PROPOSED WORKFLOW FOR OBTAINING A 3D SOLID MODEL OUT OF POINTS CLOUDS FOR A CONNECTING ROD

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Abstract: *The paper presents a detailed workflow regarding the processing steps of the information contained within a points cloud till it becomes a 3D solid model. The procedure is applied as part of a case study to a connecting rod. It presents, in gradual steps the filters and the algorithms of various software tools that were applied in order to obtain an accurate 3D solid replica of the physical previously scanned part. The originality element of the proposed procedure consists out of the type of operations and setup parameters involved in the above mentioned process. The workflow may be applied with slightly differences to any other scanned part having comparable complexity degree and multiple free surfaces.*
Keywords: *reverse engineering, 3D scanning, digitizing, points cloud, connecting rod.*

1. Introduction

Points clouds are more frequently used as the standard 3D format for the geometrical shapes due to modern technologies. They allow, among others, capturing an impressive number of points as data which represents coordinate points corresponding to the analyzed surface of a physical object. Almost every time the points clouds are united and then simplified or refined in order to allow post processing to take place at a relatively low computational cost. The paper focuses on a case study: obtaining a 3D solid model through reverse engineering of a connecting rod. The scanning equipment was a *Romer 7525SI* mechanical arm. Additional measurements were performed using an electronic caliper: *Burg Wächter Precise PS7215.*

For the points clouds processing and refinement we chose a free software solution: *MeshLab*. The corresponding mesh, further processing and eventually the developing of the 3D solid model was carried out in *Catia*. The purpose of this study was that the 3D solid model to be optimized by means of FEA in *Ansys*. Both models were then analyzed in order to validate the optimized one [3].

2. Intermediary data sets as points clouds

After the first scanning session, we have noticed that the resulting points cloud does not satisfy our need for accuracy. The number of points is relatively low and it does not provide us with a full, error free image of the scanned part. Fig. 1a shows the first points cloud as it was imported in *MeshLab*. The software allows the user to apply a mesh over the points cloud which is represented as a wireframe as it can be seen from Fig. 1b. Then the user is able to cover the mesh with a texture (Fig. 1c) which best shows the gaps and holes in the resulting geometry. This led us to the following hypothesis: the scanning sessions of our connecting rod will be carried out in steps depending on the complexity degree of the component to be analyzed. Thus transition areas, inner channels, connections between bodies, holes or other free surfaces characteristic to the part's surface will require a distinct scanning step. Were the complexity degree is higher a lower scanning step will be used whereas the complexity degree is smaller a higher scanning step value will be set [1].
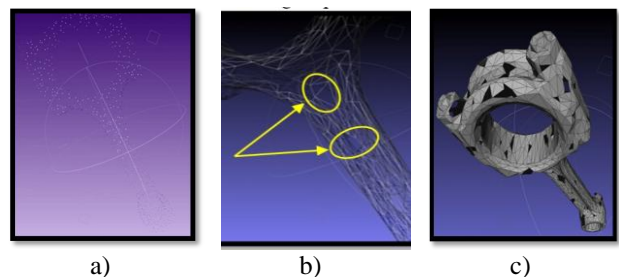

Figure 1: *Points cloud after the first scanning.*
a) the points inside the cloud,
b) the mesh,
c) the textured mesh.

In this case study we chose the solution of dividing the connecting rod in interests zones which will be scanned depending on their geometrical complexity degree. At the end the points clouds have been united in a final data set. This requires a correct identification of areas that will need multiple scanning sessions. Thus we have divided the part's geometry in three interest zones as follows (Fig. 2):

- Area I: *crank end of the connecting rod*,
- Area II: *the middle of the connecting rod*,
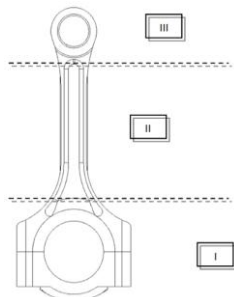- Area III: *piston end of the connecting rod*.

Figure 2: *The dividing solution*.

