Adaptive Preprocessing and Segmentation for a Region-based Surface Extraction Method

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Abstract
Because of its great possibilities, meanwhile the industrial computer tomography (CT) is used for many different applications, where three dimensional material limitations are essential. But in many cases, the results of the conventional surface extraction method, the marching cubes algorithm, are not optimal and need to be postprocessed which is time consuming and complex. Moreover there is often no possibility to generate an adequate mesh, e.g. considering multi-material objects. In this paper we present a method for region-based surface extraction which leads to a one-step-method with optimal surface results for the next evaluation step. It is separated in a preprocessing part where the surface generation is defined by a given task or problem and in a surface extraction part where the surface is determined based on the developed preconditions. We want to overcome the disadvantages of the state-of-the-art solutions and offer a modern way of task adaptive and optimized metrology.

Keywords: Segmentation, Data Preprocessing, Surface Extraction

1 Introduction
In recent years industrial CT has established for a large range of different metrological applications like nominal/actual comparison, qualifying measurements or form analysis. In addition CT data is also used for complex problems like simulation tasks or reverse engineering applications. For all these kinds of data evaluation the surface of the observed part is necessary. The conventional and proven method for surface extraction is the marching cubes algorithm [1], which separates one material and air with a global threshold. Although there exist a lot of further developments, this algorithm has disadvantages for various applications. First the global threshold is not usable in all areas of a CT volume, especially if artifacts or more than one material (excluding air) occurs in the data set. There is also no possibility to separate different materials and to generate their boundary surface directly. Furthermore the user has no influence on the resulting surface as far as region definition, point density/resolution or accuracy are concerned. Often it is not necessary to inspect the complete object but only a defined area, e.g. for a flow simulation just the canal system of a fuel injector is interesting. Moreover the surface data sets can be very large and therefore cannot be handled by standard software anymore. Various time-consuming post processing steps, like manually cutting, data reduction or filtering are required to allow data evaluation. In this paper, first we present shortly the state-of-the-art considering developments in surface extraction of volume data. In the next chapter we describe possibilites of adaptive preprocessing and segmentation steps to prepare an initial mesh for a region-based segmentation. Afterwards a new surface extraction method, including user defined, adaptive parameters is presented which will help to overcome the mentioned problems with nowadays surface extraction procedures.
2 State-of-the-art
Within the past years many research activities were dealing with the extension and improvement of Marching Cubes procedures, often focussed on the evaluation of medical CT data. One of the most important aspects is the correction of definite errors within resulting data. For this reason a multitude of papers deal with the avoidance or correction of topological ambiguities, degenerations and redundancies [2-4]. One example is the use of other geometrical structures as a basis for the triangulation. Within [5] the voxels are divided into tetrahedrons and the applied procedure is similar to the Marching Cubes procedure. The problem of a global threshold in the Marching Cubes procedure is often the reason of incorrect surfaces. Common procedures for automatic threshold determination are based on histogram analysis and therefore suitable for acquired volume data of parts which consist of only one material. Here for example the percentaged greyvalue distributions are estimated or normal distributions are approximated. One of the best known methods for threshold determination is the Otsu procedure [6].
However there is a possibility to overcome the disadvantages of a global threshold by using local, adaptive thresholds. One approach for local threshold calculation with Marching Cubes is described in [7]. The greyvalue of a voxel is used as volume value of the original object and for each determined surface point the threshold is adapted in such a way, so that the volume share in the result is maintained. In [8], a dynamic, local adaptive variant is suggested, in which for each detected surface point from the cubic environment a particular threshold is newly calculated. In [9], starting from the Marching Cubes result, the local environment of points in the form of the greyvalue profile along the surface normal is used. One variant calculates the centre of the biggest negative gradient there, the second variant searches within this area for a minimum gradient, between material and air which is given by the user. Along with the optimization and extension of the Marching Cubes algorithm, various works dealt with alternative procedures. In [10] the contours are determined in layers and validated and triangulated by surface tracking for example. In [11], surface patches are searched instead of edges, the so-called “Level Surface Patches”. For this purpose the 3D volume is first transformed into a contrast picture or –volume by gradient determination, in which on possible surface areas a statistic test is performed of probability of border area. In [12] a so-called Guidance Field is used, for generating the triangles adaptively according to the surface curvature.

