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From point cloud to finite element model

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Reverse engineering of free form shell structures; From point cloud to finite element model

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Many free form shell structures that have been designed and build in previous decades are fascinating structures. We can learn from these structures by analysing them and studying their structural behaviour. However, in some cases the geometry of these structures is not available; most notably the shapes of shell structures designed and build by Heinz Isler, who has built over 1400 shells. The geometry of many of his scale models and build structures have been obtained by the authors by making use of 3D laser scanners which create point clouds.

This paper presents a method for reverse engineering of free form shell structures from point cloud to finite element model. Since shape and force interact, special attention is given to the geometric accuracy. Every model must be sufficiently accurate. The method has been applied to data obtained by scanning Isler's shells. Important aspects that influence the quality of the resulting finite element model are described.

Key words: Reverse engineering, shell structures, point cloud, finite element analysis, mesh

1   Introduction

Early examples of reverse engineering can be found in the eighties in the car manufacturing industry and the military [1]. The goal, to recreate or understand the original form, fit, function or operation, can for example be applied to overcome defects or recreating objects of any kind of hardware. Recently, within the field of building engineering developments are made in automated as-built documentation using laser scanners [2, 3]. The authors undertook the challenge of reverse engineering a special type of structure. Namely, free form shell structures. The purpose was to perform structural analysis of structures of which the geometry was unknown until now. Previously the

geometry was only known qualitatively. This paper presents the applied method within a process from scanning until running the finite element models. The models for which this was applied are special and well known. They have been designed and engineered by Heinz Isler, a famous shell builder. No exact geometry was made available by Isler. The authors have made 3D scans of many of Heinz Isler's models and structures. Thus, the accurate geometry became available. One example is the Swimming pool in Heimberg in Figure 1.

Figure 1: Swimming pool in Heimberg designed and engineered by Heinz Isler

Both free form and mathematical shapes can be modelled using Non Uniform Rational B-Spline (NURBS) surfaces. NURBS surfaces make use of control points which have specific locations to describe shapes. They distinguish themselves from B-Splines (which consist of Bezier curves) by having weighted values for control points. The NURBS surfaces and B-Splines provide tools to model free form structures intuitively. Figure 2 shows an example of a free form surface and its control points. More on NURBS can be found in [4]. Finding the amount of required control points and their suitable locations is key to reverse engineering of point clouds.

The quality of the final model is influenced during every step in the process. These are roughly the following; (1) scanning of the geometry, (2) processing the point clouds, (3) fitting a suitable NURBS surface and (4) making a mesh suitable for Finite Element Analysis. Within the process the engineer is required to make choices and therefore it is required to understand the influences on the final result. This raises a question for each step of the method; how do steps within the reverse engineering method influence the quality of the final model? In this paper this question will be addressed for each step and a method will be presented which takes these aspects into account.
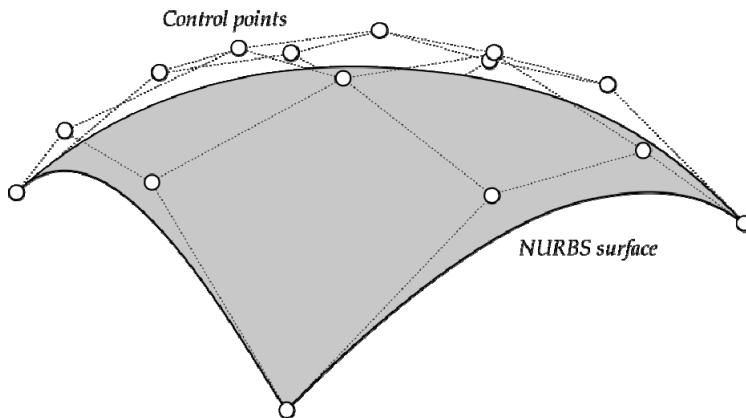

Figure 2: Example of NURBS surface and control points

2   3D scanning of free form shell structures

The method starts with choosing a measuring device. 3D laser scanners have developed quickly over the last years and have become more easily accessible since their prices have lowered. 3D laser scanners have become easy to transport, easy in use and make fast accurate measurements.

In 2011 the authors have been scanning small scale models and larger build shell structures using FARO laser scanning equipment [5]. Two different models of scanners have been used since then. The first scanner was the FARO Photon 120 and the second scanner was the FARO Focus 3D X130. The latter scanner is less than half the size and weight of the first. Figure 3 shows the two models of the scanners that were used (not on relative scale). The specifications according to the manufacturer of the scanner are shown in Table 1. Different types and brands of scanners are suitable. Usually the results of the scans are

point clouds. A number of aspects influence the accuracy of the resulting point cloud; (1) position of the scanner, (2) the number of scans required to obtain the full geometry and (3) scan settings for quality.