The scanner sensibility has been set to finest in order to capture the maximum amount of points per scanning session. The processing has started sideways. Fig. 3 shows different areas that were subjected to multiple scanning sessions. For region II a single scanning was necessary for each facet. For the other two regions multiple scans were performed resulting in several sets of points clouds. That posed a problem since this points clouds had to be united into a single final one which will contain a lot of errors like duplicate points, points that are not part of the geometry and others as they will be presented in the following sections. Details from Fig. 3 show the intermediate points clouds corresponding to the interest zones. From the details we can observe the density of points especially in the curvatures areas. This was achieved not only by multiple scans but by locally multiplying triangles [2].
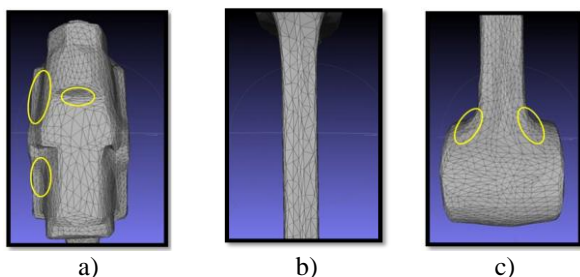

Figure 3: *Side views of interest zones.*
a) Side view of area I,
b) Side view of area II,
c) Side view of area III.

Through successive scans data sets have been recorded corresponding to the entire geometry. This was done by rotating the part 360°. The most difficult sections were those corresponding to edges, ribs and transitions zones. Fig. 4 shows captured areas related to interest zones. Those data sets were bigger due to refinement operations that were necessary given the multitude of curved areas and transitions between surfaces. Classical measurements are impossible in this case, thus certifying the importance of reverse engineering techniques in case of free form surfaces.
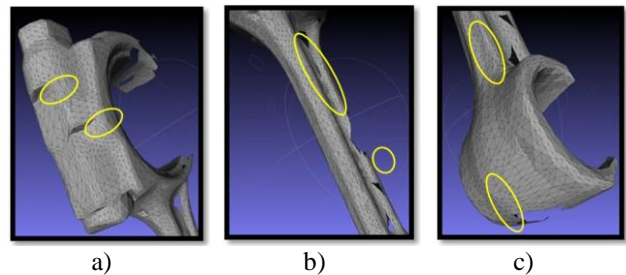

Figure 4: *Semi side views of interest zones.*
a) Semi side view of area I,
b) Semi side view of area II,
c) Semi side view of area III.

Ribs are one good example that the only possible measurement in this case is by scanning. Curvature radiuses and depth values that change along with surface transitions cannot be measured by a caliper. Reverse engineering offers a unique insight given that the captured geometry shows even the signs of wear and the effects of loads after thousands of functioning cycles, and that information is not available in any design book.

The next scans were performed correspondent to the front view of the connecting rod. Those were the hardest because these views contain the biggest number of transitions, surface connections, holes, ribs and inner depths. The scans were performed on the entire assembly, locked in by screws and nuts that were cut out after further processing. Fig. 5 shows illustrations of scanned areas by highlighting the filling operations of missing portions of the geometry after each new scan. The initial scan did not produce an accurate enough points cloud. We can see areas that were not covered or filled, gaps in the mesh and other types of errors that are generated by the scanning device's technical limitations. By multiple scans most of those errors were removed especially the gaps that were covered by merging the points clouds. But other errors remained. As the holes were not identified at edge proximity, the software offers a tool for the refinement of the mesh and

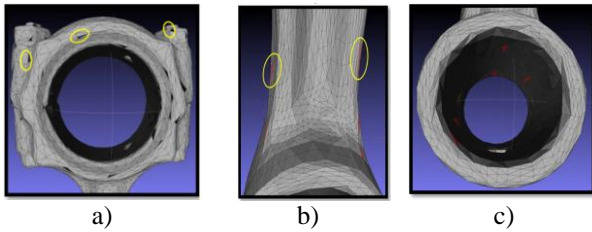holes filling (Fig. 5c - red colored zones). This filter was applied to all saved data sets.

Figure 5: *Front views.*
a) Front view of area I,
b) Front view of area II,
c) Front view of area III.

Given that multiple scans were required, region I was subdivided in four subsequent areas as did region III. Problems were detected regarding holes that were in the immediate proximity of edges. The filter for holes filling did not covered the ones that were near edges. In this case *MeshLab* allows the user to select based on points or triangles, a customized area thus making the filter to work on the exact selected portion of the geometry. Joints posed another problem. We have encountered the so called occlusion phenomenon. For example the rib's height hides the surfaces that are after the rib; it shadows them making it impossible for the scanner to properly read them. The next region taken into consideration was number III. Problems did arise in the case of the oiling hole from the piston end of the connecting rod.

