Manufacturability of Reverse Engineered CAD-models : a case study

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Abstract: Reverse Engineering is the process to construct a CAD-model from a physical model and consists of three steps : measuring or digitising the physical model, CAD modelling from the digitised points and completion of the CAD-model. This CAD model should be suitable for further processing, e.g. using CAM. This article evaluates the manufacturability of a CAD-model built through Reverse Engineering and containing free-form surfaces. The evaluation is done by means of a case study. Therefore, 5 axis milling paths are generated on the CAD model and the quality of the milled products is evaluated.

1. INTRODUCTION

Almost all modern manufacturing techniques start from the assumption that a CAD description of the physical object is available for the calculation of tool paths (CAM), simulations (CAE), CMM programming (CAQC), etc. However, the design of free-form surfaces often requires the use of physical models:

- The aesthetic design of free-form products like dashboards, fenders, windshields, … is often done by stylists. Ideas are passed by means of clay or wooden models.
- During the testing of physical prototypes (e. g. wind tunnel tests), their geometry is sometimes manually altered.
- After the complete design, the model is sometimes adapted to the needs of the production processes being used. The design is then changed directly in the workshop on the prototype or mould.

All these examples require the possibility to create or adjust a CAD-model from an existing physical model. As opposed to normal engineering, where a physical model is created from a CAD-model, this process is called reverse engineering. Figure 1 shows the three steps in reverse engineering. Starting from digitised points on the physical model, individual surfaces are modelled and the CAD model is finalised using standard CAD/CAM-tools towards a manufacturable product description [Kruth97a, Kruth97b].

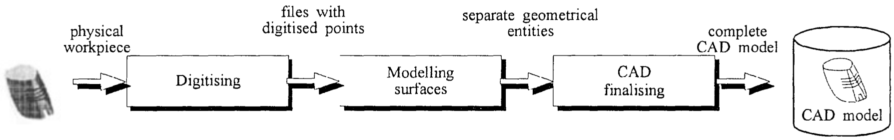

Figure 1. Reverse Engineering strategy

This article presents a case study on a plough. A CAD model is built from a physical model using the strategy of figure 1. The CAD model is then transferred to the CAM system in order to generate 5 axis milling cutter paths. Finally, these milling paths are executed on a 5 axis milling machine and the milled part is evaluated.

The original version of this chapter was revised: The copyright line was incorrect. This has been corrected. The Erratum to this chapter is available at DOI: 10.1007/978-0-387-35392-0_40

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2. DIGITISING AND POINT CLOUD HANDLING

Digitising for Reverse Engineering is performed by means of a measuring device, e.g. a co-ordinate measuring machine (CMM) and surface points are captured in 3D co-ordinates. Depending upon the digitising hardware used and the digitising strategies applied, the digitised points can be distributed according to a regular or irregular grid, following sectional lines or even randomly.

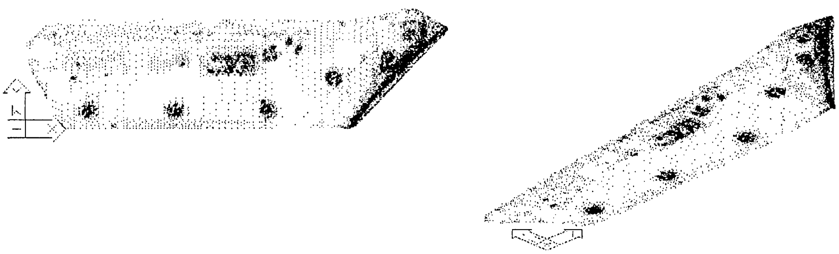

Figure 2. Plough : digitised points (top and left isometric view)

Figure 2 shows points digitised on the plough. The digitising is performed using the digitising software Surfeyor, developed at PMA-KULeuven [Janssens98]. Surfeyor is executed on a 3D CMM equipped with a point-to-point contact probe. The distribution of the resulting points is 3D curvature dependent, i.e. more points are digitised in highly curved areas and at small details of the physical object. In figure 2, a higher point distribution can be observed at spots where text was engraved in the original model, as well as along the holes in the model.