3 Adaptive Preprocessing and Segmentation for region-based surface extraction
To overcome the mentioned disadvantages of the marching cubes algorithm, a region-based surface extraction is developed. The basic idea is that an initial mesh is used, which allows to define or to preprocess parameters to guarantee the generation of an optimal surface mesh concerning the user and task requirements. This initial 3D-mesh is generated adapting the demands of the given measurement task. Different demands can be a region dependent resolution or accuracy, external and internal information, like special greyvalues in the volume for materials. In figure 1 different possibilities for initial meshes of a part are visualized. Depending on the task it is possible, that some regions of the screw are not interesting and can be left out or that some regions are needed with a higher point density.
Figure 1: Examples of a region dependent mesh initialisation for a screw (CAD-model): the same resolution (left) and separated region (up right) or different resolutions (down right).

There are different ways to define these task-based initial meshes and to separate different regions. It is possible to use a-priori knowledge and add the information as preconditions to the initial mesh. If a CAD-model of the part is given, the geometrical primitives or freeform patches can be used as basic region definition. Here the triangulation of the faces of the CAD model is performed in an adaptive way, for example by considering the curvature of the face or by defining a maximum edge length of the triangles or by defining the maximum deviation of the triangle to the original face. Thus initial meshes can be built with specific resolution depending on the particular task.

Besides geometric primitives or freeform faces which can be used as initial regions there is also the possibility to create user-defined regions on the CAD model. Here algorithms have been developed to select an area by fencing in the relevant region on the CAD model with mouse clicks. The established fence is shown and a corresponding solid is created. By performing Boolean operations on this solid and the respective faces from the original CAD model a new segmented region of one or more partial faces is created which can be used for further calculations.

One useful tool to find and define relevant regions is a pre-segmentation based on curvature analysis algorithms. Here different algorithms for automatic segmentation in 3D pointclouds were developed. The aim of this development is to pre-segment the point cloud in regions with different curvature values and is used as a pre-processing step.

For this reason three algorithms for curvature calculation in point clouds have been developed and implemented [13]. In the first algorithm the mean curvature is calculated using an estimation of normal vectors at each measure point. Therefore the normal vector in a single point is defined as follows. Take a neighbourhood $\Omega_r(P_i)$ of the current point $P_i$, in which all points with a distance smaller than a given radius $r$ lie. The normal vector of the approximating plane through all points in $\Omega_r(P_i)$ is then defined as the normal vector $n_i$ at point $P_i$. The calculation of the normal vector $n_i$ of this plane is performed by searching the eigenvalues of the inertia ellipsoid of the points in $\Omega_r(P_i)$.

The eigenvector $v_1$ to the smallest eigenvalue $\lambda_1$ is the normal vector of the approximated plane. The mean curvature for each point is then given as:

$$H_i = \frac{1}{|\Omega_r(P_i)|} \sum_{j \in \Omega_r(P_i)} \left| \frac{n_i - \bar{n}_j}{\bar{x_i} - \bar{x}_j} \right|$$

As a modification of this method a second procedure was developed. The mean curvature is here approximated by the variation $\text{var} = \lambda_1 / (\lambda_1 + \lambda_2 + \lambda_3)$ of the smallest eigenvalue $\lambda_1$. The result is not the exact curvature but it describes it in a proportional manner.

Furthermore an algorithm for the calculation of the principle curvature values has been implemented. This third implemented method starts with triangulated point clouds. In the case of triangulated points the advantage is that the two curvature values $K$ and $H$ can be easily calculated as follows:
\[
K = \frac{2\pi - \sum \alpha_i}{\frac{1}{2} \sum \text{area}(\Delta_i) - \frac{1}{2} \sum \cot \alpha_i l_i^2}
\]

\[
H = \frac{\frac{1}{2} \sum \beta_i l_i}{\frac{1}{2} \sum \text{area}(\Delta_i) - \frac{1}{2} \sum \cot \alpha_i l_i^2}
\]

From these values the two principal curvatures can be calculated. If no triangulation is available the algorithm calculates local triangulations by projecting the maximum number of points that can be projected to a plane. Afterwards a 2D-triangulation in the plane is performed and then transferred to the 3D points. As a result, the advantage of the segmentation of the point cloud using principle curvature values is that not only regions with high curvature can be separated from nearly flat regions but also geometric primitives like cylinders can be directly distinguished from spheres for example.

After the curvature calculation for each measure point is performed regions of points with similar curvature values have to be determined. This is done by two different procedures: region growing or histogram evaluation. Starting with a random point in the point cloud, the curvature values of the points in a small area around this point are compared to the curvature value at the point itself. If they are similar these points belong to the same region as the starting point. This procedure then continues recursively with the added points.

Splitting the complete point cloud in smaller regions with similar curvature can also be performed by analysing the histogram of all curvature values. First of all the number of classes has to be specified. Normally up to four classes of different curvature values are sufficient. In the histogram all maxima and minima are automatically determined and so thresholds are defined. Then the points can be classified by applying these thresholds.

