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Separation of CT-based CAD-to-Part-Comparisons

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Separation of CT-based CAD-to-Part-Comparisons

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Resumo

Atualmente, para a inspeção de plásticos moldados por injeção, métodos óptico e táteis são usados. Nestes processos, a geometria da ferramenta usada para formar a peça é derivada da medição da peça em si. Em alguns casos, a peça destinada a inspeção pode ter partes inacessíveis, devido a sua geometria complicada, as quais podem apenas ser acessadas através do corte da peça. Entretanto, este processo pode modificar as propriedades da peça pelo alivio de tensões internas e, como consequência, introduzir um erro sistemático na medição atual. Além deste problema, a correção da ferramenta baseada nestes processos convencionais é iterativa e geralmente requer uma grande quantidade de tempo.

Considerando os pontos discutidos acima, a Tomografia Computadorizada (TC) aparenta ser uma potente solução para a inspeção de plásticos moldados por injeção, tendo em vista que se trata de um processo não-destrutivo que pode ser usado para a medição de peças de geometria complicada. O resultado da tomografia é uma nuvem de pontos de alta densidade, a qual pode ser usada para uma inspeção “peça para CAD” com um modelo nominal. Alem disso, os desvios obtidos através desta comparação podem ser separados, usando uma nova metodologia, em diferentes ordens geométricas e cada ordem pode ser atribuída, tipicamente, a uma causa (por exemplo, ao processo de injeção e a geometria do molde). Como resultado, um feedback mais preciso, especifico e rápido para a correção da ferramenta é alcançado, reduzindo o número de iterações necessárias para esta. Neste projeto um software desenvolvido na plataforma Matlab com interface gráfica GUI foi desenvolvido para a comparação “peça para CAD” e separação dos desvios de superfícies em diferentes ordens.

Abstract

Currently, for the sample inspection of injection molded plastics, optical and tactile measurements methods are used. In these processes, the geometry of the cavity tool used to form the part is derived from the measurement of the part itself. In some cases the measured part may have inaccessible features, due to its high complex geometry, which can only be measured by cutting. However, this process can lead to a change in the geometry of the part by releasing its internal stresses and, as a consequence, lead to a systematic error in the current measurement. Moreover, the tool correction based on these conventional processes is iterative and usually require a big amount of time.

Considering the points discussed above, the X-Ray Computed Tomography (CT) seems to be a potential solution for injection molded plastics inspection since it is a non-destructive process that can be used to measure parts with high complex geometries. The result of the CT measuring is a high density point cloud which can be used to a CAD-to-Part comparison with a nominal CAD model. Furthermore, the deviations obtained through this comparison can be separated through a novel approach in different geometrical orders and each order can be assigned, typically, to a cause (e.g. mould tool geometry and injection mould process). As a result, a more accurate, meaningful and rapid feedback is generated for the tool correction, reducing thus the iterations needed for it. In this project a matlab GUI based software was developed to make the CAD-to-Part comparison and separate the surface deviations into different order forms.

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List of Abbreviations

- CT - Computed Tomography
- CAD - Computer Aided Design
- CMM – Coordinate Measure Machine
- DOF – Degrees of Freedom
- ICP – Iterative Closest Point
- GUI – Graphical User Interface
- NDT – Non-destructive Testing
- NNS – Nearest Neighbor Search
- WZL - Werkzeugmaschinenlabor

Chapter 1: Introduction

Part inspection plays an important role on manufacturing processes as long as it can be used for quality control reasons and also it can give relevant feedback for improving the manufacturing tools. Currently, for the sample inspection of injection molded plastics, optical and tactile measurement processes are used. In these processes the geometry of the cavity mold used to form the part is derived from the measurement of the part itself. By providing a good feedback from the inspection process, the manufacturing tool can be improved and, consequently, the quality of the manufactured part can be increased. This optimization procedure described above is illustrated in figure 1.

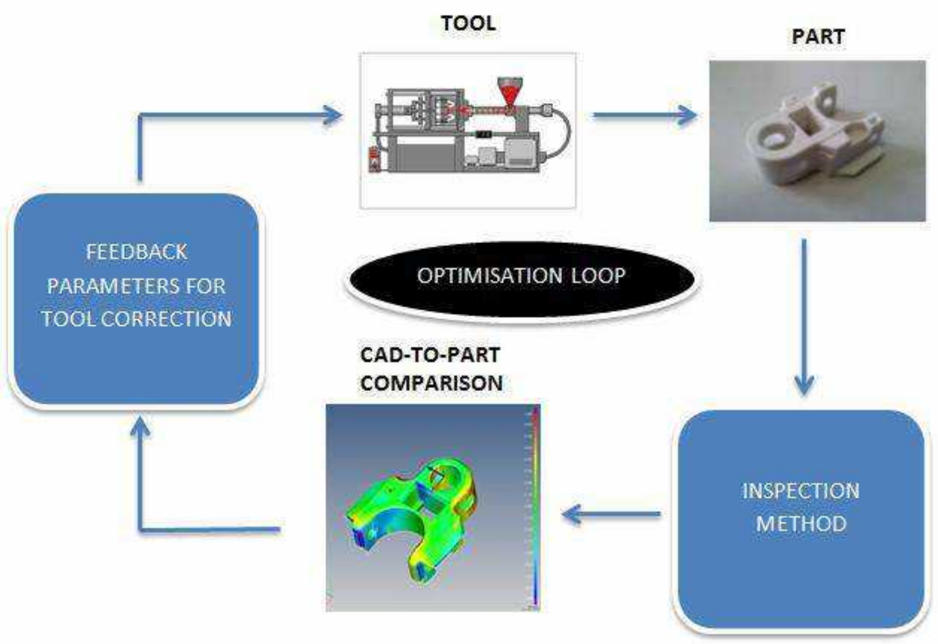

Figure 1 – Optimization loop for manufacturing quality improvement

However, is still difficult to give an accurate and meaningful feedback to improve the manufacturing tool due to two main reasons: Firstly, in some cases the inspected part may have inaccessible features which can be only measured by cutting. This process can lead to a change in the geometry of the part by, for example, releasing internal stresses of the part which may lead to a systematic error in the current measurement and, as a consequence, a non-accurate result. The second reason is that the part geometry is influenced by several causes which are, in turn, overlaid. Therefore, it is difficult to see the relevance of each cause in the total geometry deviation and thus give a meaningful feedback to the tool correction process. In addition, these conventional processes are iterative and may require a big amount of time. Taking all these aspects in account, an inspection based on a non-destructive CT based measurement with separation of deviations, through a novel approach, is proposed in this project.

1.1: Project Objective

The present work is part of a project called "SmartInspeCT – Separation of nominal-actual comparisons to improve processes in tool and mold manufacturing". Within this project WZL cooperates with BOIDA Kunststofftechnik GmbH & Co. KG, Proplas GmbH and the associated partner Carl Zeiss Industrielle Messtechnik. The project is funded by the BMBF within the program „KMU-Innovativ Produktionsforschung".

The project objective is to reduce the amount of iteration loops for the tool correction by giving, more rapid, accurate and meaningful parameters for the tool correction. In order to achieve this goal, the development of an automatic approach through a GUI based MATLAB software for surface inspection is proposed.

The software will take a high density point cloud, obtained through a CT measurement of the part, and a CAD model. These data will be used for a CAD-to-Part comparison (or also called nominal-actual comparison) in which punctual deviations are calculated for all data sets. Furthermore, the surface deviations will be separated using a novel approach in different geometrical orders (offset, slope, curvature, waviness). Typically, each order can be assigned to a deviation cause (e.g. mould tool geometry and injection mould process). With this separation it is possible to figure out their causes more easily and adapt specifically the tool correction. The figure 3 illustrates the procedure described above.

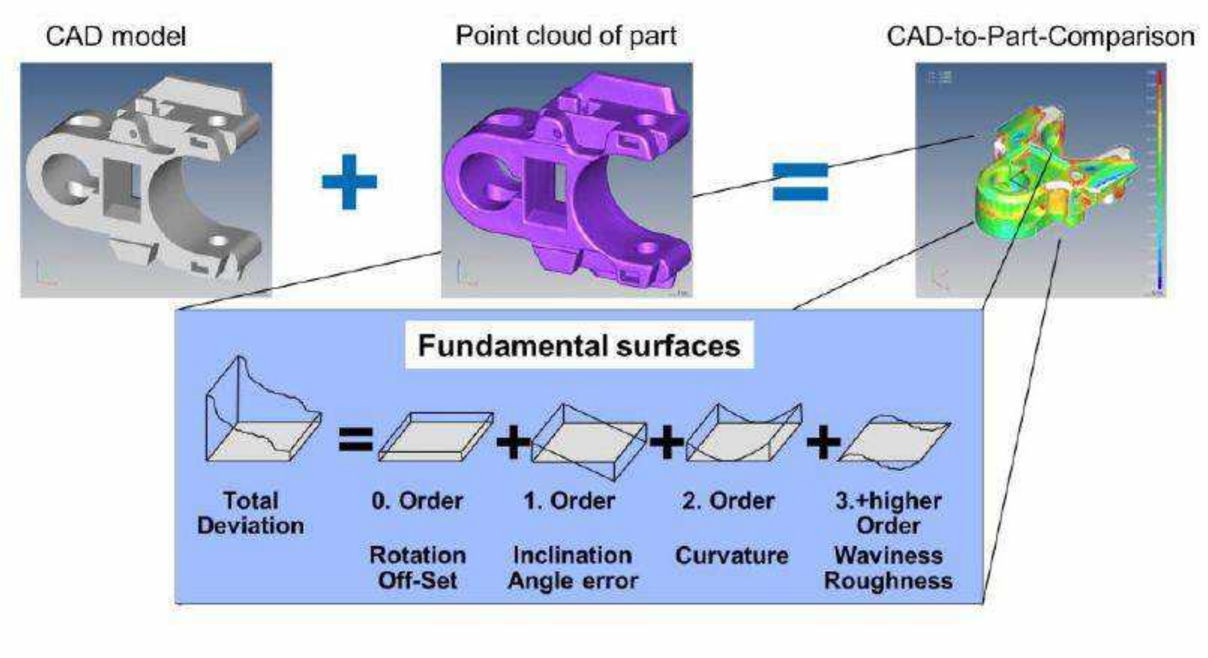

Figure 2 – CAD-to-Part Comparison and Surface Deviations Separation

1.2: Methodology

The project was developed at the Werkzeugmaschinenlabor (WZL) institute at the RWTH Aachen University. All equipment and technical resources were provided by the institute. The methodology proposed for this project was the following:

- Familiarization with separation approach (already existing for gear flank topographies), CT scanner and coordinate measurement software Calypso.
- Apply separation approach to CT-based CAD-to-Part-Comparisons.
- Systematic study of the segmentation of typical regular geometries.
- Set-up of prototype separation program in Matlab with GUI.
- Separation tests for sample work pieces using the program developed.
- Documentation of results.

In a first instance, some papers were provided in order to understand the deviations separation approach, the CT fundamentals and the coordinate measurement software Calypso. This separation approach has been already used to flank topographies using a tactile CMM machine. After the familiarization with the approach, some surfaces segmentations methods were studied and one of them was selected to be used in the software. After this step, the software development was carried out. Finally, some work pieces were scanned and used for inspection using the software developed.