In order to obtain a geometrically accurate final points cloud, scans were performed both on the upper and lower corresponding views of the assembly, especially in the screws areas (Fig. 6). Even though the screws and nuts were cut off in the final 3D model, in this stage of processing they were meshed properly.
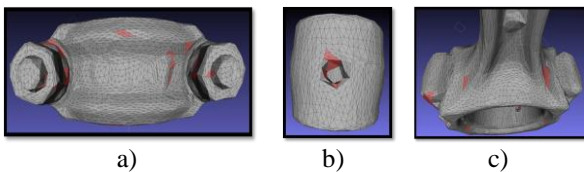

Figure 6: *Other views.*
a) Upper view of area I,
b) Lower view of area III,
c) Inclined upper view of area II.

On the lower view corresponding area problems were encountered in the case of the oiling hole. The scanner could not determine the hole's depth and inner geometry. Thus it resulted in a slightly inaccurate mesh. The solution was to fill in the holes which remained after the points clouds were merged and further processing to be made

afterwards. This is where only the scanner wasn't enough and failed to provide us with the much needed information. Measurements regarding the oiling hole were performed in detail using an electronic caliper and then used in the processing.

One last area that needed attention, although it was previously captured in scans, was correspondent to the connections between screws and the body of the connecting rod. The resulting geometry was uniform and did not provide accurate data regarding the joining areas between the elements. After applying the holes filling filter and after a local re-meshing option the screw heads show an increased density of points making it easier to eliminate them afterwards.

3. The final points cloud

The final data set was obtained by merging all intermediate points clouds. At first it contained a large number of points some of them producing errors. It was difficult to handle requiring significant computing power. Many points inside the cloud were identical and referred to the same features. Those ones were duplicates that needed to be removed [1].
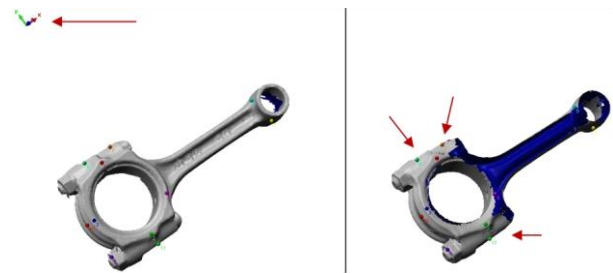

Figure 7: *The final data set.*

One of the first issues referred to the alignment of the points clouds to a global coordinate system (Fig. 7). We can observe that the final points cloud is aligned to a global unique coordinate system. As intermediate data sets were introduced to be merged, they were given by the software a number and were imported with their own coordinate system.
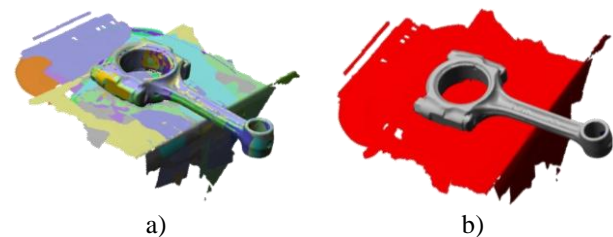

Figure 8: *Workbench removing procedure.*
a) crank end scan with the workbench,
b) crank end scan without workbench.

Another issue that needed addressing was the fact that each scan captured also the geometry of the workbench which had to be removed (Fig. 8). There were also many points that were not part of the actual geometry and had resulted due to the merging process and what was left out of the workbench removal (Fig. 9). By removing automatically these points the filter also cuts out from the part's geometry which is not desirable.

The solution came at a higher zoom factor by selecting those points or groups of points individually and then removes them.
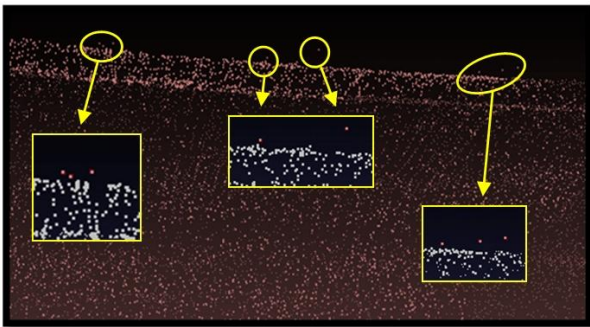

Figure 9: *Dispersed points from the points cloud.*

One other issue that had to be addressed regarding the final points cloud was the number of points that formed it. Part of it were duplicates, some were incorrectly aligned, others formed spaces with no areas, some nodes of the mesh were intertwined and all led to a slower processing time and to significant use of computational power.