Table 1: Specifications of the laser scanner FARO Focus 3D X130

range	0.6 – 120 m
measuring speed	976 000 points per second
ranging error	± 2 mm at 25 m range, depending on the scanning speed

Figure 3: Two models of scanners; FARO Photon 120 (left), FARO Focus 3D X130 (right)

2.1   Position of the scanner

The scanner makes use of laser technology. A laser is projected onto a rotating mirror. The laser is used to measure the distance towards an object. Combined with information on the angles (the scanner and mirror both rotate) a coordinate is determined.

In the case a shell structure would be a perfect sphere and it would be scanned from its centre point the density of points on the surface would be equal all-round. However, in other situations this will not be the case. The point clouds of objects close to the scanner will have a larger density. This is show in Figure 4. This should be taken into account since the density of points in an area could become too low.

From experience it was found that for very reflective surfaces it is difficult to obtain the geometry. It seems that a laser beam reflects in a way that the scanner is not capable of tracing the point. In some scans made by the authors the results became unusable. The
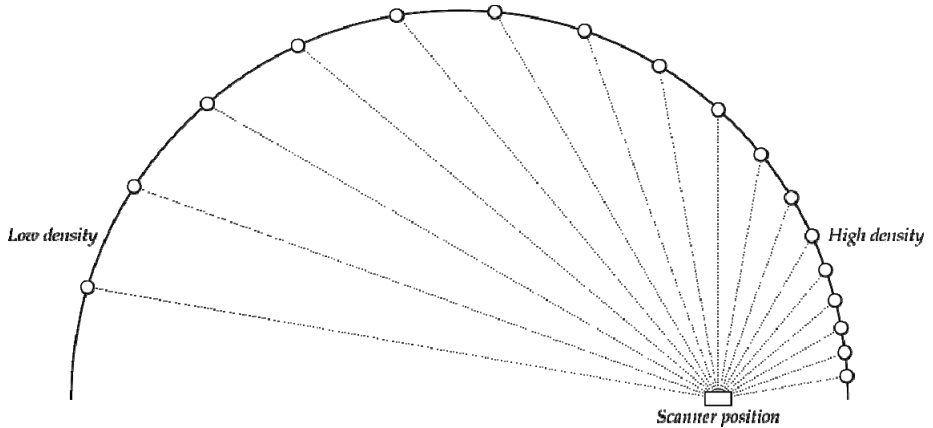
Figure 4: Effect of position of scanner on the density of points

position of the scanner cannot change this. However, it might be useful to strategically place less reflecting surfaces, like sheets of paper or cloth.

2.2   *Number of scans*

Large objects, like shell structures, might be too large to be scanned in a single scan. Depending on the situation it might also be that there is no position for the scanner at which the whole surface of the structure is scanned at a suitable angle or there might be obstacles that block the view. In these cases multiple scans are required. For the structures that were scanned by the authors this was caused by equipment hanging from the ceiling and large pieces of furniture. Figure 5 shows an example where the authors encountered this during the scanning of the Wyss Garden Centre in Solothurn (Switzerland).

It is possible to combine multiple scans by placing reference objects within the range that is scanned. Suitable targets, like spheres, can be detected later. When processing the point
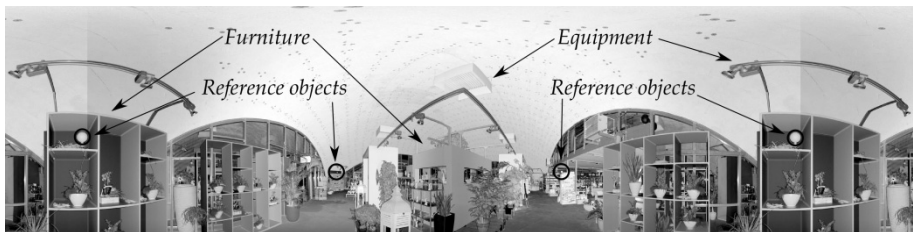

Figure 5: Scan of the shell roof of the Wyss Garden Centre in Solothurn (Switzerland) where equipment and furniture block the view

cloud it is required to plan the layout of the reference objects before making the scans because the reference object cannot be moved during the scans. It is only possible to align scans when multiple reference objects are visible on different scans. An example of a plan for scan setup is shown in Figure 6. In this example, always three reference objects can be observed form each position.