1.3: Document Structure

This document is organized in chapters in the following form. In chapter 1 an introduction to the project theme and goal is provided. In chapter 2 the fundamentals of X-Ray CT technology are discussed. In chapter 3 a mathematical background for the separation approach understanding is given, in chapter 4 are presented the main project problems and possible solutions methods. Chapter 5 includes the implementation of methods and solutions chosen for the software development. In chapter 6 some results are presented from a sample inspection of a typical part. Finally, in chapters 7 and 8 some conclusions about the current work are presented and possible future work is discussed.

Chapter 2: X-Ray Computed Tomography Fundamentals

The X-Ray Computed Tomography (CT) is an innovative technology on the metrology field. It was initially developed for medical applications and more recently it is being used for industrial purposes.

Dimensional metrology is the most recent utilization of CT scanners for the industry. It can be used to measure not only the outer but also the inner geometry of work pieces without the need of cutting the work pieces into slices to evaluate hidden or inaccessible features, which is an innovative aspect on metrology. So far CT is the only technology for the holistic quality control of work pieces with non-accessible internal features at very high resolution. [1]

The main advantages of the CT measurement over the conventional processes such tactile CMM's (Coordinate Measure Machine) or 3D laser scanners are the ability to check non-accessible features for parts with high geometry and the fact of being a non-destructive inspection method.

2.1: CT Operation Basics

The CT is a non-destructive technique to obtain cross-sectional images from a work piece. A schematic figure of the CT operation is shown in figure 3. In a typical operation, a work piece is placed in a rotary table and some parameters, such as tube voltage, exposure time and number of projections, are set. A source inside the CT machine emits x-rays that penetrate the part and are attenuated according to the part geometry, density, material and x-ray energy. A detector placed after the rotary table is used to record the intensity of the attenuated x-rays. The detector provides a bi-dimensional greyscale image representing the amount of attenuation of the current projection. After several attenuation images from different rotation angles are obtained it is possible to create, through a mathematical reconstruction, a 3D voxel model (equivalent 3D of the pixel) in which the voxel gray value represents the absorvity of the material. This 3D voxel model can be used to generate a 3D data set (point cloud) of the current scanned part.

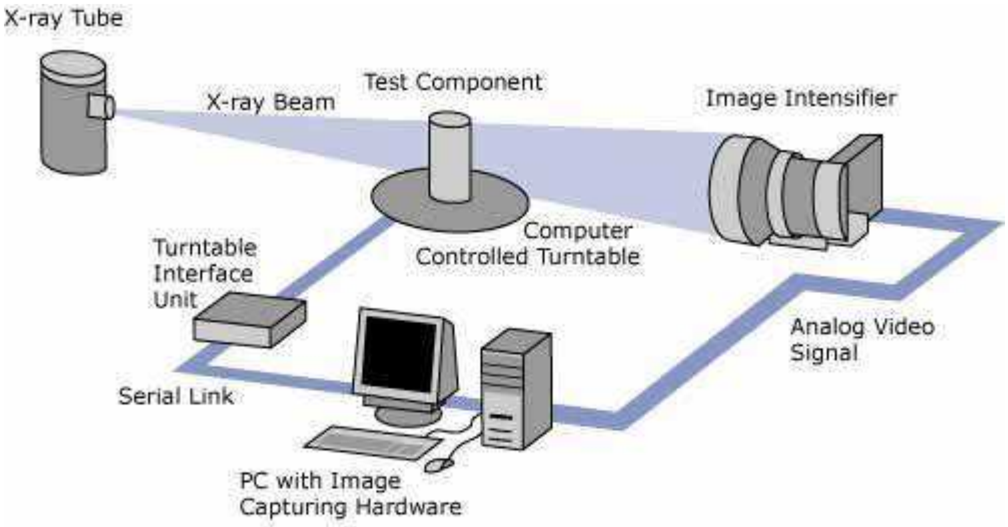

Figure 3 – CT Operation

Chapter 3: Separation of Deviations Mathematical Background

A separation approach for flank topographies using CMM measurements as measuring instrument was proposed in [2]. This approach was adapted and used for the current work. All mathematical derivations presented in this chapter are credited to the approach authors.

The punctual deviations between a nominal and actual surface can be considered as an overlaid of several order form deviations. In this project we will consider, basically, the three first global forms deviations and the residuals forms:

1. The 0th order form with the meaning of an offset.
2. The 1st order form with the meaning of inclination.
3. The 2nd order form with the meaning of curvature.
4. The residual forms composed by the 3rd order form, with the meaning of waviness, plus the higher orders.

The global forms and residuals are represented in figure 4.

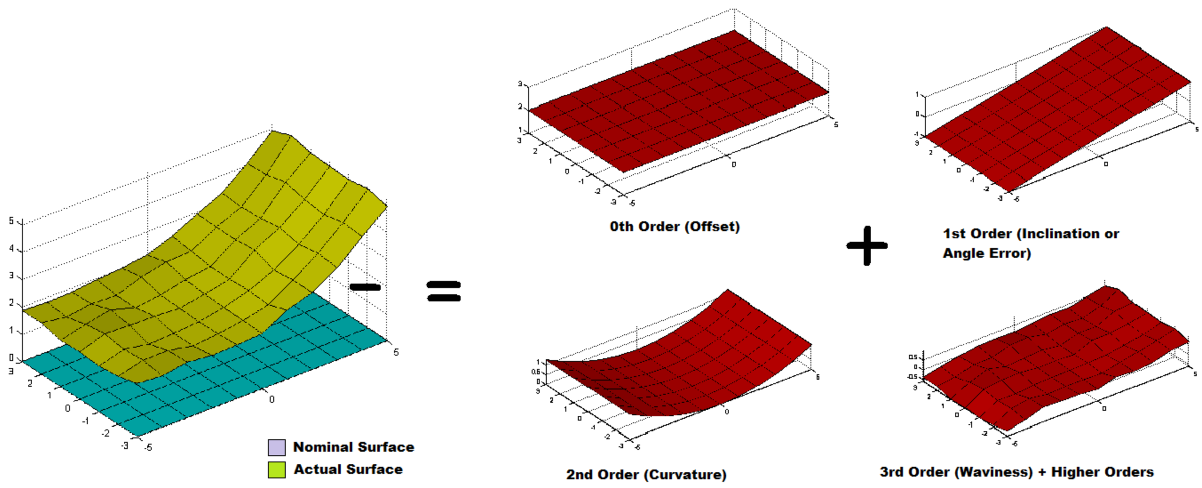

Figure 4 – Global forms and residuals from deviations separation

The separation and calculation of parameters of each order can be done by best-fit approximation and least square method by minimizing the sum of the squares of the residual deviations δi and the best-fit function s for each order. The objective function is given by:

$$f(\mathbf{x}) = \sum_{i=1}^{n} (\delta_i - s_i)^2$$

3.1: The 0th order form deviations

The 0th order form deviations have the meaning of an offset or in some cases can be described as a pitch error. The best-fit function for this order is given by:

$$s_0(x, y) = z_0$$

The deviations used are the current deviations between nominal and actual surfaces.

$$\delta_0 = \delta$$

3.2: The 1st order form deviations

The first order form deviations are considered as a plane which has the meaning of inclination of the global topography. The equation of a plane is given by:

$$Ax + By + Cz + D = 0$$

In this case the domain is considered as the set of pairs (x,y). Thus the best-fit function s for this order can be written as:

$$s_1(x, y) = z = ax + by + c$$

The deviations values used for the first order are the difference between the nominal deviations and the zero order form.

$$\delta_1 = \delta - s_0(x, y)$$

3.3: The 2nd order form deviations

The second order form deviations can be interpreted as the curvature and anisotropy of the global topography. The general form of a second order surface can be written as:

$$a_{11}x_1^2 + a_{22}x_2^2 + a_{33}x_3^2 + 2a_{12}x_1x_2 + 2a_{23}x_2x_3$$
$$+ 2a_{31}x_3x_1 + 2b_1x_1 + 2b_2x_2 + 2b_3x_3 + c = 0$$

or

$$\sum_{i,j=1}^{3} a_{ij}x_ix_j + 2\sum_{i=1}^{3} b_ix_i + c = 0 \quad (a_{ij} = a_{ji})$$

The second order surface can also be expressed in the matrix notation by:

$$s(\mathbf{x}) = \tilde{\mathbf{x}}^T\tilde{\mathbf{A}}\tilde{\mathbf{x}} = \langle \tilde{\mathbf{A}}\tilde{\mathbf{x}}, \tilde{\mathbf{x}} \rangle = 0$$

Where the matrix A and x are given by:

$$\tilde{\mathbf{A}} = \begin{pmatrix} \mathbf{A} & \mathbf{b} \\ \mathbf{b}^T & c \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} & b_1 \\ a_{21} & a_{22} & a_{23} & b_2 \\ a_{31} & a_{32} & a_{33} & b_3 \\ b_1 & b_2 & b_3 & c \end{pmatrix}, \qquad \tilde{\mathbf{x}} = \begin{pmatrix} \mathbf{x} \\ 1 \end{pmatrix} = \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ 1 \end{pmatrix}$$

The second order surfaces are the points that satisfy the equation S(x)=0 when rank(A)=0. Moreover, since the second order surface expressed as matrix notation is a quadratic form and A is a real symmetric matrix, it is possible to classify the surfaces in five forms as shown in figure 5.

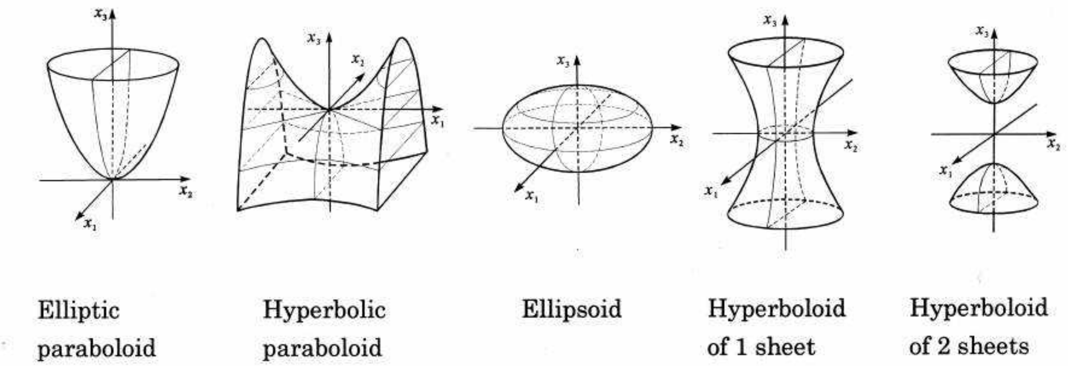

Figure 5 – Second order surfaces forms

These forms are, basically, described by the following equations:

Name	Equation
Ellipsoid	$X^2 + Y^2 + Z^2 = 1$
Hyperboloid of 1 sheet	$X^2 + Y^2 - Z^2 = 1$
Hyperboloid of 2 sheets	$-X^2 - Y^2 + Z^2 = 1$
Elliptic paraboloid	$X^2 + Y^2 = Z$
Hyperbolic paraboloid	$X^2 - Y^2 = Z$

This means that an arbitrary surface can be obtained from the proper forms by applying a suitable rotation R, parallel translation Q and scaling transformation S matrixes. Where the matrixes R, Q and S are given by:

$$\mathbf{S} = \begin{pmatrix} S_x & 0 & 0 & 0 \\ 0 & S_y & 0 & 0 \\ 0 & 0 & S_y & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad \mathbf{Q} = \begin{pmatrix} 1 & 0 & 0 & Q_x \\ 0 & 1 & 0 & Q_y \\ 0 & 0 & 1 & Q_z \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad R = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$$

Although there are five fundamental forms we can reduce them into two types: a paraboloid and an ellipsoid/hyperboloid function.