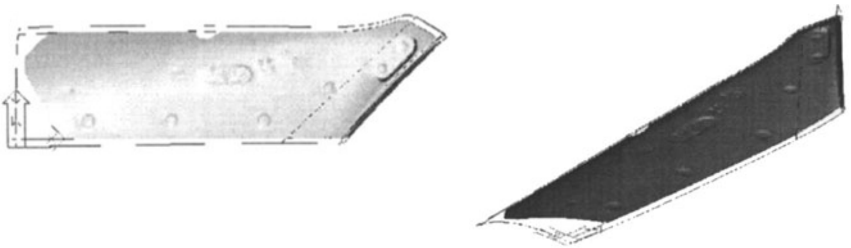

Figure 3. Plough : subdivision of the pont cloud (top and left isometric view)

To enable further processing, the digitised points need to be divided into different areas that describe different entities. Point handling techniques [3Dfax96, Hoppe92, Stucki94, Keppel75] form a useful tool for this purpose. The complete set of digitised points is grouped in a single entity, called a point cloud. By triangulating the cloud, the point cloud acts as a single facetted CAD entity on which operations can be performed. Figure 3 shows a shaded image of the triangulated point cloud created from the points of figure 2, using the Metris Base software of the company Metris n.v. (Belgium). From this shaded image, zones of high curvature as well as the defects due to the engraved text can be clearly seen. The zones of high curvature usually coïncide with the design lines or 'strong' lines of the object and can divide the object into different parts or entities. The user can use this visual information to project polylines onto the cloud and to make a sensible division of the cloud. Figure 3 shows internal and external curves that represent the surfaces' design lines and boundaries. Regions displaying surface defects can be cut out so as not to be incorporated in surface modelling.

3. CAD MODELLING

In a next step, a CAD model is reconstructed from the point clouds. Each area is modelled with the appropriate entity by means of a surface modelling software. All geometric entities together compose the physical model. Modelling software usually represent free-form surfaces by Non-Uniform Rational B-splines (NURBS), due to their interesting properties such as the ability to handle large surface patches, local controllability and the ability to represent analytical features as well.

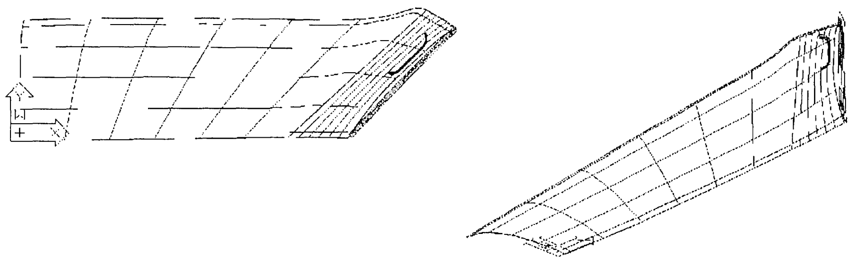

Figure 4. Plough : base surfaces (top and left isometric view)

The modelling of the plough is performed using the modelling software Shapid developed at PMA-KULeuven [Ma94, Kruth97a, Kruth97b] in co-operation with Metris n.v. Whereas most fitting algorithms require that the digitised points are structured in some way, the presented method does not presume any structure at all. Any point cloud will do, as long as the cloud contains enough information on the shape of the physical object, in particular in the critical, highly curved surface areas. In order to ensure the manufacturability of the surfaces, three surface modelling aspects are focussed upon : a regular parameterisation, smooth surfaces and continuous joins between different surface patches.

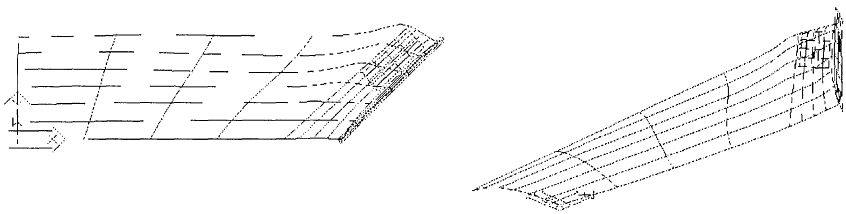

Figure 5. Plough : modelled surfaces (top and left isometric view)

Since most toolpath generation methods for multi-axis machining depend on the isoparametric lines of the object, the isoparametric lines should represent the object's design lines and should be smooth. Shapid controls the parameterisation of the surfaces by means of base surfaces [Ma95] created using the design curves on the point cloud. Figure 4 shows base surfaces created with the design curves of figure 3. The base surfaces and the point clouds then serve as input for the surface modelling.

In order to obtain smooth surfaces, the algorithm uses least squares fitting to filter out random measuring noise. The user can always choose between smoothness and accuracy of the surface to meet specific requirements. Special attention is paid to regions with a lack of points, like the left boundary region in figure 3. To ensure smoothness over such regions, additional smoothing conditions are imposed on the surface modelling algorithm. Figure 5 shows the modelled surfaces, which are smooth in the regions with a lack of points as well.