2.3   Scan settings

The scanner that was used by the authors provided settings for scan quality. The accuracy is directly linked to these settings. Very accurate scans require more scan time compared to less accurate results. Therefore, the accuracy of the scans depends on the time available and it is advisable to beforehand consider what the required accuracy of the scan is. Not
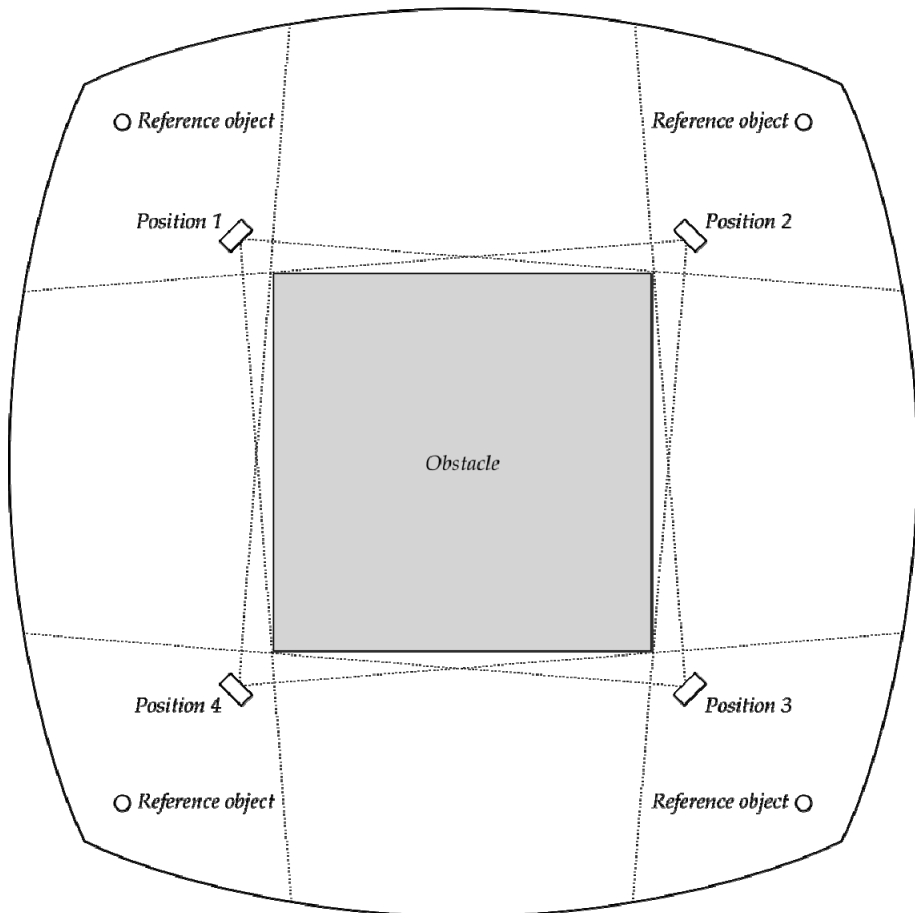
Reference object   Reference object

Position 1   Position 2

Obstacle

Position 4   Position 3

Reference object   Reference object

Figure 6: Plan for scan setup for positions of scanner and reference objects

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only take higher quality scans more time, also the processing of the point cloud becomes more time consuming.

The size of the file of the point cloud grows linear with the number of scanned points. The number of points scanned can easily grow to millions of points making the files size multiple Gigabytes. Software supplied by the scanner manufacturer is capable of handling the amount of points, however not all software is optimized to deal with large amount of data. For this reason it is also advisable to determine the required accuracy before scanning. Off course the authors were not aware of this in the beginning. Methods were applied to reduce the number of points afterwards. This will be explained later. But it shows that in case the engineer is not sure which settings to choose a high quality and large number of point could be a safe option because the number of points can be reduced afterwards. However this will take more scan and processing time. A high quality scan can take up to approximately 15 minutes.

3   Processing the point clouds

After the scanning is finished the method becomes digital. In general the following steps must be performed; (1) align relatively and clean the point cloud(s) from unnecessary points and (2) exporting, modifying the data and aligning with coordinate system.

3.1   *Align relatively and cleaning the point cloud(s)*

Often multiple scans must be made for large structures. For the scanner used by the authors software was supplied that could both align multiple scans and clean the point cloud. Special reference objects can be recognized and located within the scans. Once these are found scans can be aligned relative to each other.

