”, which will return numbers of the data-type needed, i.e. in this case “float”.

“Input B” should be connected to the volumetric representation of the CAD model *GeometrySurface.scanConverted*.

Arithmetic will create a new data object by evaluating what is in “Expression”.

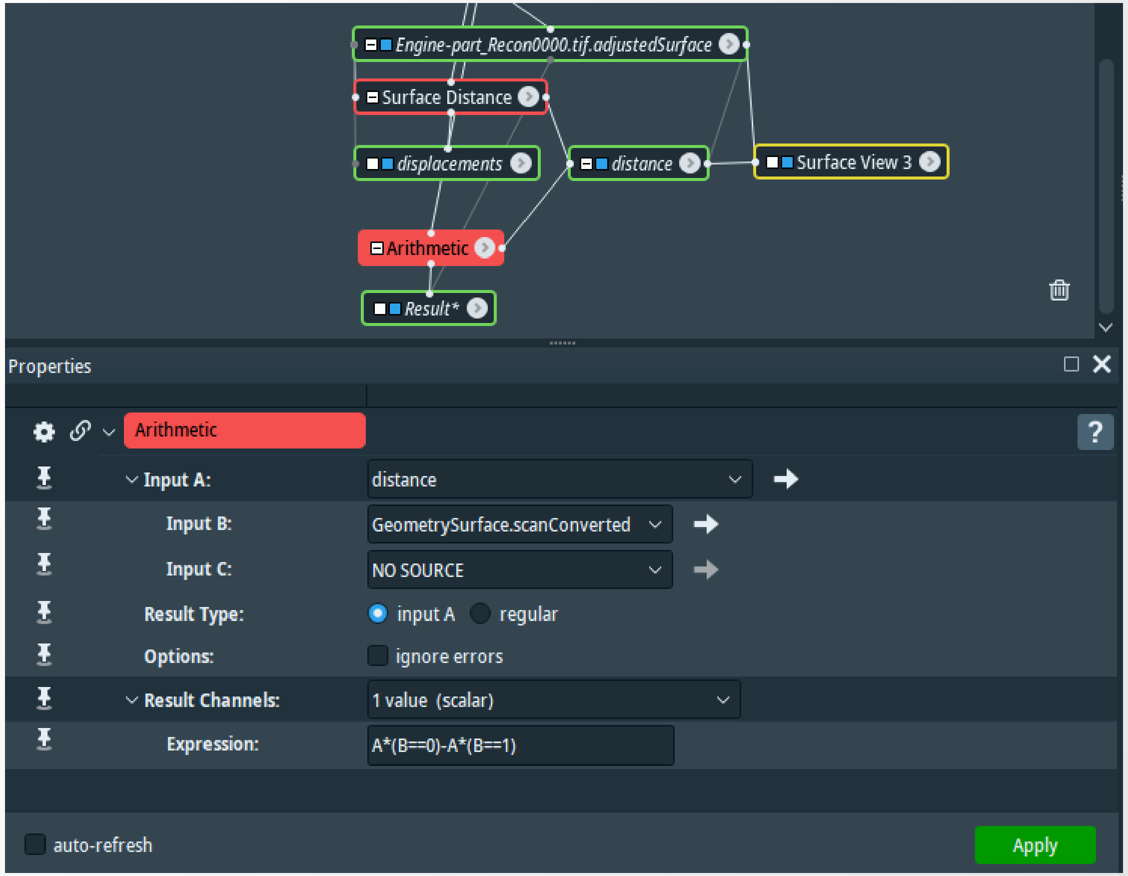


Visualisation of surface comparison

Understanding the expression

The expression used, “A*(B==0)-A*(B==1)”, combines comparisons (in this case “equality”, denoted by “==”) and arithmetic operations (in this case multiplication and subtraction).