The developed algorithms for automatic segmentation have been tested on different data sets of real parts. These tests showed that segmentation in two steps delivered the best results. First of all the mean curvature values are calculated for all points. Then a rough segmentation is done dividing all measure points in points with large curvature values and points with low curvature values (the more or less flat regions). Afterwards a refined segmentation of the points with low curvature values is performed (see figure 2).

![Figure 2: Curvature calculation and rough segmentation: regions with high curvature (right) and low curvature after refined segmentation (left)](image)

The result of these steps is a triangulation of the region-of-interest with the optimal point density depending on the task and given preconditions. Additionally a-priori knowledge can be included to the nodes as restrictions and preconditions that are used during the surface extraction. These preconditions can be defined curvature values or greyvalue or contrast limitations.
4 Method for region-based surface extraction

The region-based surface extraction method uses the given initial mesh with the defined preconditions for finding the optimal surface positions in the CT-volume. Therefore local information of the CT-data like local grey values, gradients and surface parameters like the actual curvature are determined. These parameters are used for developing energy functions which can be minimized iteratively. As result, we get an optimal mesh for the defined application for which no post processing steps are necessary, different materials can be separated by local analysis, regions-of-interest can be extracted and areas of artifacts can be ignored. In figure 3 the process is explained on a multi-material example: For the two different cylinders, only the inner surface of contact has to be inspected and the resulting mesh should have less than 2 MByte. After the determination of the initial mesh with the adequate point density, the surface is adapting itself on the inner cylinder based on a given grey value and maximal gradients by considering the curvature structure of the initial cylinder form.

This developed algorithm is based on the method of active contours and composed of several steps. First of all the initial surface is needed which represents the basis for the algorithm. Regarding the specific task the generation of an optimal surface can be performed as described in the preceding section. The next step is the covering of this surface with the volume model. This requires an intermediate step a rough alignment which can be solved with already existing algorithms, e.g. Best-Fit methods. After the correlation between the initial surface and the CT data the automatic and iterative search for the actual surface begins. Therefore a so-called greyvalue profile of constant size is determined for each point of the initial triangles. The profile’s size can also be entered by the user and complies with the maximum difference of the actual points from the real surface points. Within these greyvalue points each point is now varied in its position and for each alteration the so-called energy function is set up. This function evaluates each mesh variant and has to be minimized in order to approximate the real surface. The energy functions can cover different aspects of a condition to the quality of the result. Within the scope of this work the following conditions in energy functions had been realized

• Evaluation of greyvalue transitions: the gradient at material transition must have a large value, so for this energy E_image the negative absolute value of the gradient is assumed.

• Evaluation of the local curvature: The local curvature around a point should be as low as possible in order to avoid false discontinuities. For the energy E_curvature a discreet Gauß curvature in combination with a medium curvature in the point’s neighbourhood is minimized.
All in all the result is a minimizing evaluation of the complete Energy $E$ with weighted elements/components:

$$E = a \cdot E_{image} + b \cdot E_{curvature}$$

Within first tests these two energies were implemented. Here further approaches are possible, e.g. the comparison with nominal values from the CAD-model and predefined values. First trials are limited to the principle functionality and have to be optimized and evaluated with regard to precision. One example is presented in the next section. In general it is possible to add different restrictions to the predefined meshnodes depending on the given problem.

5 Applications

The new preprocessing and surface extraction method are useful for different kinds of applications. One problem is the defined extraction of special geometrical areas. One example is shown in image 4. Here again the composed part already presented in section 3 is given and the limiting surface between the two materials is the Region-of-interest with a restriction of data (2 MByte in this example). In figure 4 the comparison of the new procedure with the conventional procedure is illustrated.

![Example: Extraction of an inner geometry](image)

Figure 4: Comparison of the state-of-the-art and the presented processing

It is obvious that fewer steps are needed to reach the necessary resulting surface and that especially at the boundary areas no data loss occurs by cutting due to the completeness of the initial contour. Here the principal functionality is demonstrated and no comparision of precision is made.

A real application for example here is the generation of surface models of a diesel injection system for flow simulation. In this case only the inner structures are necessary with a high resolution and outer geometries are only needed with few nodes. Additionally, for an efficient simulation process the data set has to be as small as possible. Another application is the local analysis of special areas for tool compensation. Here the interesting, varying regions are located manually or by curvature analysis and the local analysis can be used to investigate and influence the compensation process.
6 Future Work

The presented work offers the possibility of region-based surface extraction and adaptive preprocessing for many applications. The further working steps are the evaluation of precision, limits of accuracy and the development of different and individual adaptive energy functions. Especially this last step contains experimental work with test data sets that allow a predictable and adequate process evaluation. In the end we aim to achieve an optimal surface extraction for any kind of surface processing task.

References