MeshLab shows a total number of 406080 faces before any adjustment had been performed. We have applied the option for the removal of duplicates, first on vertices then on facets. Then we have applied the filter for the removal of area zero faces. They were the result of overlaps and did not characterize any geometrical feature.

Subsequently we have applied the following filters for the refinement of the mesh:

- *"Merge Close Vertices"*: we have specified the 0.167279 threshold value corresponding to the joining distance which is about 10% out of the total existing nodes in the mesh. We have obtained a points cloud with 403970 faces without losing any geometrical feature. Above 10% the filter cuts out from the geometry.

- *"Remove Unreferenced Vertex"*: there were nodes in the final set that did not align with the global coordinate system by the merging process of points clouds. Visualizing the mesh as texture we could see small cracks in the geometry. Those represented non-manifold regions being either nodes or edges.

- *"Snap Mismatched Borders"*: it breaks the edges that were not correctly aligned to the global coordinate system. This can occur due to adjacent surface patches that were wrong triangulated by the software. The filter found 580 edges and the mesh had now only 401833 faces.

- *"Split Vertexes Incident on Non Manifold Faces"*: after the filter was applied we had a points cloud containing 401253 faces.

Even though the corresponding mesh will be generated in *Catia*, we have optimized the points cloud through its point of view applying the following filters:

- *"Close Holes"*: the threshold value of 0.01 was set to ensure that all holes in the mesh are closed. The points cloud had now 401581 faces.

- *"Curvature flipping optimization"* and *"Planar flipping optimization"*. Now the mesh has reduced to the very limit of keeping the geometry unaltered.

We now needed to reduce the total number of points to the smallest possible without affecting the structure of the corresponding mesh. To do that, we needed a software tool that would report changes in mesh quality. It is called *"Quadric Edge Collapse Decimation"*. The options of *"Weighted Simplification"* and *"Simplify only selected faces"* were not checked as they would have produced changes in the geometry.

Table 1 shows the values obtained after applying the filter several times.

Table 1: *Results obtained after applying the filter for Quadric Edge Collapse Decimation.*

No.	Faces no.	Results
1.	401581	Mesh Bounding Box Size 151.356812 66.685410 24.936337
2.	200789	Mesh Bounding Box Size 151.356262 66.681190 24.935505
3.	100393	Mesh Bounding Box Size 151.355164 66.684013 24.934780
4.	**56919**	**Mesh Bounding Box Size 151.352347 66.688370 24.933414**
5.	28459	Mesh Bounding Box Size 151.349915 66.679977 24.935581
6.	14229	Mesh Bounding Box Size 151.346252 66.748756 24.937092

We considered that dimensional precision of results is sufficient up to two decimals. Changes occur after the 56919 faces mesh creation, leading to loss of geometrical features. In addition we have checked the integrity of the mesh by applying again the *"Close holes"* filter which turns out with no holes found to be closed. The above presented filters are part of a more laborious work of trial & error. The resulting mesh satisfies the dimensional accuracy conditions keeping intact the part's geometry.

4. Transformation of points cloud into 3D solid

In this stage of the refinement process we have a point cloud with 56919 faces and 28474 vertices. Although processed, it is not enough to become a 3D solid model. We have imported in *Catia* the points cloud as an *.asc* file. This will be, subsequently run through several software tools and modules. The first module is called *"Digitized Shape Editor"*. Even though the points cloud had been aligned to a global coordinate system, this has been done in software which *Catia* does not recognize. So the first step consists of the alignment to the global coordinate system. This operation is called repositioning [2].