At each vertex location of the surface connected to *distance* (i.e. Surface1, the adjusted surface representation of the component), it is checked if the closest voxel of “Input B” is either 0 or 1, i.e. if that vertex lies outside or within the CAD surface. Those comparisons (“B==X”) return the value 1 if they are true, and 0 if not. The return value is then multiplied by the value of “Input A” at that vertex position, i.e. the (unsigned) surface distance. The sign is introduced by using a positive sign for the first part, and a negative sign for the second.



Visualisation of surface comparison

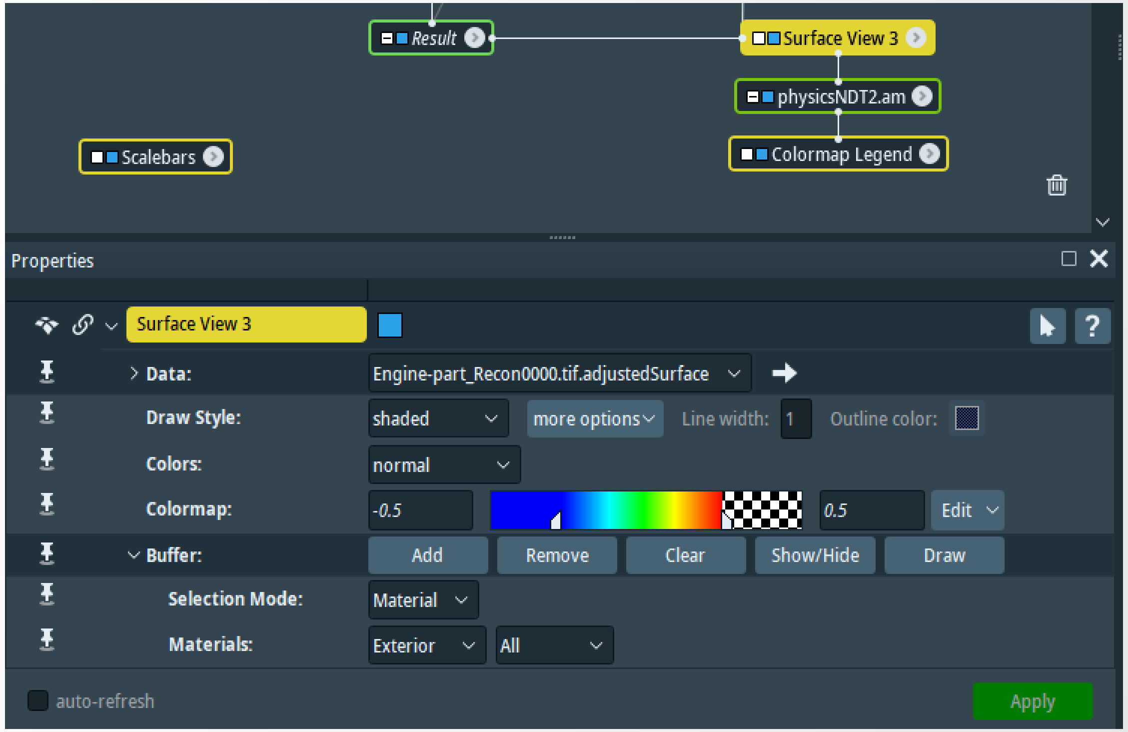
physicsNDT colormap

The result from the Arithmetic module can be visualised using a **Surface View** as shown here. The colormap has been changed to *physicsNDT*.

physicsNDT colormap is a modification of standard *physics* colormap.

For getting a nice annotation using Colormap Legend, the opacity curve was set to fully opaque at all points.

The lowest and highest values of the colormap were set to special “out of range” colours, violet at the low end, and pink at the top end.