The paraboloid equation is given by:

$$z = x^2 \pm y^2$$

After applying the rotation, parallel translation and scaling transformation the equation can be written by:

$$s_2(x, y) = z = \frac{S_z}{S_x^2}[\cos\theta_z x + \sin\theta_z y - Q_x]^2 \pm \frac{S_z}{S_y^2}[-\sin\theta_z x + \cos\theta_z y - Q_y]^2 + Q_z$$

In the case of the hyperboloid/ellipsoid the equation is given by:

$$z^2 = 1 \pm x^2 \pm y^2$$

After the transformation the equation can be written by:

$$s_2(x,y) = z = \pm\sqrt{\begin{matrix} S_z^2 \pm \frac{S_z^2}{S_x^2}[\cos\theta_z x + \sin\theta_z y - Q_x]^2 \\ \pm\frac{S_z^2}{S_y^2}[-\sin\theta_z x + \cos\theta_z y - Q_y]^2 \end{matrix}} + Q_z$$

In this project the paraboloid function has been chosen as best-fit function for the second order. The paraboloid is enough to evaluate the curvature and the anisotropy of the second order. In addition, it has more stability and is more time saving, as long as it needs to calculate 6 parameters (instead of 7 as in the case ellipsoid/hyperboloid function). [2]

In contrast with the first and zero order, the second order form cannot be solved analytically. For a good approximation the quasi-Newton method can be used with initial values chosen so that:

$$p_1 \ll 1.0, \quad p_2 \ll 1.0$$
$$Q_x = \text{Xlength}/2, \quad Q_y = \text{Ylength}/2, \quad Q_z = 0.0$$

The deviations used for the best fit, in this case, are the difference between the nominal deviations and the sum of the zero order and first order form.

$$\delta_2 = \delta - s_0(x,y) - s_1(x,y)$$

Chapter 4: Deviations Separation Overview

In order to carry out the deviations separation two basic elements are required: a CAD mesh model of the nominal part, and a high density point cloud of the actual part. Both data should be aligned in order to proceed with the surfaces deviations calculation. After the actual and nominal data are aligned, a surface for inspection must be chosen by the user. The surface deviations are calculated using the surface and the aligned point cloud. Finally, the deviations can be separated using the mathematical derivations presented in chapter 2. This procedure is illustrated in figure 6.

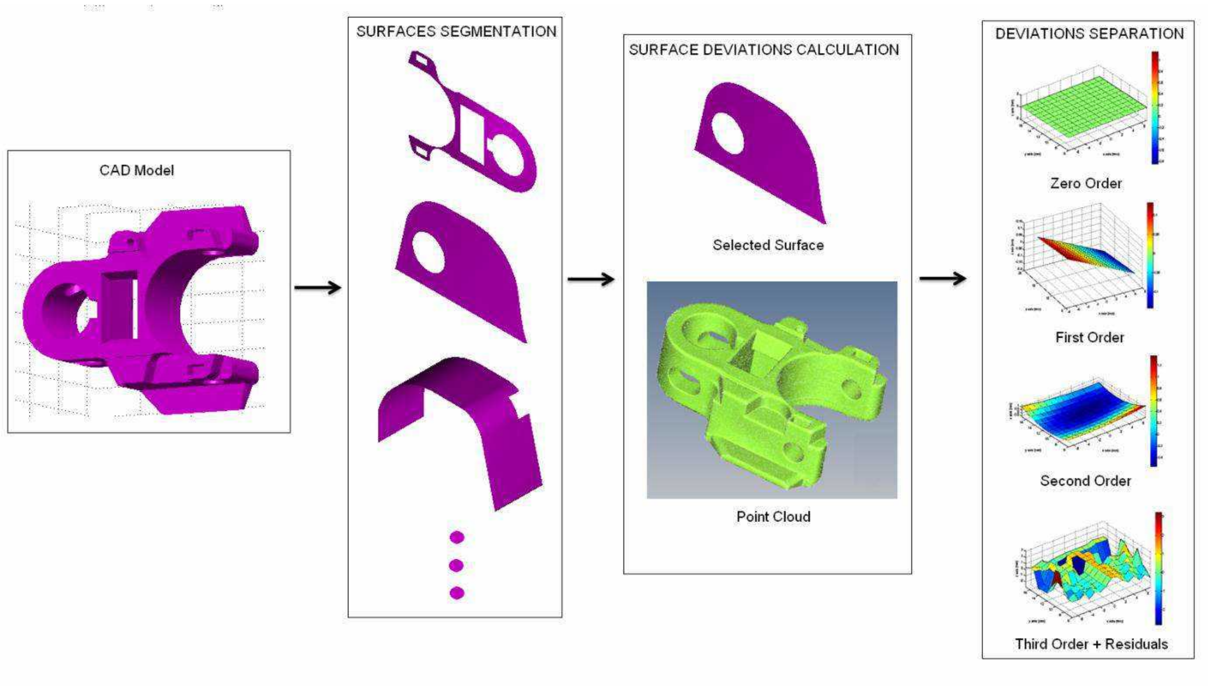

Figure 6 – Deviations Separation Procedure

4.1: Point Cloud Generation

The point cloud generation is the first step necessary for making the comparison. A high density point cloud is recommended in order to have good punctual deviations accuracy. A CT machine provided at WZL and developed by Zeiss was used for generate the voxel model of the part. Then, the measurement software Calypso was used to generate the point cloud. The basic procedure is illustrated in figure 7.

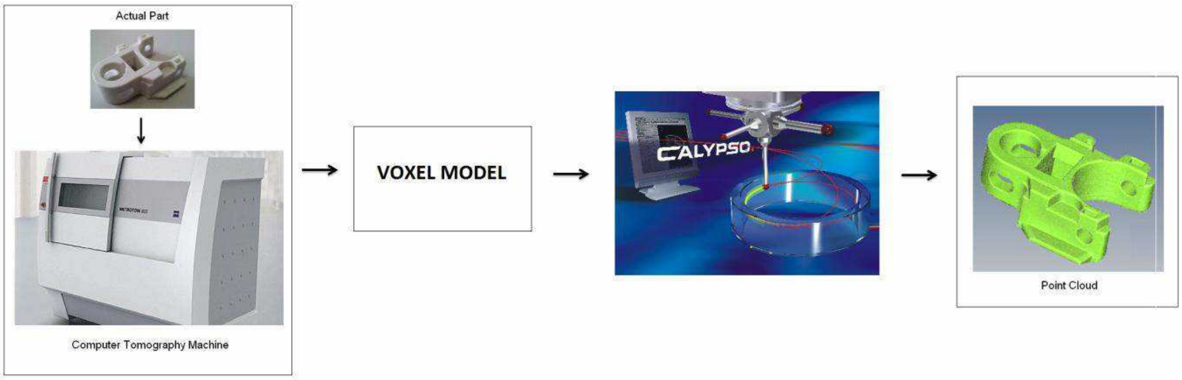

Figure 7 – Point Cloud Generation

4.2: Mesh Segmentation

Typically, a CAD mesh model can be conceived as a set of fundamental features. However, the data contained in it is generally a set of unorganized information (triangles, edges, points). Thus some methods to segmentate these information and extract meaningful surfaces from meshes were studied. Segmentation consists on the process of partioning data points into regions that can be approximated by standard CAD surfaces (e.g. planes, rounds, etc). There are several approaches formulated for the mesh segmentation problem. All of them have their computational advantages and drawbacks according to the application they are used. Nevertheless, it is important to keep in mind that the most important factor, in the segmentation result, is the condition that rules which elements belongs to a determined segment. [3]

The methods can be, basically, classified into five classes:

1. Region Growing
2. Hierarchical Clustering
3. Iterative Clustering
4. Spectral Analysis
5. Implicit Methods

4.2.1: Region Growing

In this approach the segments are generated by the expansion of seeds elements from a mesh (e.g. triangle, point). The region growing keeps expanding (clustering neighbors) until a termination criteria is reached. In the literature, this set of rules is called either termination or growing criteria [4]. The process finishes when all elements are clustered into some region. In figure 8 a sample region growing process is shown

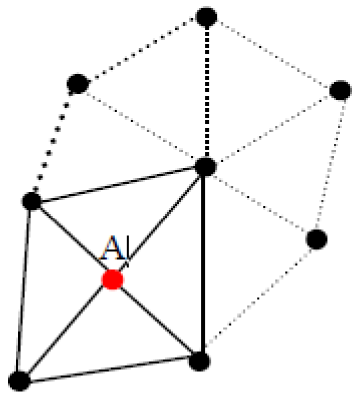

Figure 8 – Point A “grows” adding its neighbors until a termination criteria is reached [4]

4.2.2: Hierarchical Clustering

For some applications a hierarchical segmentation structure is beneficial [3]. The basic algorithm for hierarchical clustering can be defined as follows:

a) Define every point as cluster.
b) Find “most similar” pair of clusters.
c) Merge it into a single cluster.
d) Repeat until the whole data set has been merged into one cluster.

In figure 9 an example of hierarchical clustering is shown. In this case the “most similar” pair is defined as the closest pair.

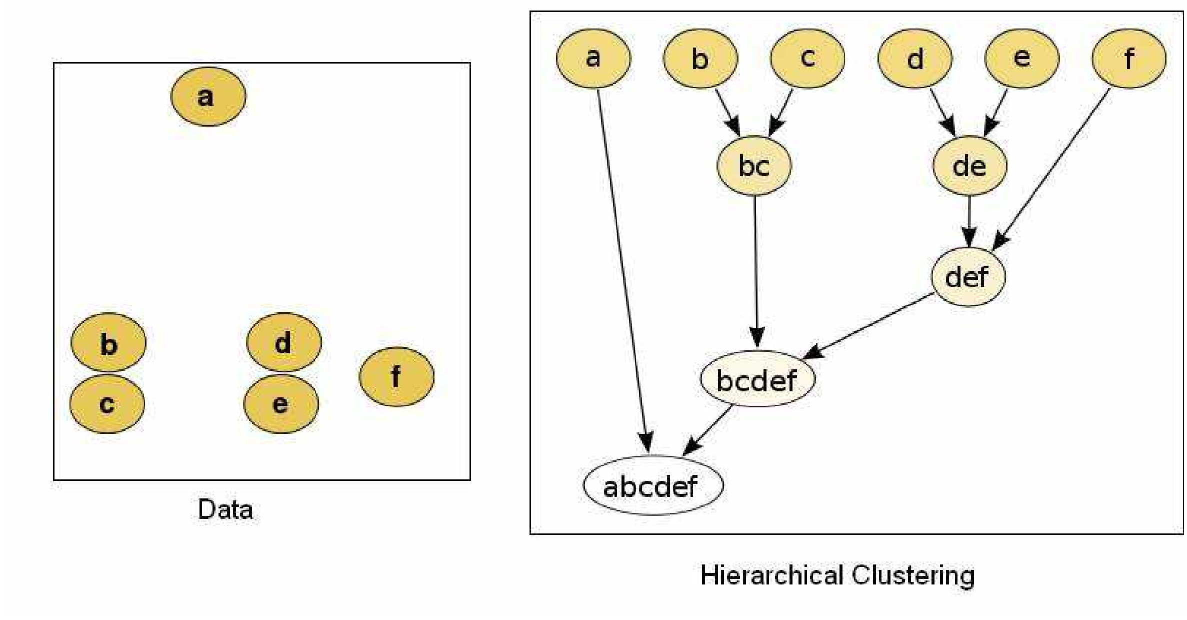

Figure 9 - Hierarchical Clustering

4.2.3: Iterative Clustering

In this algorithm the numbers of clusters needs to be assigned before processing the elements, different from the two algorithms described above in where the number of clusters is only knew at the end of processing. Thus this algorithm can be formulated as a problem of finding the best segmentation for a given numbers of clusters. The algorithm starts basically, initializing a number k of clusters and k-representatives elements for each cluster. Subsequently, all elements are assigned to a specific cluster depending on its representative. Then the cluster representatives are recalculated and the process starts again. The algorithm stops when the representatives do not change anymore. The evaluation of best representatives of each cluster should be chosen with care, so that the process can converge.