In order to maneuver more easily the points cloud we have decided to filter the total number of points. We have selected the adaptive type because it turned out to be significantly more accurate than the homogeneous one. By applying the filter the software informs us that a reduction of geometry had been performed by 0.00336 mm. After applying the filter the software shows a relevant geometry which is formed with just 8.17 % points out of the total number that is as relevant as the entire points cloud (Fig. 10).
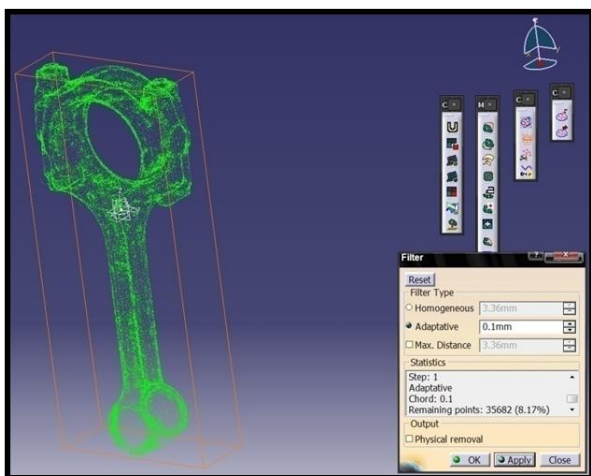
Figure 10: *Adaptive filter applied to the points cloud.*

In *MeshLab* we have virtually covered the points cloud with a mesh and we have optimized the cloud through the mesh's accurateness point of view. Now, in *Catia*, the real mesh has to be developed for it to be covered afterwards by a solid shell. We selected a 3D mesh option with a random value of 1.913 mm for its elements (Fig. 11a). The result was unsatisfactory so, by trial & error we have came up with the value of approximately 1 mm between elements which led to a complete 3D mesh, easy to process (Fig. 11b).
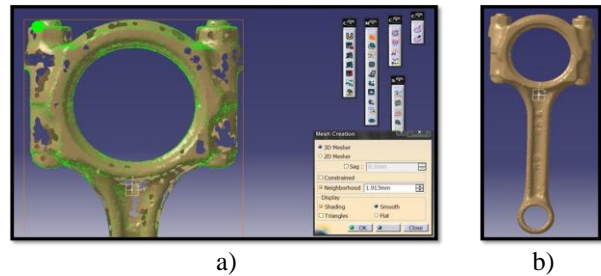
a)   b)

Figure 11: *3D mesh creation.*
a) mesh corresponding to 1.913 mm,
b) mesh corresponding to 1 mm.

Before we have entered surface reconstruction module we have applied a mesh cleaner filter. After the first run the filter indicated 44 non-manifold remaining vertices. The identified problems are shown in white squares (Fig. 12). By applying the filter successively after two more runs the filter came up with zero value for all its parameters.
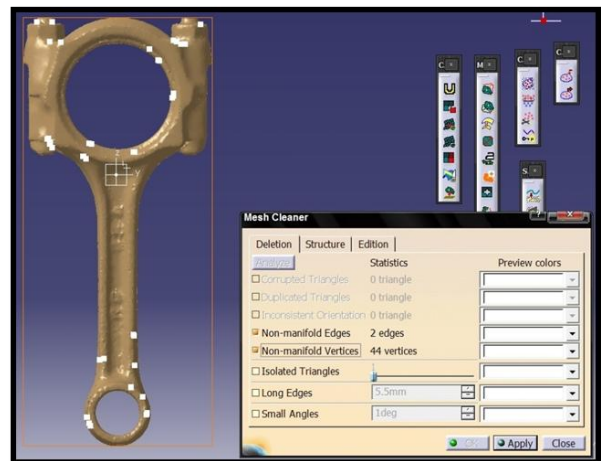
Figure 12: *Mesh cleaner filter's first run.*

The next stage of the processing is carried out in the *"Quick surface reconstruction"* module.
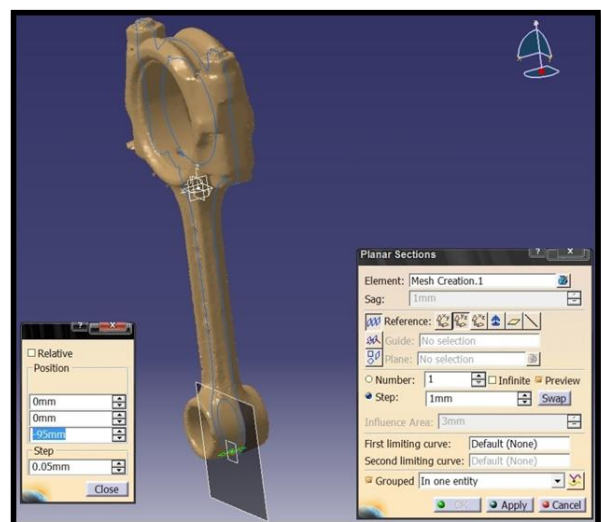
Figure 13: *Planar sections of the mesh.*

The first step consists of the creation of planar sections for the entire geometry on all axes. The first planar section is positioned right at the center of the mesh on *yz* plane view (Fig. 13).