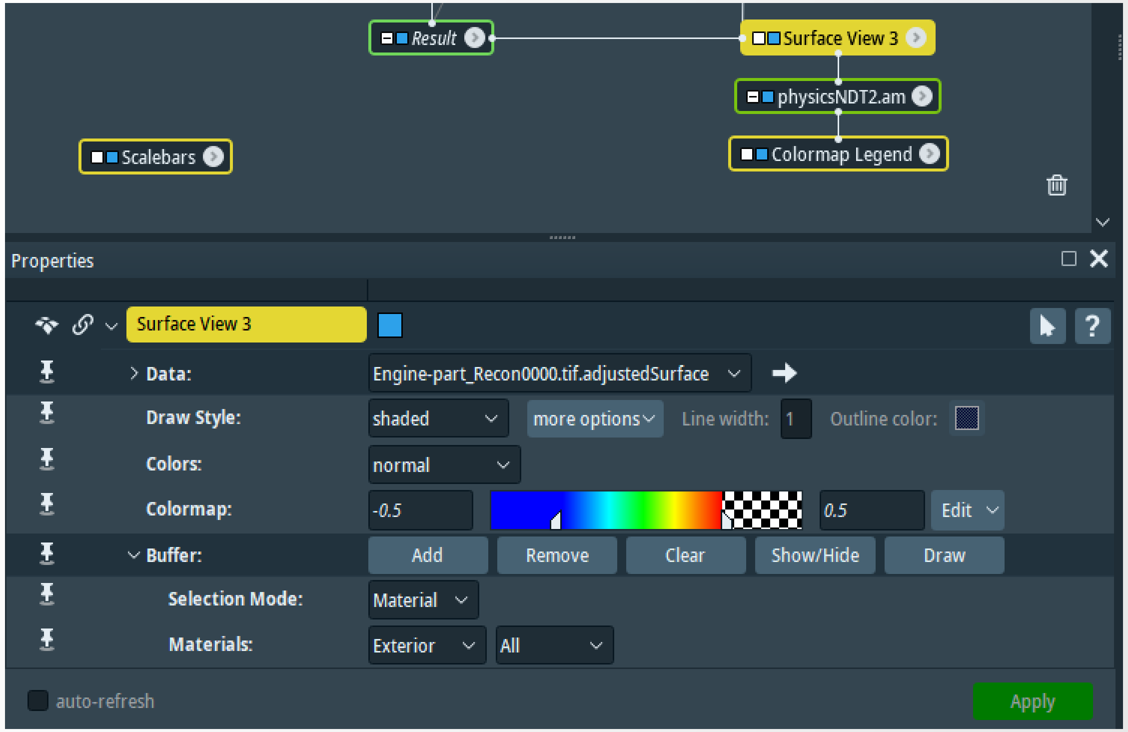
Visualisation of surface comparison

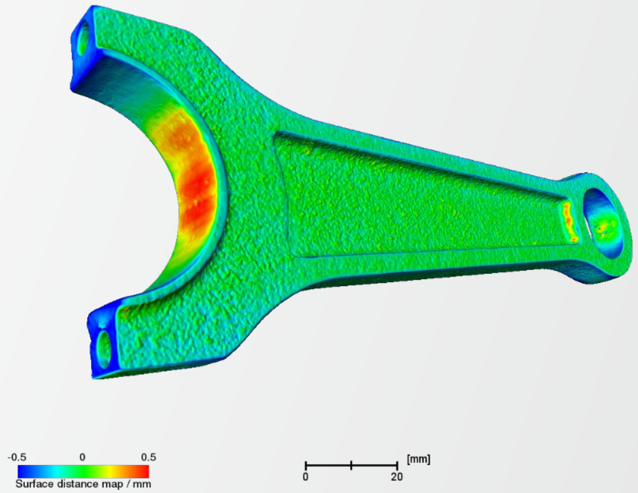
Scaling the colormap

When applying the colormap, it is important to have the scaling correct to ensure features are neither over or under represented. The output (named *Result*) from the calculation will show the range for the histogram. This range can then be applied to the colormap in the Surface View.