4.2.4: Spectral Analysis

In the spectral analysis segmentation method, an affinity matrix W is constructed with elements $w_{i,j}$ which represent the likehood that faces i and j can be clustered in the same segmentation area. From this matrix W, a matrix V can be constructed using the largest eigenvectors of the normalized affinity matrix Wn as columns. Then the row vectors of V are used for an iterative clustering using the standard Euclidean space. One of the disadvantages of this method is that the separation is based, basically, in concavity which may lead to low quality segmentation areas.

4.2.5: Implicit Methods

In these methods, instead of directly partition the elements of a mesh, the boundaries between segments areas are extracted. More specifically, these methods extract the feature contours based on the minimum negative curvature and convert them into closed contours, by finding the shortest path in the mesh to close the contour. Others use a different structure or object such a skeleton to partition the mesh. Then, the segmentation is said to be implicit. The method is illustrated in figure 10.

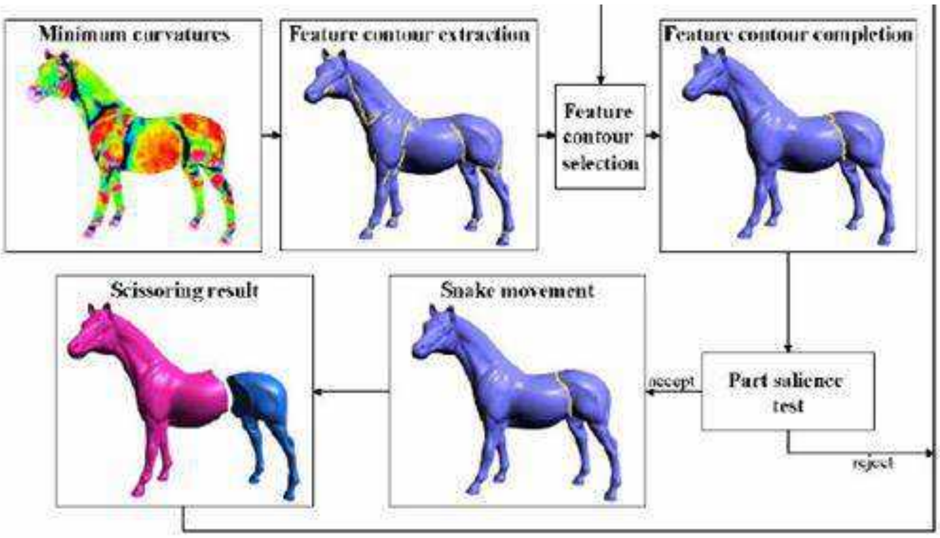

Figure 10 – Implicit Segmentation Method [4]

4.3: Surface Deviations Calculation

The deviations need to be calculated at each point of the selected surface at the normal direction of it. The mesh surface deviations are usually represented in a scale of colors as shown in figure 11.

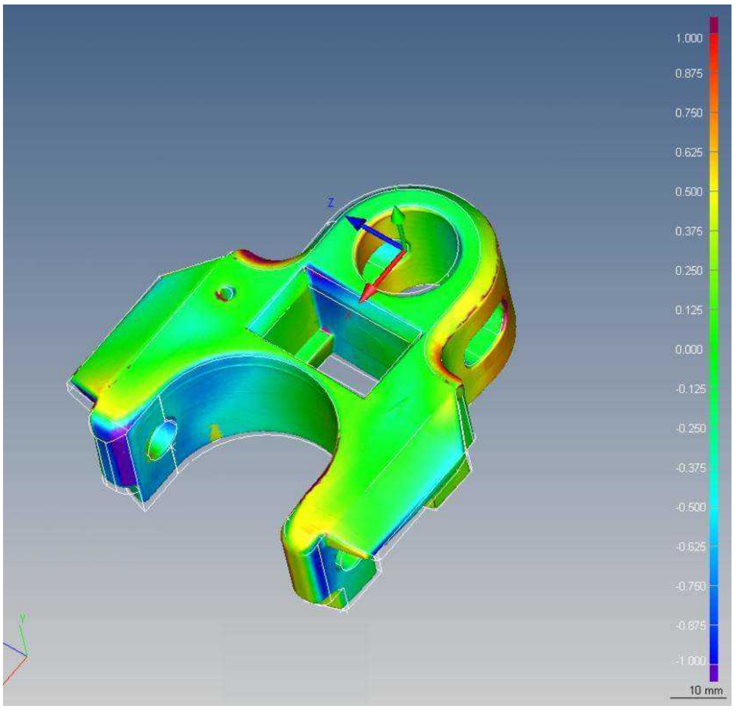

Figure 11 – Color representation for deviations obtained through the software Calypso

Chapter 5: Software Implementation

For the automatic separation of surface deviations a software has been developed in the context of this project. The software was created in a MATLAB environment. In this chapter the main block functions implementation and some aspects of the software will be discussed. Basically, the software can be divided in:

a) User Interface
b) Mesh Segmentation
c) Best-Fit
d) Deviations Calculation
e) Deviations Separation
f) Results Visualization

The connection between the block functions and the I/O can be visualized in the software schematic illustrated in figure 12.

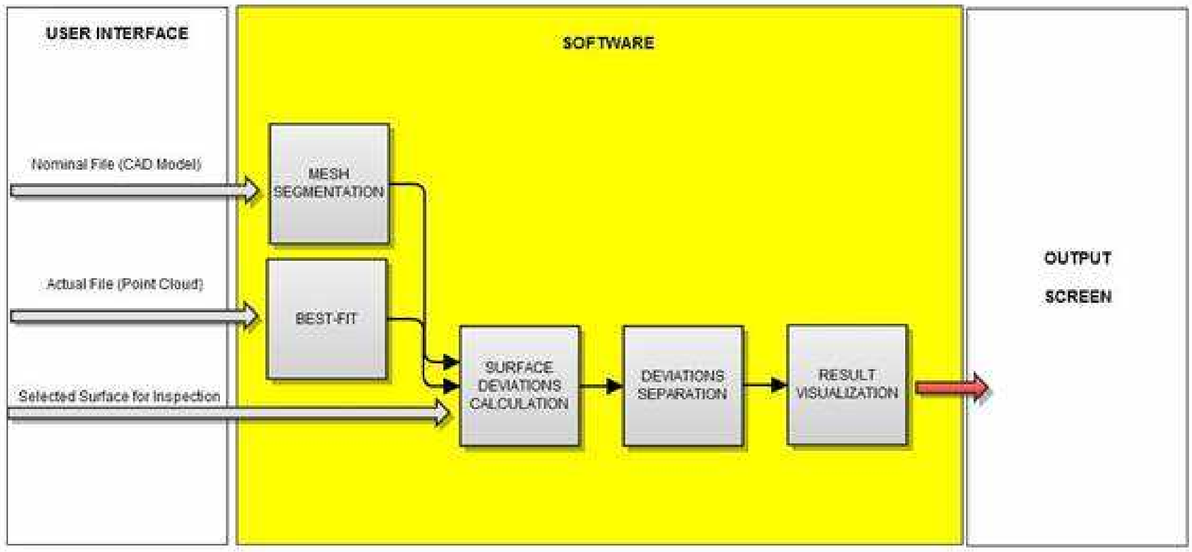

Figure 12 – Software main block functions schematic

5.1: User Interface

The user interface is charged for the communication between the user and the software itself. In figure 13 it is possible to visualize the interface developed in the current project.

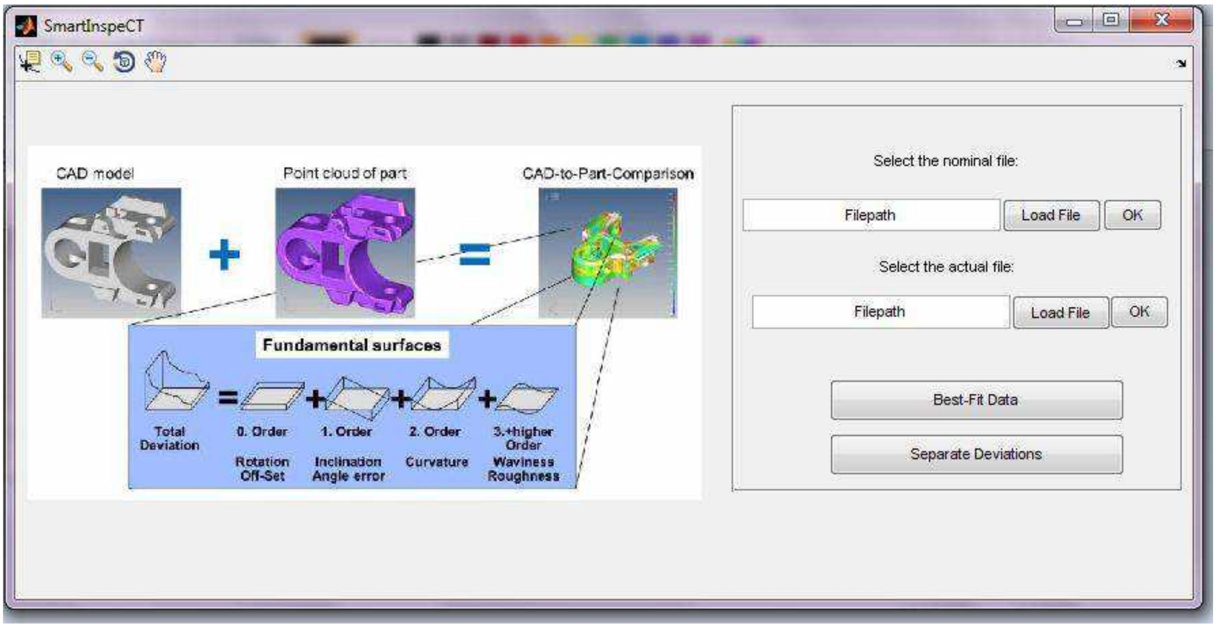

Figure 13 – User Interface

Indeed, it is very simple and intuitive. It basically, allows the user to select a nominal file (CAD model) and an actual file (point cloud). These data can be best-fitted, if needed, using the "Best-Fit Data" button. After the nominal file is loaded the user can select a surface from the current model for the separation by clicking with the data cursor in the desired surface. Every time the data cursor gets a new position, a software interruption is generated. The interruption handle calculates the closest surface from the data cursor position and highlights it. The surface selection is illustrated in figure 14.