The points from the points cloud must be aligned to form a continuous curve. We have decided to select a threshold value of 0.1 mm for the admissible tolerances (Fig. 14).
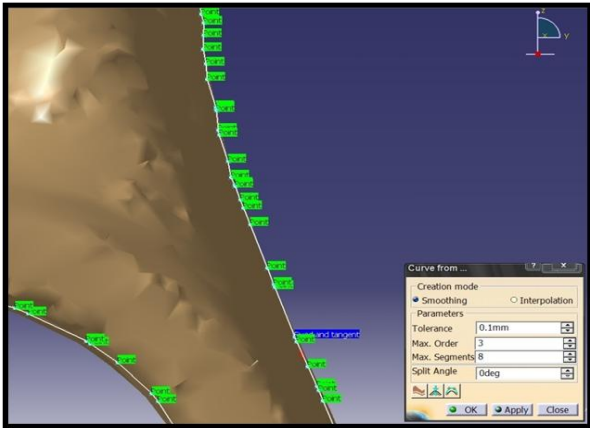

Figure 14: *Curvature creation tool.*

After the curves were created it was time to check their accurateness. In many cases on a bigger zoom factor we could see that in fact the curves (composed out of segments) did not lied exactly at the edge of the mesh by means of the *"Curves from scan"* option (Fig. 15a). The curves were created depending on the surrounding found points along the entire geometry. This problem was overcome by selecting the *"Curves from points"* option (Fig. 15b).
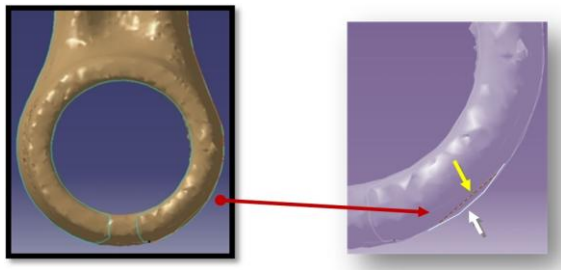
a)   b)
Figure 15: *3D curves creation.*
a) "Curves from scan" option,
b) "Curves from points" option.

Other issues were related to the fact that after the creation of a planar section, the 3D curve may be slightly modified. Such a case is presented in Fig. 16 where the profile was erroneously read and it generated a wrong 3D curvature line. This was overcome by turning to the option of 3D curve generation through control points. We could manually select which points and how many turned

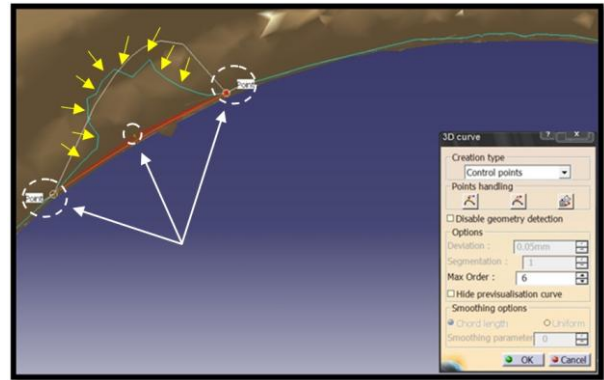into control points and then we could apply the filter.

Figure 16: *3D curve generation through control points.*

After all the curves were generated and checked they had to be merged as close profiles (Fig. 17). We have applied the *"Curve slice"* option in order to form closed contours out of selected 3D curves. Thus we have obtained a curves network correspondent to the entire geometry.

Figure 17: *3D curves merged into closed profiles.*

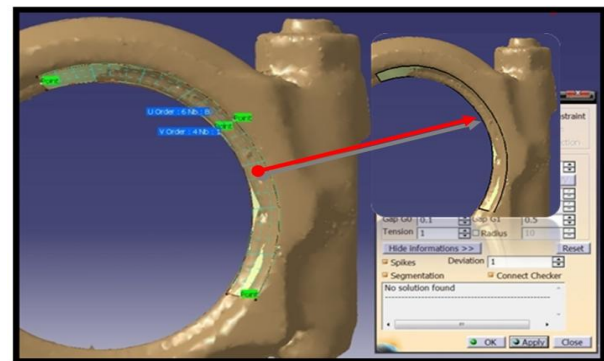The next step consisted out of covering the closed profiles with surfaces (Fig. 18).