Continuous joins between surfaces can be either imposed during surface modelling or on the modelled surfaces afterwards. In the presented case study, the surfaces are forced to interpolate their boundary curves during surface modelling. Higher order continuity with adjacent surfaces is imposed in the CAD finishing step.

4. CAD FINISHING

Figure 6 clearly shows a discontinuity in tangent and curvature between two neighbouring surfaces, that is not present in the original model. Therefore, both surfaces need to be stitched with the required degree of continuity. Since most CAD systems do not supply sufficient tools for CAD finishing of NURBS surfaces, some specialised tools, like surface stitching, are incorporated in Shapid [Kruth97a].

Traditional CAD tools can further be applied in order to create surface fillets, trim off the boundaries along the point cloud's boundary, and trim out the holes of the model. Figure 7 shows the complete CAD model of the plough, obtained from the surfaces in figure 5 after performing the above surface and CAD operations.

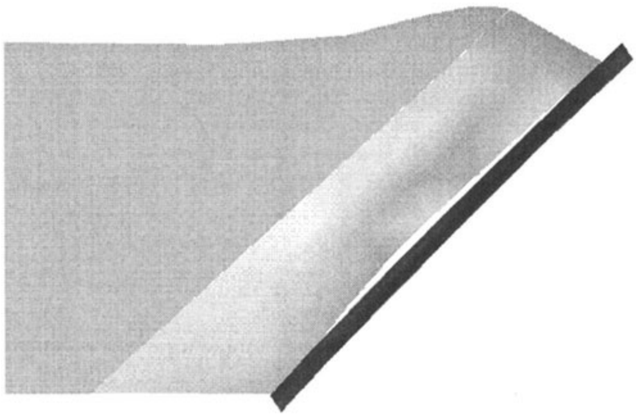

Figure 6. Plough : discontinuïty in tangent and curvature

5. GENERATING 5-AXIS MILLING TOOL PATHS

Figure 7 shows a CAD model that can be used to start production, e.g. by generating milling paths. Many commercially available CAM-systems support multi-axis milling operations. However, the functionality of those CAM-systems is subject to certain limitations. Unexperienced users often are not able to detect these limitations. The case study reveals some of the most frequent multi-axis CAM-problems. The CAM-programming for this case study was carried out with Unigraphics of Unigraphics Solutions, a partner of K.U.Leuven in the EU project OPTIMACH.

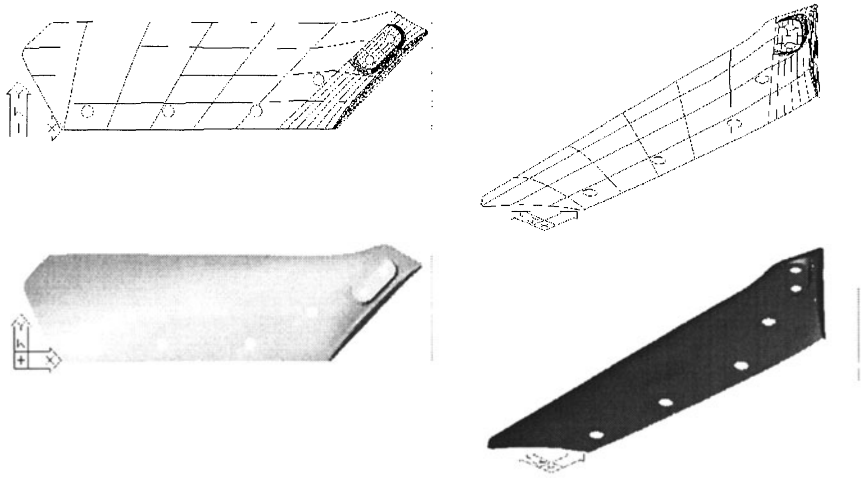

Figure 7. Plough : CAD-model (top and left isometric view)

Figure 8 shows a simplified version of figure 7 that is used for the milling tests : the detail and holes are removed. They can be added easily afterwards by local milling of the detail and drilling out the holes.

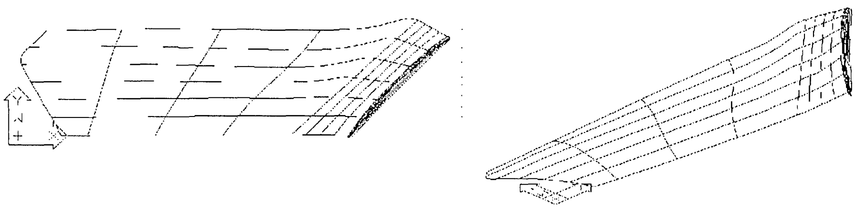

Figure 8. Plough : simplified CAD-model (top and left isometric view)

In general, three toolpath generation methods can be applied for five-axis machining : using a 'drive' surface, Cartesian milling (according to the Cartesian xy-plane) or parametric milling (according to isoparametric lines of the part surface) [Kim95, Lee90]. This case study uses the first, most general, method.