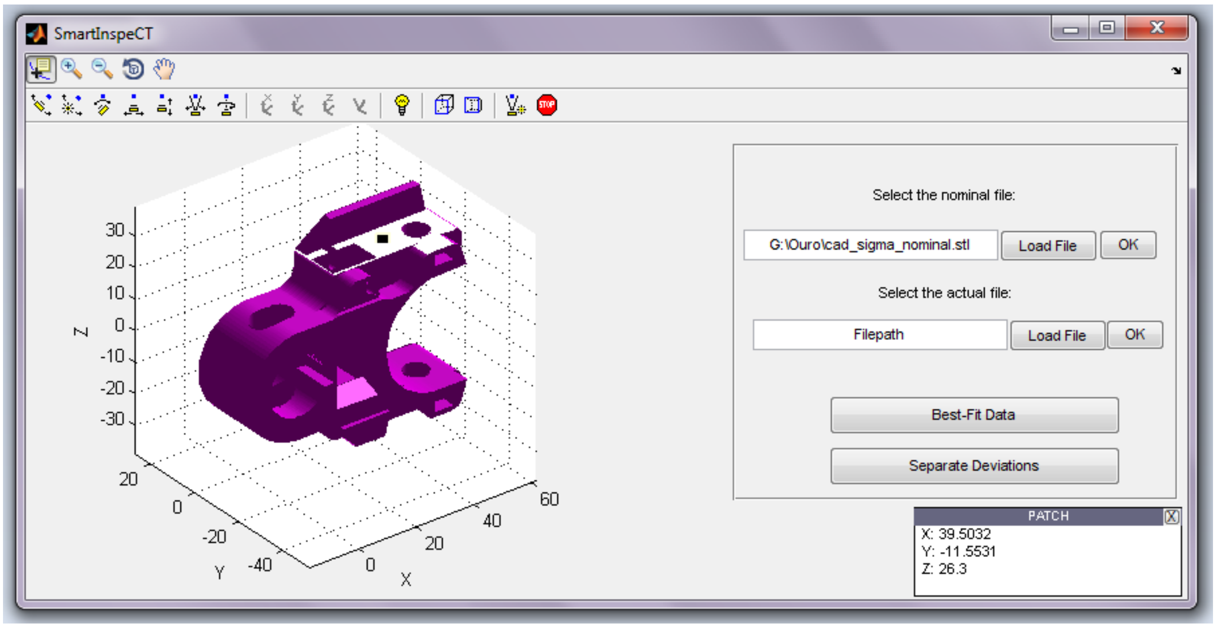

Figure 14 – Surface Selection

The CAD model filetype used for this application is a standard STL (stereolitography) ASCII file which is supported in many CAD softwares. The STL file contains unstructured information (vertices and normals of triangles) from the model in the form of triangulations. The triangles information in an ASCII STL file is presented as follows:

```
facet normal ni nj nk
outer loop
vertex v1x v1y v1z
vertex v2x v2y v2z
vertex v3x v3y v3z
endloop
endfacet
```

On the other hand, the point cloud contains the actual points in the xyz coordinates obtained from the measurement of the real part. This information can be introduced to the software using three different formats: STL ASCII file (.stl), text file (.txt) and spreadsheet file (.xlsx).

5.2: Mesh Segmentation

As discussed in section 3.2, the surfaces segmentation provides a more meaningful inspection and is also required for the deviations separation. In order to carry out the segmentation a region growing algorithm with a pre- and post-processing was developed. The region growing method was chosen due to its easy implementation and high efficiency. The procedure schematic can be visualized in figure 15.

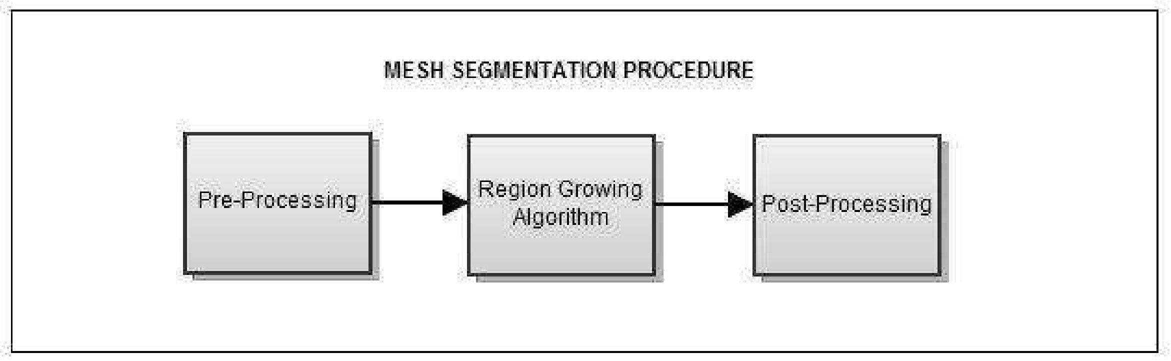

Figure 15 – Mesh segmentation procedure

5.2.1: Pre-Processing

The pre-processing consists in the neighbors calculation for each triangle of the nominal file. The neighbors of a triangle are considered, in this case, as triangles that share at least one point with the triangle in consideration and that do not have discontinuity in their normals.

5.2.2: Region Growing Algorithm

A region growing algorithm for the mesh segmentation was implemented in this project. The algorithm segmentates surfaces with continuity in their normal. All triangles of the nominal model are placed to a specific feature k during the algorithm processing. The algorithm flowchart is shown in figure 16.

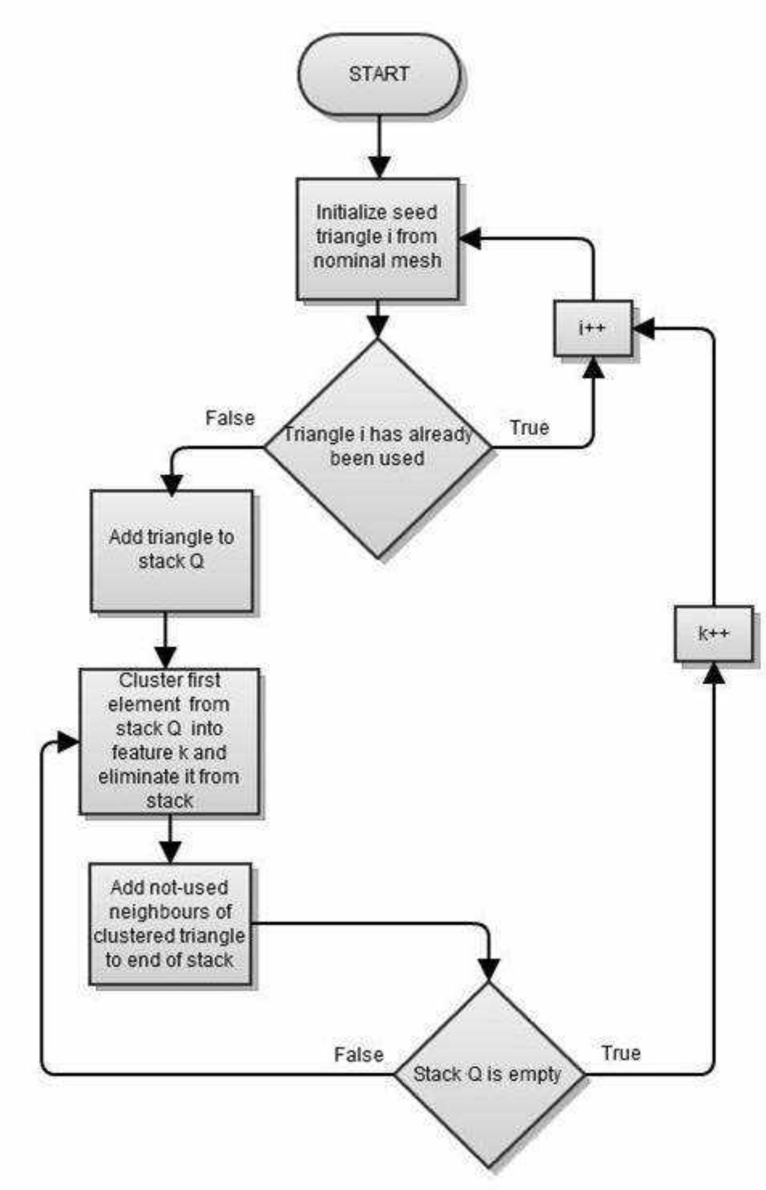

Figure 16 – Region Growing Algorithm Flowchart

5.2.3: Post-Processing

After the region growing algorithm is finished, some features may still need to be prepared to the deviations separation or segmented into more meaningful surfaces. Two filters were implemented for this purpose. The first filter separates plans from rounds from features composed from both. The second filter segmentates surfaces that cannot be expressed as a combination of 0^{th}, 1st, and 2^{nd} order surfaces in order to be able to proceed with the deviations separation

5.2.3.1: **Filter Plan-Round**

Surfaces composed by a plan and a round are considered as a unique surface by the region growing algorithm since they have continuity in their normals. In order to separate plans from rounds a filter was implemented. The filter, basically, checks the surface orientation and filters the elements that present their orientation (normal vector) in a specific direction. It is convenient to observe that this algorithm does not work with the relatives normal directions between neighbors triangles but, instead, with the nominal direction of vectors.

5.2.3.2: **Filter Surface-to-Function**

In order to proceed with the separation, a domain should be selected for the best fit functions. However, for some surfaces extracted by the region growing algorithm, it is not possible to select a domain taking into account that each element of the domain should have no more than one image. In order to represent this problem lets considerate a sample cylinder extracted by the region growing algorithm. A domain should be selected for the best fit function. In this case we will choose the domain as the set of pairs from the xy coordinates. Nevertheless, each pair from the domain is associated with two elements of z. Therefore, the cylinder must be divided in two semi-cylinders. The filter algorithm is very simple. It gets the domain of the function and divides the surface according to the normals signal. The surface elements with positive normal component along the orthogonal vector of the domain basis vectors are set as part of one surface and those with negative normal component are set as part of a second surface.

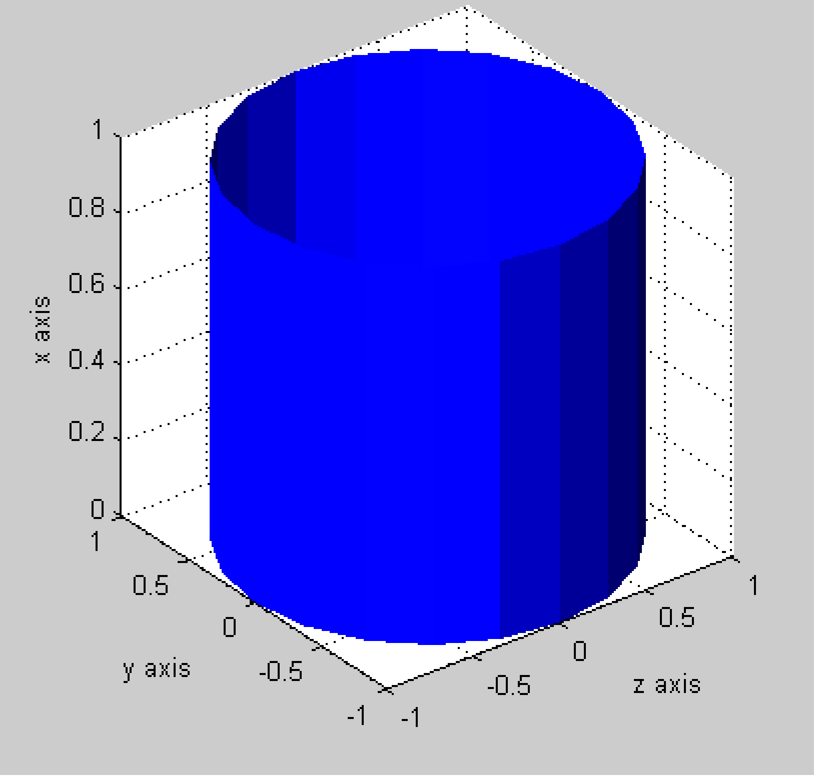

Figure 17 – Sample Cylinder

5.3: Best-Fit Algorithm

The best-fit is used to align the point cloud generated through the CT machine and the model. A widely-used and well-studied algorithm proposed in [7] was chosen for the best-fit. This algorithm starts with two data sets and an initial estimate of the aligning rigid-body transform. It then iteratively refines the transform by alternately choosing corresponding points in the meshes and finding the best translation and rotation that minimizes an error metric based on the distance between them [8]. The algorithm main advantages are, basically, easy implementation, good convergence speed and good results [9]. Although it is important to highlight that the quality of alignment obtained by this algorithm depends heavily on choosing good pairs of corresponding points in the two data sets [8].