When the scan is made no distinction is made between shell surface and other surfaces. Unnecessary points must be removed manually. For example points below the shell surface and objects hanging from the ceiling. These points would disturb fitting of a surface. The selection of points must be manual since each situation is unique. This makes this part of the method time consuming. What must remain for further processing are points on the surface and points that can be used to align the model with a new coordinate system. The latter is required since the position of the scanner might not be an appropriate

reference point for further modelling. It is advantageous to include parts of the floor being as far apart as possible. This will be explained in the next part.

3.2   ***Exporting, modifying and aligning***

For 3D modelling of free form surfaces geometric software can be used. Therefore, the data of the point clouds must be exchanged using a suitable file type. In general a text format can be used for exporting since it can be read by most available software packages. The authors used Rhinoceros [6] for modelling.

In some cases the files size of the point cloud is too large to process within the used software. Manually removing points results often results in reduction of points in a specific area. The authors at first used random sampling of points to reduce the files size in the following way; next to the list of coordinates a parallel list was made with index 0 or 1. A specific percentage of this list would be 1 using random sampling. Only coordinates with index 1 would be reused to create a new shorter list. This way each coordinate has equal probability of being reused and therefore points would be removed from the point cloud in a distributed way. However, since the original density is not equal, the position of the scanners determines whether the resulting density is sufficient.

It would be more convenient to obtain an overall equal density. This helps making an accurate over-all fit for the NURBS surface. A method is required that depends less on the original point cloud. For this purpose the authors made use of an open source software package called CloudCompare [7]. Other packages might include the same features. Especially useful was the feature to reduce the number of points in the point cloud based on distance between points. This feature produces a point cloud that fulfils the preferred equal density. Of course only if the original density is higher.

Also relevant for free form shells is the shell thickness which is not likely to be constant. In some cases the authors were able to subtract the shell thickness by making scans outside the shell structure, like in Figure 1. Here it can be seen that the shell thickness towards the supports becomes larger.

Finally, points are scanned relative to the position of the scanner. By fitting a base plane through scanned points of the floor the horizontal orientation can be found. Further, by

translation and rotation of the point cloud and the base plane the model can be aligned with new coordinate system.

4   Fitting a suitable NURBS surface

The geometry of double curved shapes can be described by NURBS surfaces. A surface is created by making use of control points. These points can be used to describe a free form surface of different degrees. This becomes more relevant when multiple surfaces are combined to represent one shell structure. The connections of the surfaces can only be continues to the degree of the used NURBS surface. Modelling a suitable surface that represents the geometry consist of the following steps: (1) estimating the required number of control points, (2) fitting multiple NURBS surfaces and (3) checking for accurate and smooth fitting.

4.1   *Estimating required number of control points*
For this paper a feature of Rhinoceros was used to fit a NURBS surface through the point cloud. This feature is called "Patch". The precise fitting method is not provided by the developers. Various implementations are possible of least square NURBS fitting. These make use of a fixed number of control points. Examples can be found in [8] and [9]. Rhinoceros does provide a method to check the deviation of each point in the point cloud with the fitted surface. Always a number of control points must be chosen independent of the method for fitting a NURBS surface onto a point cloud. An approach to determine this was found in [10]. However, although its implementation is justified in the presented examples, it did not provide practical instructions for finding and choosing an appropriate number of control points for this particular situation. To find a well-fitting NURBS surface the authors developed their own method. Therefore, first an estimation is made of the minimum and maximum amount of control points that would be required. This provides a range of control points to consider. This method will be called the "Range Estimation and Validation Method" (REVM).

Further, in the structural analysis, when curvature changes quickly this (often) results in locally higher stresses due to local eccentricities. Therefore, a smooth as possible model is required that follows the geometry sufficiently close. A dilemma presents itself. Here called the "smoothness dilemma"; a model becomes more smooth and less accurate when the number of control points reduced. In opposite way the model accuracy increases and

smoothness decreases when the number of control points is increasing. An exaggerated example is given in Figure 7. A specific number of control points must be found that balances these aspects.