5.1 General approach using drive and part surfaces

In the 'drive' surface method, drive geometry is used to 'drive' the toolpath over the part surfaces. Toolpaths are created through generating drive points on the drive surfaces along constant *u* or *v*-parameters. These drive points are projected along a specified projection vector on the part surfaces in order to form the contact points.

It is up to the user to select or generate the drive surfaces. The limitations posed to these drive surfaces are more decisive than those posed to the part surfaces. Part surfaces can lie in an arbitrary way, trimmings are allowed and the surfaces may overlap each other. Drive surfaces on the other hand should not be trimmed and, in case of having more than one drive surface, should be located in a grid.

In this case, the same set of surfaces is used as drive and part surfaces. However, internally Unigraphics will use the untrimmed surfaces (figure 5) as drive surfaces, while the part surfaces to be milled are the trimmed surfaces of figure 8..

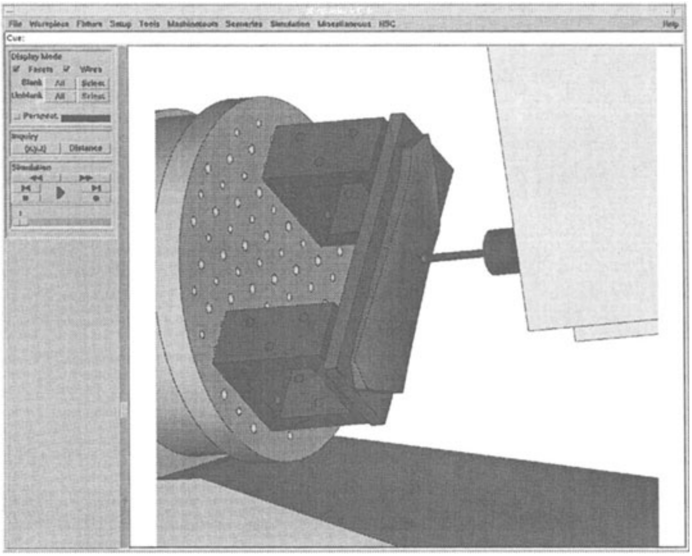

Figure 9. The Unisim simulation system, with the plough mounted on the table

5.2 Simulation software

The OPTIMACH project uses and evaluates the NC-simulation software Unisim, see figure 9. Simulation gives the possibility to check in advance whether the programmed toolpath is error-free. In this way, the feedrate doesn't need to be lowered by the NC-operator at the time of execution of the NC-program and a good surface quality can be guaranteed.

6. 5-AXIS MILLING

6.1 Preparation of the workpiece

The workpiece is machined in the following way :

- Roughing with a rather large cylindrical cutter (diameter = 20 mm)
- Semi-finishing using the same torical cutter as for the finishing pass (diameter = 20 mm, corner radius = 4 mm), but still with a part stock of 1 mm. The step-over between the milling tracks is larger as compared to the finishing pass.
- Finishing.

The workpiece is machined on a 5-axis MAHO 600C machine at our facilities, see figure 10.

6.2 Tooldiameter problems

The two largest surfaces in figure 8 are selected as part and drive surfaces. At first sight, the curvature of the surfaces is sufficiently low, so a rather large cutter can be used. A torical cutter of diameter 20 mm and a corner radius of 4 mm is used. After the generation of the toolpath, a first visual check of the toolpath on the screen does not show any irregularities. However, a closer look at the toolpath reveals spikes, see figure 11.