The algorithm procedure can be basically synthetized as follows:

1. Create a pairing between point sets where closest points are matched.

2. Calculate the optimal rotation and translation transformations.

3. Apply the transformation to the data and compute the mean distance between point sets.

4. If change in mean distance has not decreased below a given threshold or the number of iterations has reached a maximum value terminate.

In order to establish pairs between data sets a point-to-point matching is used. In this kind of matching a sample point in the point cloud is matched to the closest point from the model in Euclidean space.

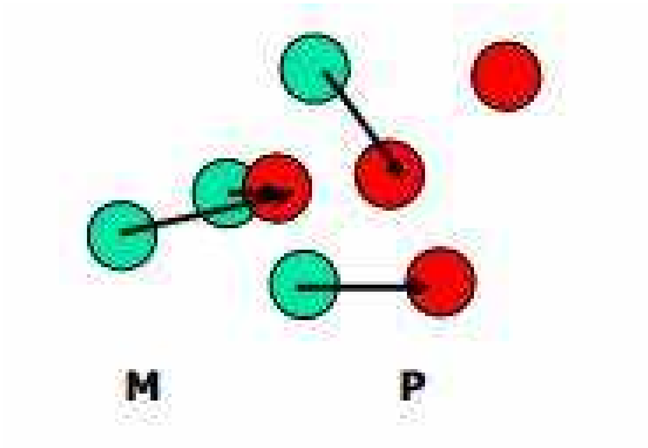

Figure 18 – Closest Point Matching

A nearest neighbor search (NNS) was used to calculate the matches of each point taking advantage of the nearestNeighbor function provided by MATLAB. The nearest neighbor searching can be described as the following problem: we are given a set S of n data points in a metric space, X, and the task is to preprocess these points so that, given any query point q ∈ X, the data point nearest to q can be reported quickly. [8].

After the points matching have been completed by the nearest neighbor algorithm the rotation and translation transformations matrixes should be calculated. The translation transformation matrix is given by:

$$T_{\mathbf{v}} = \begin{bmatrix} 1 & 0 & 0 & v_x \\ 0 & 1 & 0 & v_y \\ 0 & 0 & 1 & v_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The translation matrix multiplication with a point with coordinates p_x,p_y,p_z is shown below:

$$T_{\mathbf{v}}\mathbf{p} = \begin{bmatrix} 1 & 0 & 0 & v_x \\ 0 & 1 & 0 & v_y \\ 0 & 0 & 1 & v_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} p_x \\ p_y \\ p_z \\ 1 \end{bmatrix} = \begin{bmatrix} p_x + v_x \\ p_y + v_y \\ p_z + v_z \\ 1 \end{bmatrix} = \mathbf{p} + \mathbf{v}$$

Where v_x,v_y,v_z are the translation values in each coordinate, The rotation matrixes about the x,y,z axis are given as follows:

$$R_x(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix}$$

$$R_y(\theta) = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix}$$

$$R_z(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

A general rotation can be conceived as a multiplication of the three matrixes which, in turn, can be written as follows.

$$R_z(\psi)\,R_y(\theta)\,R_x(\phi) = \begin{bmatrix} \cos\theta\cos\psi & -\cos\phi\sin\psi + \sin\phi\sin\theta\cos\psi & \sin\phi\sin\psi + \cos\phi\sin\theta\cos\psi \\ \cos\theta\sin\psi & \cos\phi\cos\psi + \sin\phi\sin\theta\sin\psi & -\sin\phi\cos\psi + \cos\phi\sin\theta\sin\psi \\ -\sin\theta & \sin\phi\cos\theta & \cos\phi\cos\theta \end{bmatrix}$$

Therefore, the objective function that should be minimized can be written as:

$$f(R,t) = \frac{1}{N}\sum_{i=1}^{N} \|p_i - R(p_i) - t\|$$

Where R is the general rotation matrix, t is the translation vector with components v_x,v_y,v_z, and p_i are the point cloud points. As a result, a non-linear 6 DOF system need to be solved. In order to make this calculation the the *lsqcurvefit* function from the Matlab optimization toolbox was used. This function can solve curve-fitting (data-fitting) problems in least-squares sense [5]. It basically finds coefficients x that best fit the equation:

$$\min_{x} \|F(x, xdata) - ydata\|_2^2 = \min_{x} \sum_{i} \left(F(x_i, xdata_i) - ydata_i \right)^2$$

The xdata, ydata and F are considered in this case, respectively, as the point cloud points, the matching points from model and the objective function.

After obtaining the matrixes parameters the transformation can be carried out. This procedure is repeated iteratively until the mean values differences between two iterations have reached to a threshold value or a maximum number of iterations have been reached. This iterative procedure is illustrated in figure 19.

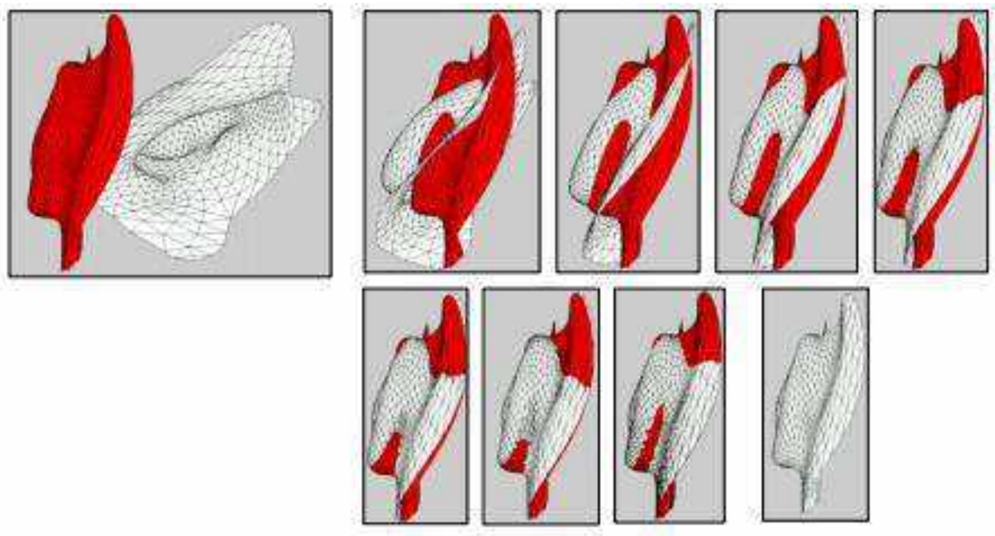

Figure 19 – Sample use of the ICP algorithm

The convergence of this method is proved in [7].

5.4: Deviations Calculation

The deviations are calculated at each point of the nominal surface by computing, through a nearest neighbor method, the norm of the vector that connect the point in consideration and its closest point at the point cloud and calculating, sequentially, the projection of it at the normal direction of the point. Therefore, a normal approximation of the nominal surface points was required. In addition, in order to have an accurate separation result, a good amount of sampling points from the nominal surface with their respective deviation is required. For this purpose, a surface enrichment process was implemented.

5.4.1: Surface Enrichment

The surface enrichment consists on adding points (creating more triangulations in the mesh) to the current surface in order to increase the density of information of it. The enrichment process of a single triangle can be visualized in figure 20.

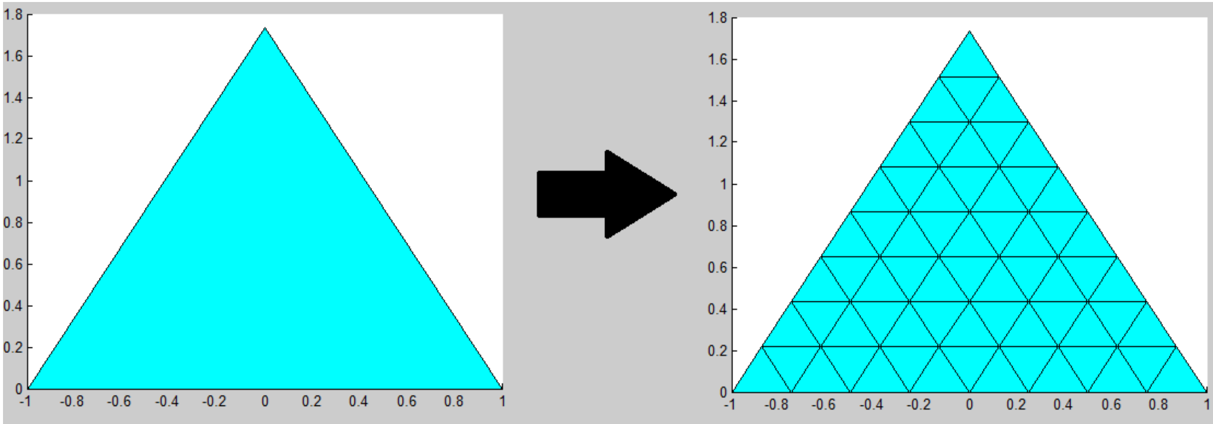

Figure 20 – Surface Enrichment Example

5.4.2: Vertex Normals Approximation

There are a few methods in the literature for approximating the vertexes normals. The most common method, which has been implemented in this project, consist in sum the normals of the triangles that share the vertex and then normalize the sum to produce the vertex normal. [6]

5.5: Deviations Separation

After all punctual deviations were calculated, the deviations separation can be proceeded. The *lsqcurvefit* function, described in section 5.3, from the Matlab optimization toolbox was used for the calculation.

The xdata is considered, in this case, as a set of 2D points of the current surface depending on its orientation and can be conceived as the domain from the best fit function. The ydata is the normal order deviation at each point. The function F is the best-fit function and x_i are the best fit parameters values. The best fit function of each order was derived in chapter 2.

5.6: Results Visualization

The visualization screen can be divided, basically, in four frames as it can be seen in figure 21. Each ax has a “new window” button whereby the user can open it in a separate figure and analyze it more carefully with more resources. In the first frame, the nominal surface selected by the user and the actual surface extracted from the point cloud can be visualized together. This is an important part in which the user can directly visualize the difference between surfaces, although there is not any deviations separation. Frame 2 shows the best fit functions surfaces using the parameters obtained, so that the user can visualize the form of the surfaces generated. All parameters values can be visualized in frame 3 with their correspondent measurement unity. In addition, the RMS values of each order are given. The RMS value of each order gives a practical notion about the relevance of the order form in the total deviations. Finally, in frame 4, is shown a direct comparison between the nominal surface and the nominal surface plus the deviation form and also between the nominal and the residuals of the correspondent order.