The positions of the control points determine the shape of the NURBS surface. Control points can be placed close together but also far from each other. If control points are weighted equally, shapes of high curvature require control points being placed close together. A shape can be described using view control points placed at unequal distance but also placing control points at approximately equal distance. This makes the number of possibilities unlimited. Figure 8 shows two options to model an approximately equal shape. The method used for fitting a surface determines how well a fit can be found using a specific number of control points.
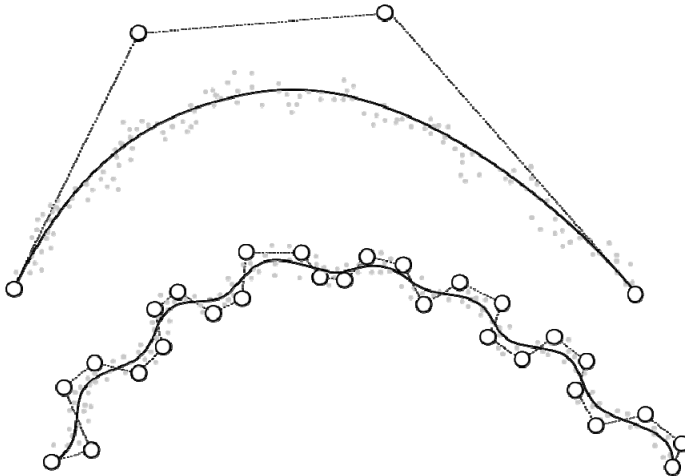

Figure 7: two curves fitting the same point cloud. The top curve is smooth but does not fit the point cloud well. The bottom curve does fit the point cloud well, but is not smooth
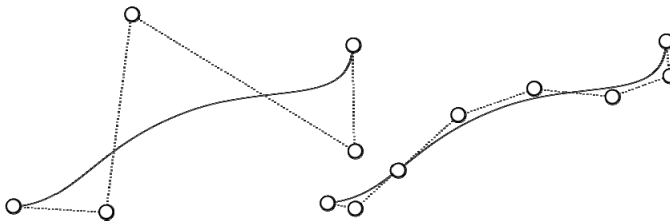

Figure 8: two approximately equal shapes are modelled using curves with different number of control points

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Although there are multiple possibilities it is possible to estimate a minimum and maximum required number of control points (*CP*). This can be done after a visual check of the shape. A cross-section can be selected. This cross-section should have the largest change in curvature. It requires some experience to recognize a suitable cross-section. Curvature measurement features that are provided by software packages can help. The locations of areas where the curvature changes are to be spotted. For transitions from convex to concave these are obvious. However for curves in which the curvature does not change sign this is slightly more difficult, but still possible. These points can be used to divide the curve into a number of parts (*P*). An example is given in Figure 9.
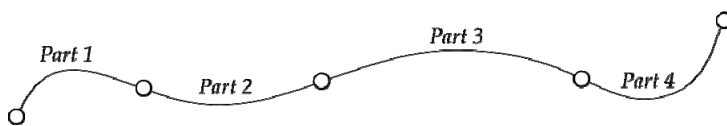

Figure 9: Subdivision of NURBS curve in four part (P = 4)

A NURBS curve requires at least one control points for each part and one for each end point. Also, the number of control points should be higher than the degree of the curve. Therefore, REVM estimates the least number of control points as described by equation 1.

$$CP_{\min} = \text{Largest of } (P + 2, \text{ degree of curvature} + 1)$$ (1)

Also, an estimation can be made for the maximum amount of required control points. To this end, it is assumed that the control points will be distributed approximately equal along the curve. Again, Figure 9 will be used as reference. The ratio of the length of a part and the length of the shortest part is used. If the shortest part can be described using one control point than any other part will be described by this ratio (rounded to the closest larger integer). The number of control points for each part can then be added. Additionally, at each end of the curve points can be added to influence tangency and curvature near the curves end. For a NURBS of degree five two points per end are used (so four in total). And finally the endpoints should be added. The additional points together make 6 control points. REVM uses a summation of all this number of points to estimate the largest number of required points. This is formulated in equation 2.

$$CP_{\max} = \sum_{P}^{i} \left\lceil \frac{L_i}{L_{\min}} \right\rceil + 6$$ (2)

Figure 10 shows a similar NURBS curve of Figure 9 with the estimated minimum and maximum amount of control points. Since $P = 4$, $CP_{min} = 4 + 2 = 6$. Part three and four are approximately twice the length of part one and four. Therefore $CP_{max} = 1 + 2 + 2 + 1 + 6 = 12$.

4.2 Fitting multiple NURBS surfaces and checking for accurate and smooth fitting

Since an upper and lower bound are estimated for the number of control points, NURBS surfaces can be fit and checked for accuracy. The accuracy can be checked by collecting information of the distance from each point of the point cloud to the fitted surface. The mean and maximum can be obtained. The authors have taken into account 99% of the total number of points to exclude obviously bad fitting points in the point cloud. Also important is the accuracy of the point cloud due to ranging error of the scanner (Table 1). The fitting of a surface will not become better than this accuracy.