Figure 18: *Surface generation on to closed profiles.*

By subsequently covering profiles with surfaces the geometry became a surfaces network. The next step was to merge all these surfaces to form a 3D solid model. For this we have opened the *"Wireframe and surface design"* module. By applying the blend option, surfaces were merged in a continuous profile (Fig. 19). Between the selected surfaces the filter forms a bridge. The continuity was set to tangential.
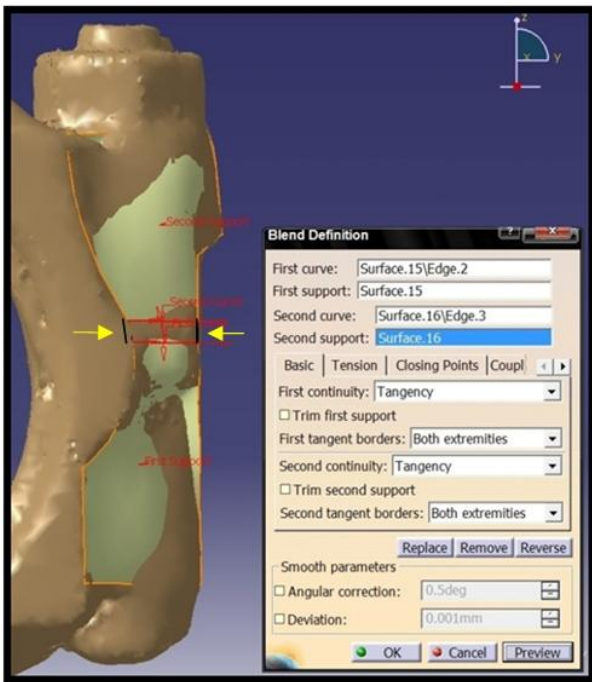

Figure 19: *Blending surfaces.*

The resulted closed contours in form of covering surfaces were joined together to form the desired 3D solid model of the connecting rod (Fig. 20a).
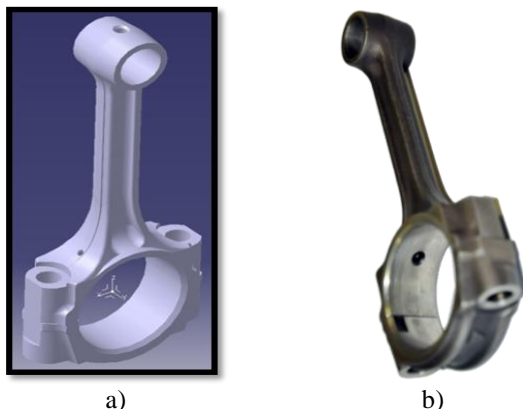

a)   b)

Figure 20: *Connecting rod models.*
a) 3D solid model,
b) physical model.

The model had to be further processed by cutting out all unnecessary elements of the assembly. This included the removal of screw and nuts, drilling the correspondent holes for those parts but more important, as highlighted above, the oiling hole was modified to meet the exact dimensions and angles.

5. Conclusions

The proposed workflow shows a detailed procedure of points cloud processing and refinement. The originality of this paper stands in the fact that before developing a corresponding mesh, the authors turned to a free points cloud processing related software solution for the optimization process. That led to a significant ease in the post processing given that most of the points cloud acquisition related errors were already solved. *MeshLab* helped also because we were dealing with multiple sets of points clouds and merging them produces errors in any software solution. By optimizing the final cloud by means of corresponding mesh, although not recognized in *Catia*, it delivered a smooth geometry and a lower number of points. *Catia* was the main processing solution because it produced a 3D solid replica of the physical model. The workflow extended on a period of almost three months work and it consisted out of a lot of trial & errors. The obtained 3D model is seen as a solid body by *Catia*. This allowed us to export a full copy of it for further FEA analyses in order to be validated from the geometrical and functional points of view. Also, on its basis further FEA analyses delivered an optimized 3D model which eventually was physically obtained by means of a CNC centre.

6. References

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