In the example, a range of -0.5mm to 0.5mm was chosen as the threshold for sections that are out of tolerance. By using a symmetric range around 0, the areas with the smallest deviations are shown in green, whereas areas where the measured object is larger than the CAD are shown in red, and those where the object is smaller, in blue.

Finally both a **Colormap Legend** and **Scale Bar** are applied as shown here, for purposes of scaling both the object size and deviation from the original CAD design.



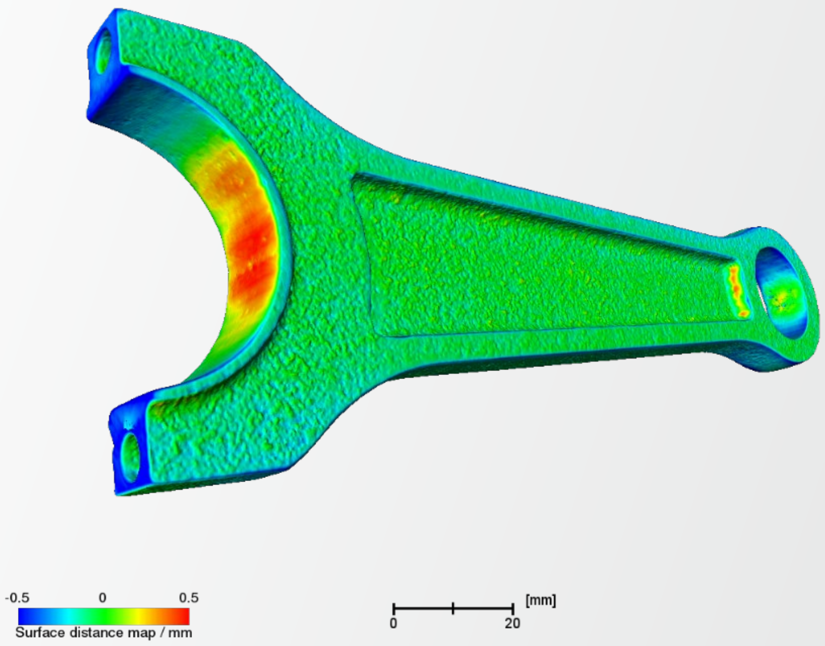


Combining internal defect analysis

Introduction

The analysis of components in X-ray CT usually combines a number of different measures and their respective interactions. Although these features and relationships are very apparent during the 3D analysis it is difficult to capture these interactions using 2D images for standard documented reports. In this case it is important to combine a number of imaging tools in order to convey subtle details.

A simple **Surface View** is the most useful demonstration for showing the surface geometry departure from the original design.



Combining internal defect analysis

Combining imaging tools

In this example the **Surface View**, both solid and transparent, of the distance map has been combined with the **Ortho Slice** to show the relationship between the component surface departures from the original model and the impact of internal flaws.

By combining the Surface View for the distance map and the CAD surface (Fig.1) it is possible to clearly show the regions where the physical dimensions of the component have extended beyond the original 3D print design (CAD). This is a useful tool when first demonstrating the results.

Hidden surface variations can be observed by using a combination of a transparent CAD surface, distance map and clipping using an Ortho Slice (Fig.2).