The above has been applied to a small scale study and design model of a shell roof of the swimming pool in Heimberg shown in Figure 1. The point cloud was first scaled to real size and it's accuracy was then determined to be 0,014 meter. This was to serve as a reference since the fit is expected to converge to this accuracy. It was determined by isolating 16 small areas that were known to represent a very smooth surface parts of approximately 0,5 x 0,5 m. A plane was fitted through the points and the mean deviation of the points to this local plane was averaged. The accuracy differs from Table 1 since the point cloud was scaled up to the size of the real structure.
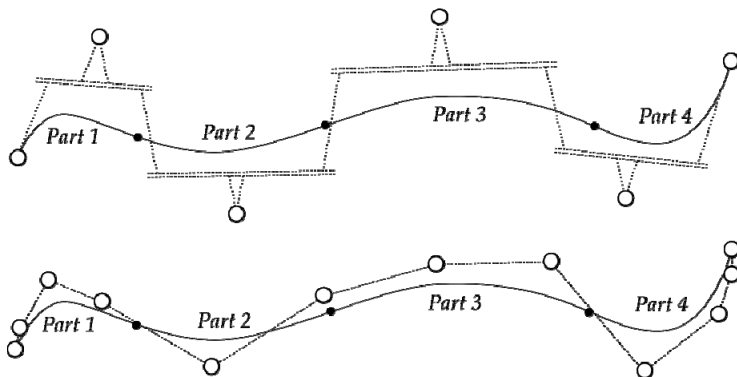

Figure 10: Example of NURBS curve (P = 4) with estimated minimum (top, CP = 6) and maximum (bottom, CP = 12) amount of control points
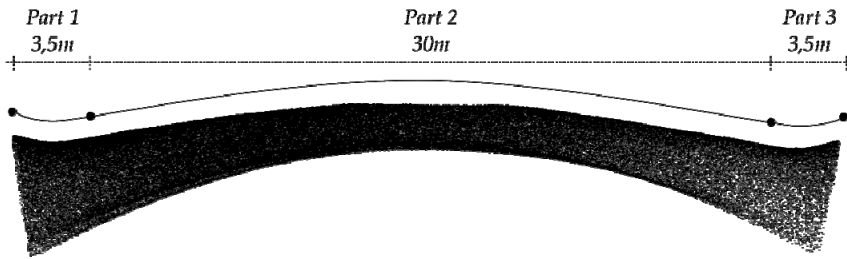
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Figure 11: Side view of point cloud showing the most curved section of the model. The section is divided into three parts

The most curved cross-section of the model was divided in three parts like in Figure 11. So CP_{min} = 3 + 2 = 5. However, for this model a NURBS surface of degree 5 was used. Therefore, CP_{min} = 5 +1 = 6. The ratio of the longest and smallest parts are estimated to be 30 / 3,5 ≈ 9. Therefore CP_{max} = 1 + 9 + 1 + 6 = 17. Since the example is a symmetric model a grid of control points of equal size for both directions is used. For each number of control points within this range a surface was fitted using the Patch feature of Rhinoceros. The results for maximum and mean point deviation with the surfaces are shown in Figure 12. This shows that increasing the number of control points results in a closer fit. However at some point the fit stops improving and maintains to be approximately equal to the point
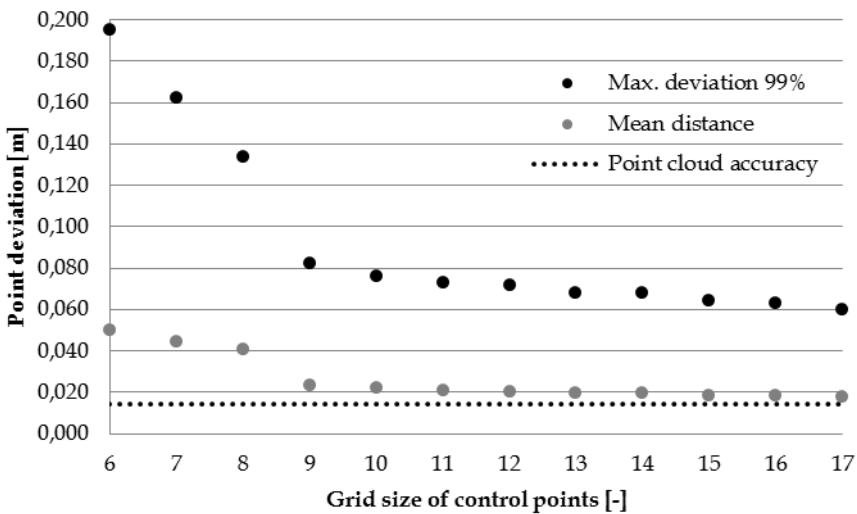

Figure 12: Results of point deviation with the surface for a range of NURBS surfaces

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cloud accuracy as expected. The lowest number of control points with acceptable accuracy can be chosen to represent the geometry. In this case a grid of 10 x 10 control points was chosen. The resulting surface is shown in Figure 13.