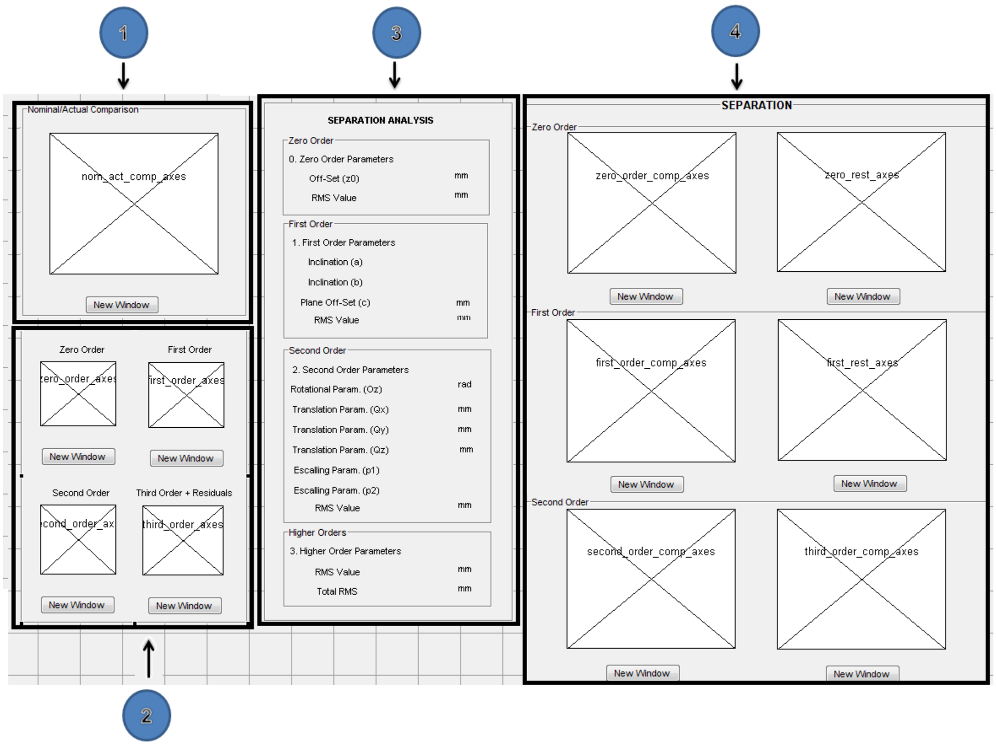

Figure 21 – Results Screen

Chapter 6: Results Discussion

A work piece from real industry provided by WZL was inspected through the software developed. The work piece selected for inspection is called “Sigma 3D” and can be visualized in figure 22. The piece was selected taking in account its complex geometry and its suitable dimensions.

Figure 22 – Sample Work piece

Firstly, the work piece was measured using a CT machine and the software Calypso was used to generate the point cloud. Then, the point cloud obtained and the CAD model were loaded and best-fitted using the software developed. Two arbitrary surfaces were chosen for the deviations separation. The surfaces chosen for the results discussion can be seen in figure 23.

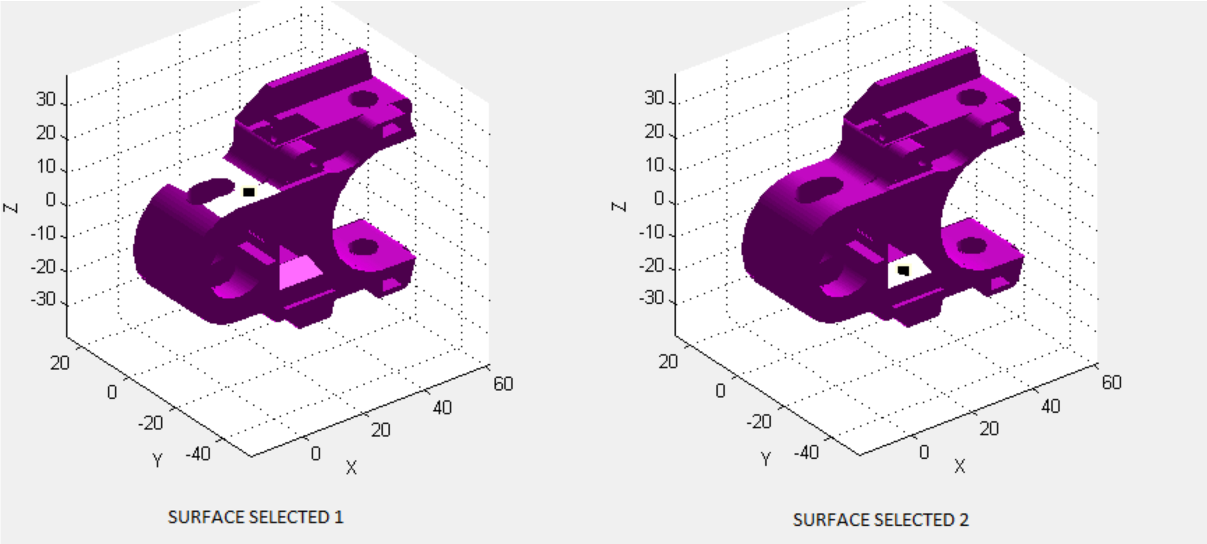

Figure 23 – Sample Surfaces

The results screen for the first surface selected is shown in figure 24.

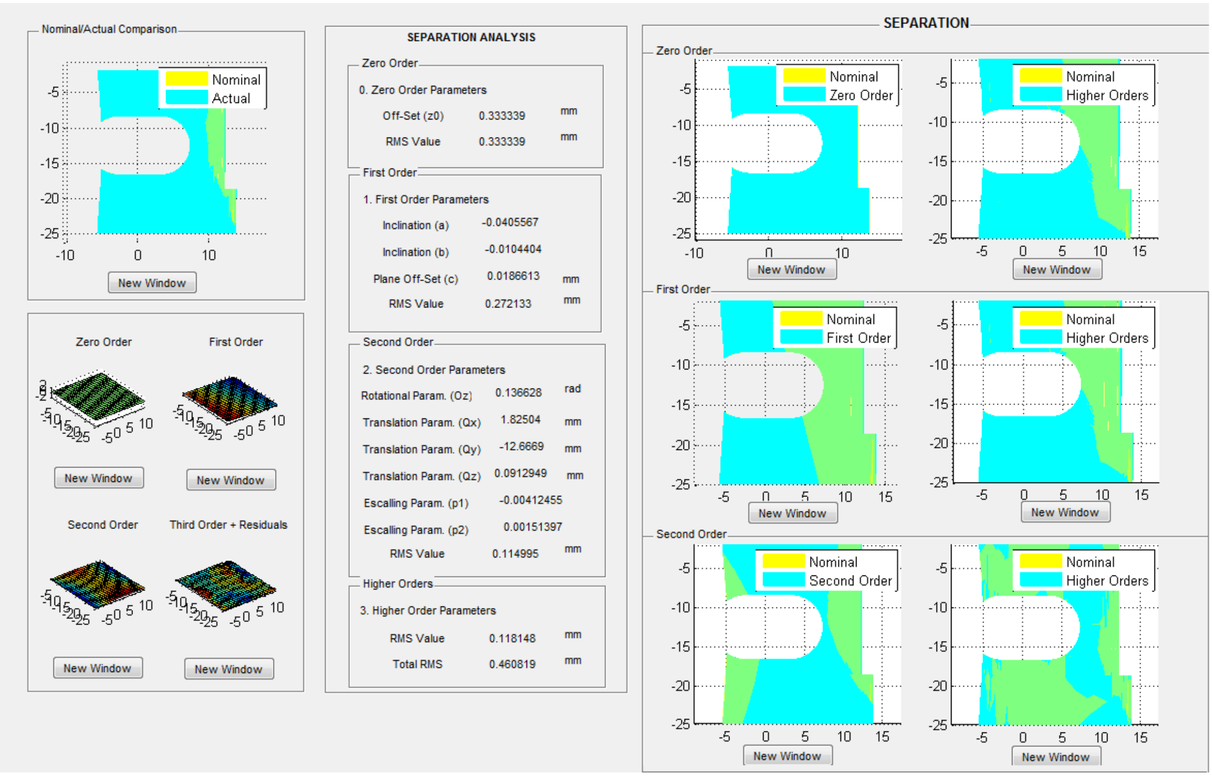

Figure 24 – Separation results for the first surface selected

From the RMS values of each order it is possible to state that the zero order form, which has the meaning of an off-set, is the most relevant deviation form in the total deviations. The first (inclination deviation), second (curvature deviation) and residual orders forms have a moderate relevance in the total deviations. A high relevant residual order is not desired since it is more difficult to assign these deviations to a cause and thus eliminate it from the total deviations. The difficulty relies on the fact that the CT resolution is not enough for evaluate higher orders. It is convenient to observe that the causes of each deviation form should be studied more carefully after the inspection and it is not the aim of the project to figure them out.

Using the “new window” resource, the deviations forms indirect representation can be observed deeper. All order forms have been put together into figure 25 for visualization reasons.

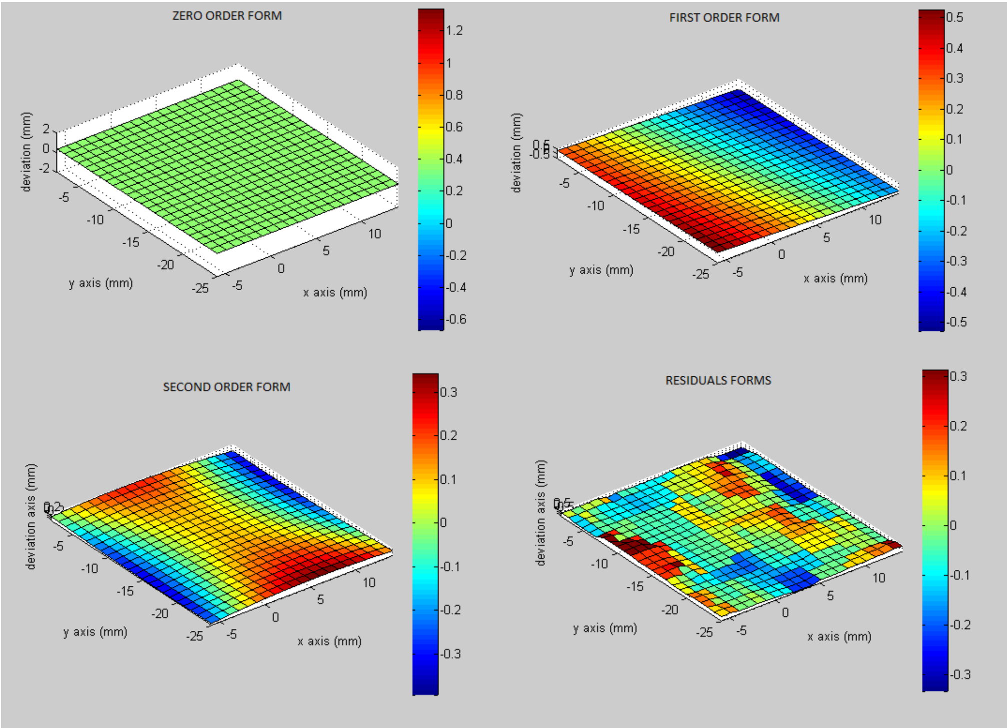

Figure 25 – Global Form Deviations

A color bar is used to indicate, in each form, the deviations values. The global forms direct representation can be also visualized in figure 26.