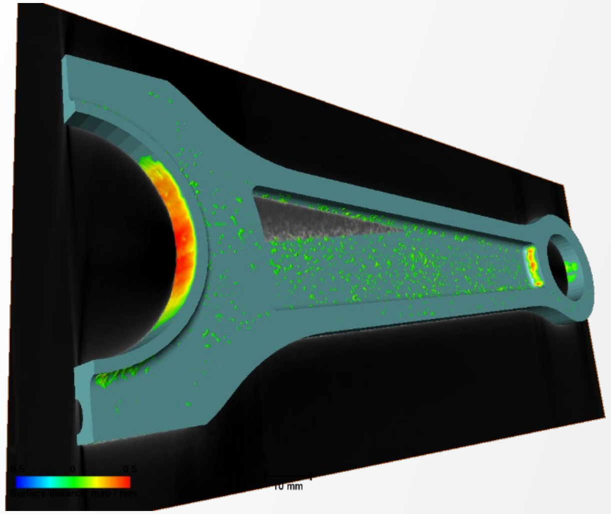


Fig.1: CAD surface (solid), surface distance map and ortho slice

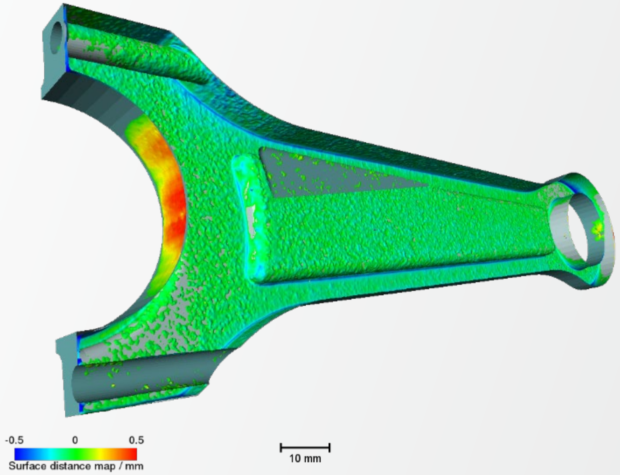


Fig.2: CAD (transparent) and surface distance map cut using ortho slice clipping

Combining internal defect analysis

Hidden internal surfaces visualization

The Surface View of the distance map is a very useful tool when analysing the dimensional variations on the components open surface. Hidden surfaces are sometimes a little more difficult to visualise in isolation.

Snap shots of an **Ortho Slice** revealing the internal structure (Fig.1) are very useful for showing the scale of surface variations and internal component cross-sections.

These can be used to add additional information to the dimensional variations shown by the **Surface View** of the distance map (Fig.2).

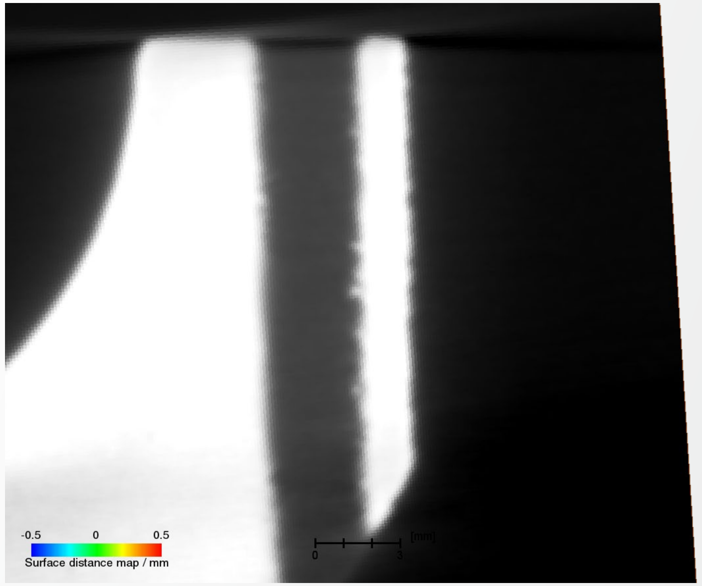


Fig.1

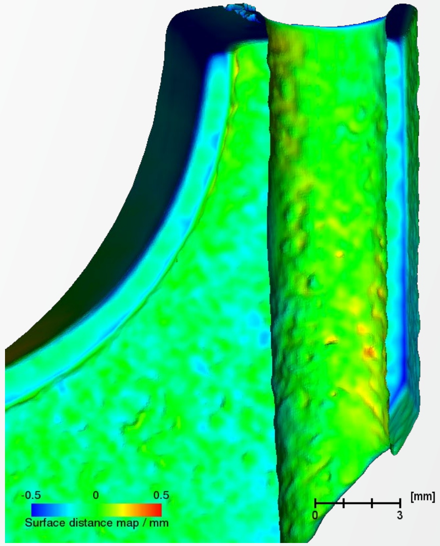


Fig.2

Combining internal defect analysis

Internal defects visualization

The analysis of internal defects is a key strength of X-ray CT. In Avizo Software, the distribution of pores can be combined with both the component surface (Fig.1) to identify production problems. This can also be linked to the distance map to identify any relationship between dimensional variations and internal defects.