5   Making a mesh

Finite element programs have in-build mesh features. Using these it is the task of the engineer to make a mesh that is suitable for interpretation of results and has sufficient density in critical areas. Sometimes the offered features are limited and some modifications
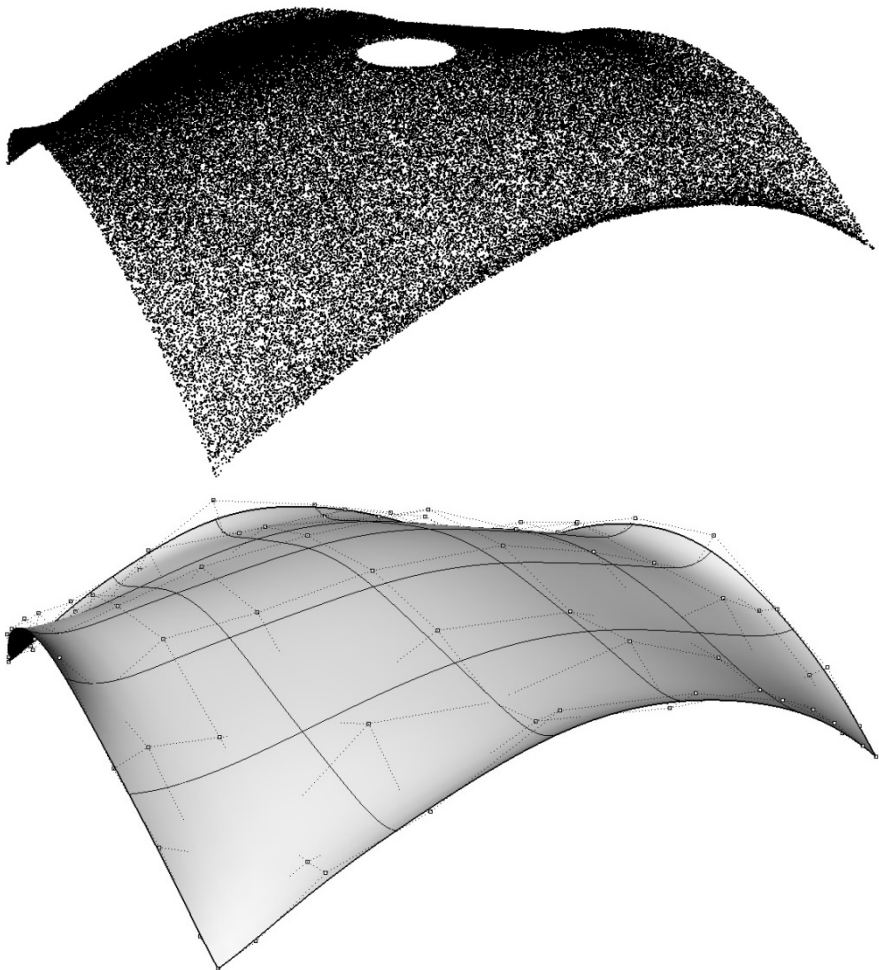

Figure 13: Point cloud (top) and fitted NURBS surface (bottom) with a grid of 10x10 control points

can be made to the NURBS surface in order to achieve better results. This can be done by (1) trimming and (2) splitting.

5.1 *Trimming the NURBS surface*

Fitted NURBS surfaces often exceed the area of the control points. Therefore the surface needs to be trimmed at the edges of the point cloud. Often this results in support conditions within a single point. Therefore the surface must be trimmed again such that a suitable support is created.

5.2 *Splitting for increase of mesh density*

For free form structures the mesh features in finite element programs often results in random-like pattern (depending on the available meshing features). Here Diana FEA was used [11]. For two reasons it can be convenient to have additional control over this pattern; (1) some area(s) require a more dens mesh with smooth transition towards the less dens mesh (for example at supports) and (2) interpretation of the results along specific sections may be required (for example useful for making graphs). The NURBS surface can therefore be splitted within the geometry modelling environment. By splitting the surface identical shapes are created. However they do not appear as the same shape because what is shown is a specific parts of the original surface. The control points are not influenced by splitting.