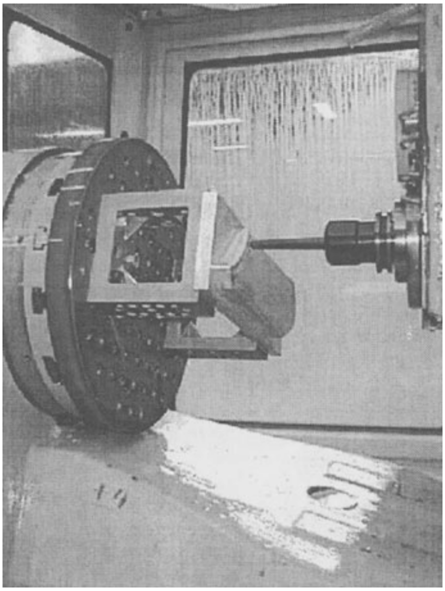

Figure 10. Overview of the machine during the 5-axis milling finishing pass

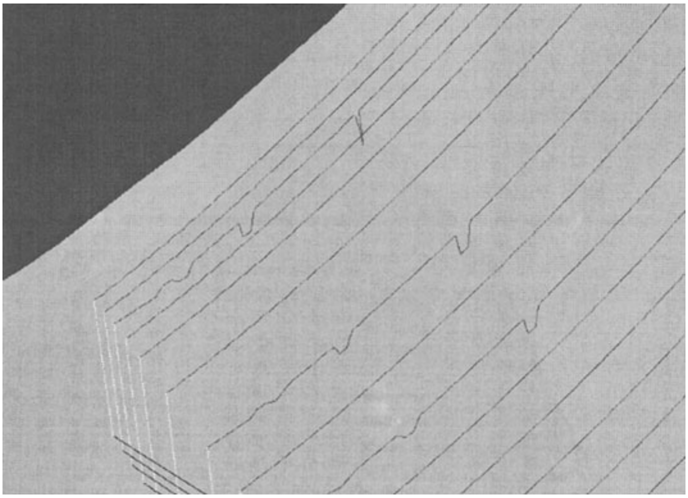

Figure 11. Spikes occuring in the toolpath

These irregularities in the toolpath are removed by changing some of the available parameters (like the lead and tilt angle of the cutter) and the toolpath is regenerated. The resulting workpiece however still shows many surface marks, especially in the regions where the curvature is high. The CAM-operator can see on the machined workpiece that the curvature in the region near the border is too high to mill it with this cutter, see figure 12. As a consequence, a smaller cutter is applied, which improves the result drastically.

The selection of an appropriate cutter is a well known problem in multi-axis machining [Lee96]. In the OPTIMACH project, an estimation of the tooldiameter will be provided inside the operation. This estimation will be based on the behaviour of local curvature [Kruth94, Saar98].

7. DISCUSSION

7.1 Surface connection

In this case study, two different sets of surfaces (i.e. parts) have been milled. The first part only has C^1-continuity between the two main adjacent surfaces, the other part contains surfaces with C^2-continuity. The same CAM operations are calculated for both parts. It was expected to find a difference between the two workpieces, but the resulting workpieces show no difference in continuity. This means that, in this case, the resulting error of having C^1- instead of C^2-continous surfaces is smaller than the error caused by the CAM-system and the milling process. Furthermore, the C^2-discontinuities could be 'masked' by using an appropriate milling strategy. In the case of the plough, the milling path was given the same direction as the common surface edge.

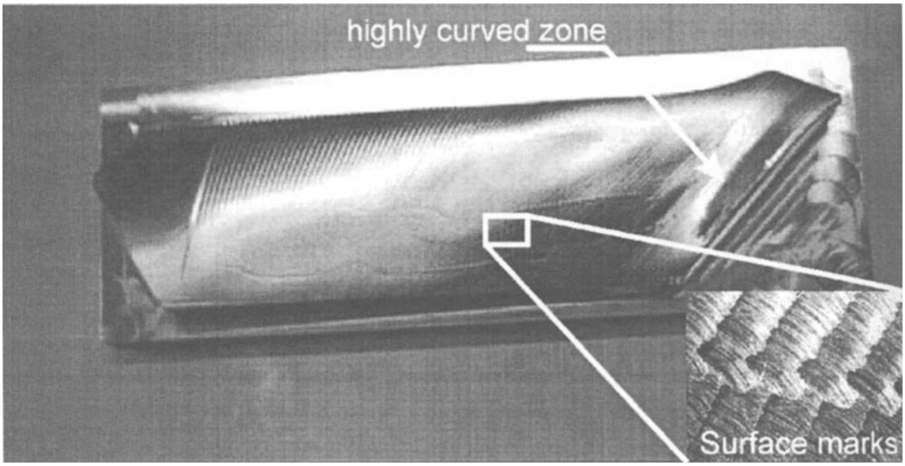

Figure 12. The resulting workpiece and the surface marks

7.2 Surface marks

The resulting workpiece shows lines with little furrows, see figure 12. After an accurate investigation of the toolpath, it was found that these surface marks are caused by the reversal of one of the rotary axes. They can be removed by final polishing.

8. CONCLUSION

This article presents a case study on a plough that underwent a reverse engineering and CAM process in order to produce a milled part from a physical model. Critical factors are outlined and some suggestions for improvements are given.

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