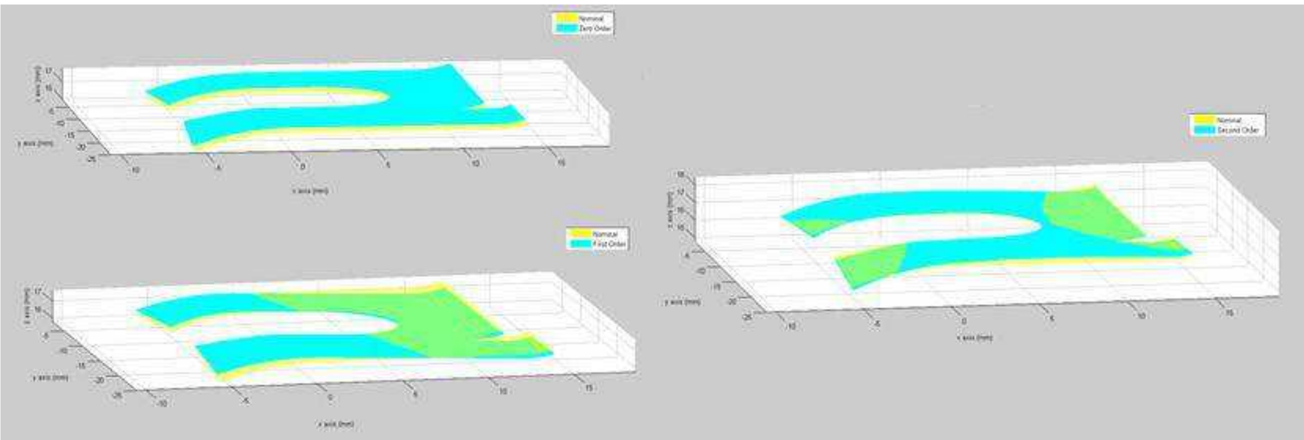

Figure 26 – Global forms directly applied to the nominal surface

The results of the second surface selected are shown in figure 27.

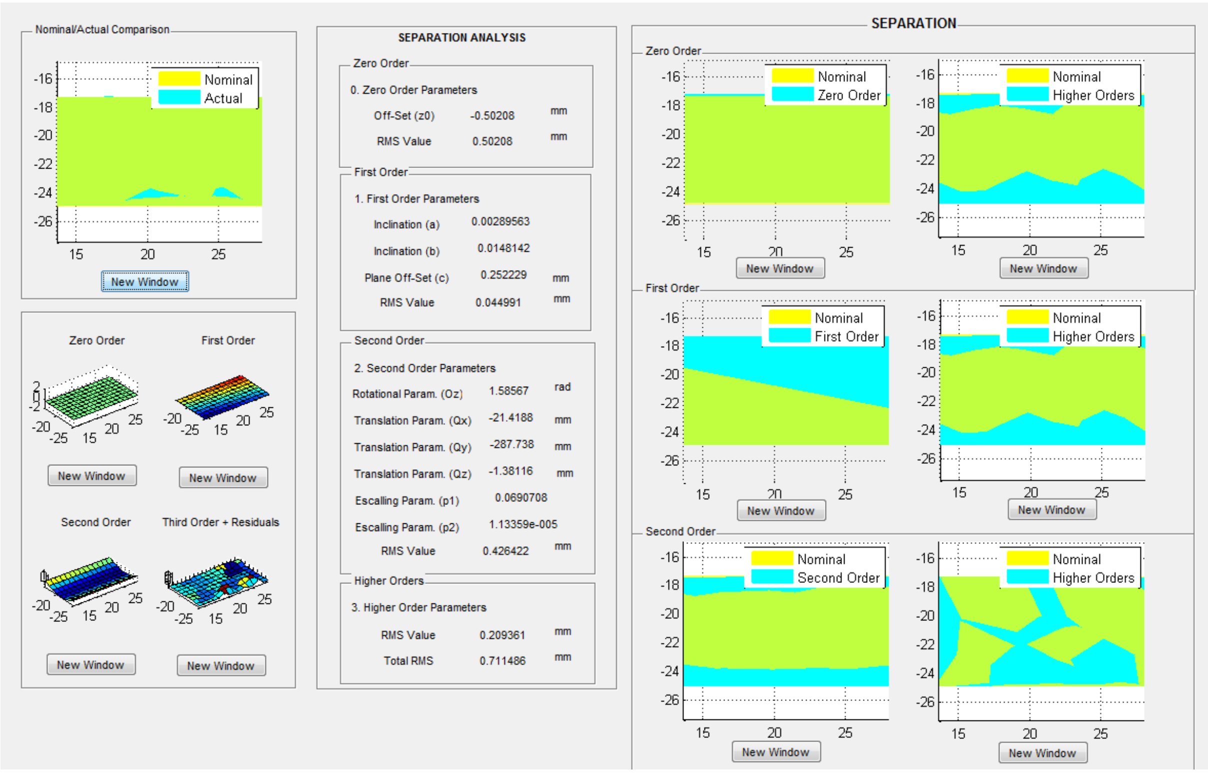

Figure 27 – Separation results for the second surface selected

The parameters obtained indicate that the zero and second order deviations forms are the most relevant in the present surface. The zero order mentioned before correspond to an off-set between the actual and nominal surface. Whereas, the second order indicates that the actual curvature does not strictly follow the nominal curvature. The surface inclination seems to be correct since the first order form has a very low relevance. In addition, the residuals orders have a moderate relevance in the global deviations for this surface.

The global forms indirect representation using the “new window” resource can be visualized in figure 28.

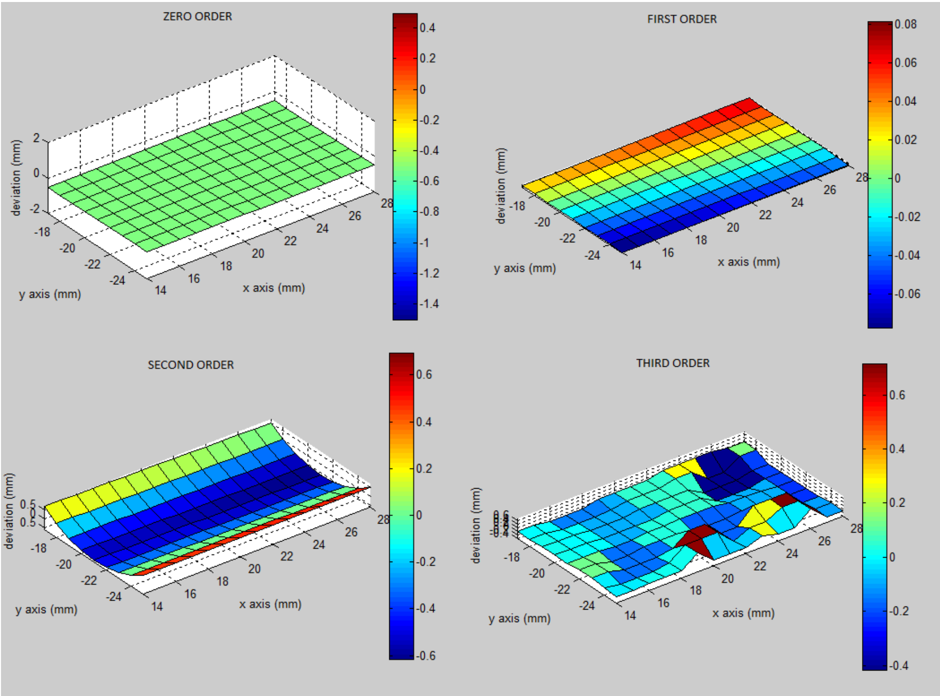

Figure 28 – Global Form Deviations

The direct representation is also shown in figure 29.

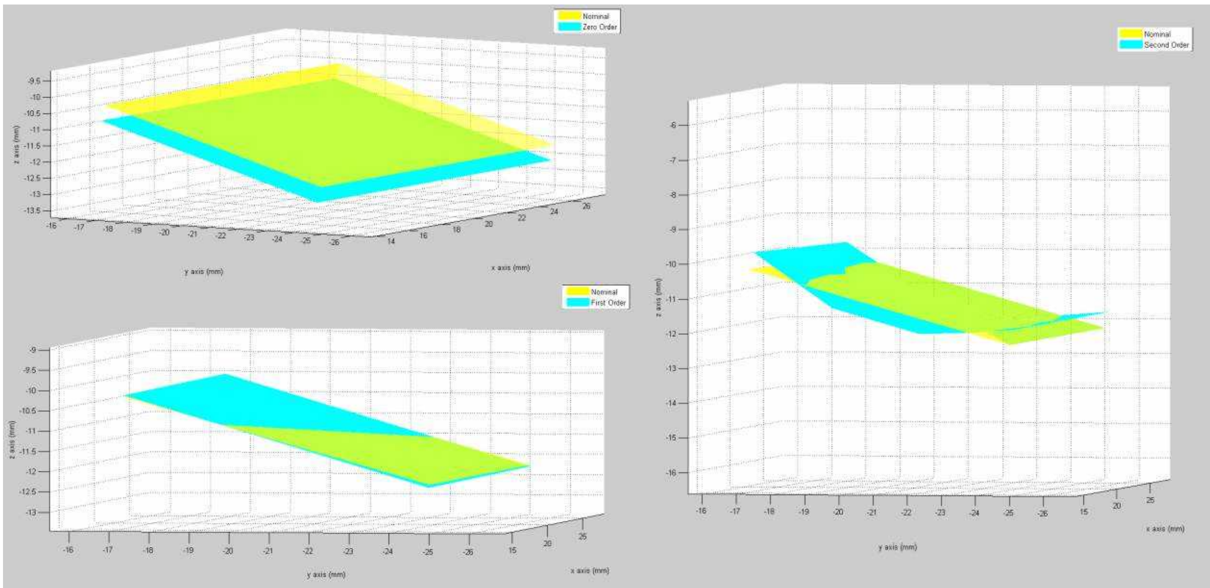

Figure 29 – Direct Representation

Chapter 7: Conclusions

Through this project a software for surface deviations evaluation and separation was achieved. The deviations separation is a novel approach in which the deviations are separated in different orders of geometric deviations. With the parameters obtained for each order it is possible figure out their causes more easily and adapt them specifically to the tool correction. Another feature of the software is regarding the time needed for inspection. After extracting data from the real part, which is the most time-demanding inspection step, any surface can be analyzed in a few seconds. In addition, a non-destructive CT based measurement was proposed for obtaining data from the real part. The CT measurement provides a high density and accurate information which is very suitable for surface deviations analysis. Currently, the most part of inspection methods are destructive which means that they change some property of the part during the measurement process introducing thus some systematic errors and are generally very time consuming.

Therefore, the current work may represent a good advance in injection molded parts inspection as long as it can provide a fast, meaningful and accurate feedback which may severally reduce the iterations needed for tool correction.

Chapter 8: Future Work

For the future, new algorithms for the mesh segmentation can be tested in order to increase the calculation performance. New methods for calculating deviations between the nominal and actual parts can be searched in order to increase the accuracy of results. In addition, new resources can be introduced to the current software such as a Region of Interest (ROI) analysis in which the user, instead of selecting a surface, can draw a closed region on the part for inspection. Finally, the relation between the derived parameters and the setting of machine tools can be investigated in order to automate the tool correction feedback.

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