In case of the example only a quarter of the model is shown for more clear illustration. In Figure 14 the division of the edges at the support (lower left corner) and the inner hole (top right) was chosen smaller than the overall mesh size to locally increase the mesh density. These area are expected to be more critical because of concentration of forces. A smaller mesh size provides more accurate results. The area effected at the support remains small and does not have a smooth transition towards the rest of the mesh. Also, at the edge of the middle hole a large area was effected. In the figure these areas have been approximated by the authors eyes and marked grey. This effect on the mesh might be inconvenient because the area where the mesh density was increased was either too small or too large. Also, a there is no cross-section at which the nodes are aligned. Figure 15 shows the same surface, but splitted at the thicker black lines into four parts. This effected the mesh significantly. The areas in which the mesh density was increased are more reasonable and together smaller.
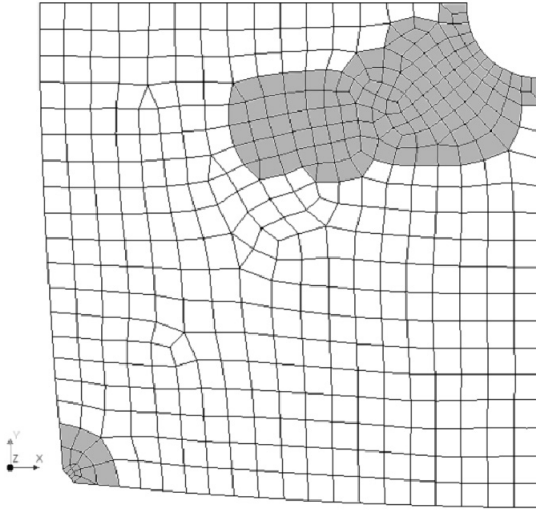
Figure 14: Top view of mesh of trimmed surface (1446 nodes). In the grey areas the mesh size is effected by choosing a smaller division at the edges (bottom left and top right) compared to the overall mesh size
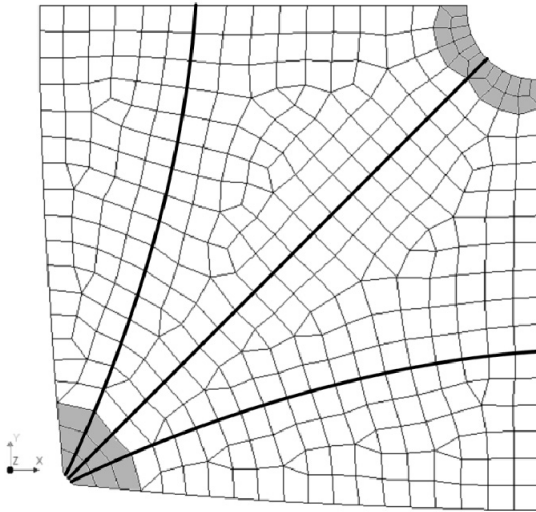

Figure 15: Top view of mesh of trimmed and splitted surface (1155 nodes). The geometry was splitted along the black lines. In the grey areas the mesh size is smaller than the overall mesh size

Another advantage is the result of splitting the surface. The mesh of Figure 14 consists of 1446 nodes. The mesh in Figure 15 consists of 1155 nodes. Therefore analysis would take less calculation time while providing more accurate results for the therefore intended areas. The advantage becomes more significant for large models or models that require lots or iteration, for example various types of non-linear analysis.

6   Conclusions

The quality of the final finite element model is already influenced by the choices of the engineer while making the scans. It is advisable to make a plan based on the final purpose of the model. The plan should include; number of scans, their positions(s) and the scan settings for density and accuracy.

Processing the data requires effort of the engineer with special attention to accurate selecting of points. This process is time consuming. Further, data must be exchanged between different software packages which sometimes limits the files size.

A specific number of control points must be chosen to fit a NURBS surface. The presented "Range Estimation and Validation Method" can be used to find a surface that is both smooth and accurate. An estimation can be made for an upper and lower bound of a range of the number of control points. When the number of control point increases the accuracy increases until the maximum deviation comes close to the point cloud accuracy.

Mesh generators of Finite Element Analysis software sometimes offer limited capabilities for the engineer to influence the pattern of the mesh. Trimming and splitting the NURBS surface before importing it into the Finite Element Analysis software can be used as means to increase the influence of the engineer on the mesh pattern.

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