It should be noted when analysing porosity close to the spatial resolution limit there is a tendency to include defects (Fig.2). Improper surface determination can smooth out these features resulting in them being falsely identified as internal pores. Any pores that appear on the surface of the distance map should be verified using both 3D **Surface View** (Fig.1) and 2D **Ortho Slice** (Fig.2)

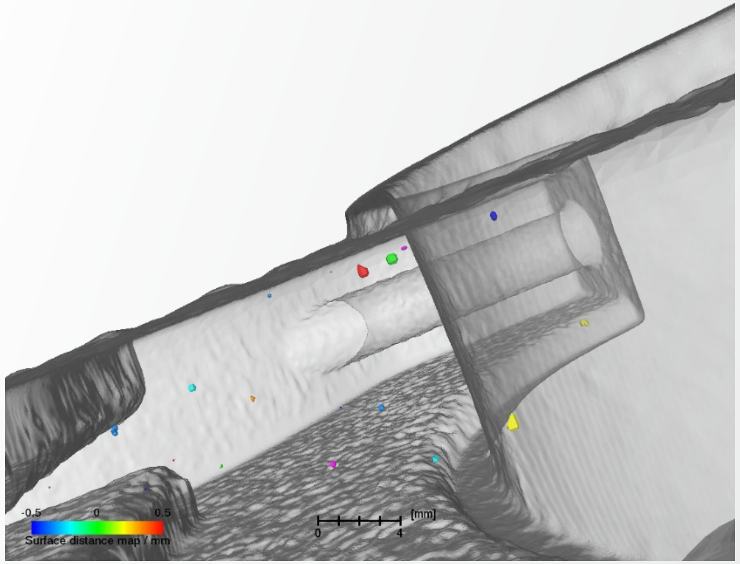


Fig.1

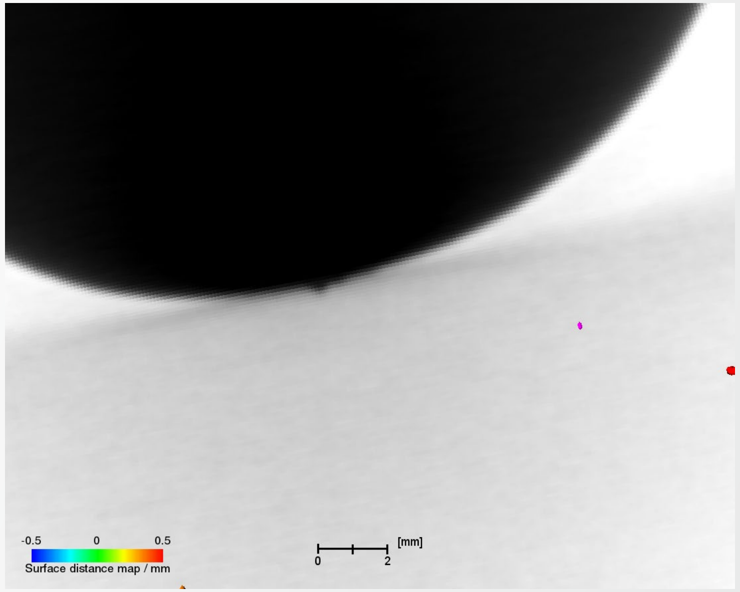


Fig.2