

## 3D MODEL GENERATION FOR DEFORMATION ANALYSIS USING LASER SCANNING DATA OF A COOLING TOWER

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**Abstract:** Development plans for the Hellenic electricity producing company Public Power Corporation S.A. required a quantitative assessment of the surfaces of an old cooling tower for shape imperfections. The 3D survey of the external and internal surfaces of the tower and the production of a 3D solid model was required. The tower's external dimensions are: 83m diameter of the base, 56m of the top, and 97m height. According to the technical specifications points should be collected at least every 10cm on the surface of the shell, and a dense network of vertical and horizontal sections had to be produced. The use of time-of-flight laser scanners HDS2500 and HDS3000, with spot size of 6mm and position accuracy of 6mm in 50m was selected. The scanning density varied between 5 and 8 cm. 20 scans in the interior, from 4 positions, and 7 scans for the external surface were made. Approximately 22,000,000 points were collected. For the accurate alignment and merging of the scans, using the Cyclone software, special targets were used and their coordinates were measured with an accuracy of 6mm by use of a reflectorless total station. The 3D model production was produced in Geomagic Studio software and it involves: in polygon mode the creation of triangles (approx. 5.000.000), waterproof solid model (in stl format) and definition of boundaries, and in shape mode curvature detection, creation of contours, patches (approx. 6.500), grids and fitting of NURBS surfaces. The final product was delivered in IGES format. An accuracy control of the 3D model by using field-measured points and a comparison test with the initial construction plans were made. The deformation and crack control on the shell was proved negative.

### 1. INTRODUCTION

The Hellenic electricity producing company Public Power Corporation S.A. (PPC) had to perform maintenance work in a thermoelectric power unit at Megalopolis, southern Greece. The unit includes a natural-draught cooling tower with significant height in order to provide the draft of the rising exhaust air. A cooling tower is a heat rejection device, which extracts waste heat to the atmosphere through the cooling of a water stream to a lower temperature. Common applications for cooling towers are providing cooled water for air-conditioning, manufacturing and electric power generation [2].

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<sup>1</sup> The project sponsored by the Greek Public Power Corporation S.A. (PPC)

Megalopolis Cooling Tower No3 was designed at 1972 and the construction was completed a couple of years later. The tower is 97m high with an 83 m basal diameter. The shell lies at 8.20m above the level of the cold water basin with a 74.70m basal and 55.70m top diameter, respectively. The thickness of the shell is approx. 15cm. The shell is supported from 40 pairs of columns. Each pair has a V-shape and deviation approx.  $14^\circ$  from the azimuth direction.



Figure 1: Western side of the cooling tower

The tower is in continuous operation for more than 30 years. This long operation together with the planned from PPC change in its use in the near future, caused the need for specific and accurate knowledge of the state of degradation. After all, several collapses of such cooling towers have been recorded in various countries, e.g. in UK in 1973 [1], and in USA on the 12.07.1998, when one of the two seven-cell mechanical draft cooling towers serving American Electric Power's suddenly collapsed into the cold water basin [4]. Before any type of work took place for the conversion of the cooling tower of Megalopolis, the following steps were decided:

- to make concrete quality measurements using visual inspections and determination of the concrete properties with non-destructive and destructive tests
- to make a detailed geometric recording of the inner and outer surface of the shell. The products of this will include a series of 20 horizontal and 25 vertical intersections of the shell and the creation of a 3D model of the exact present shape of the tower. The required density of the measurements was greater than 10cm and the accuracy of the 3D position of each point had to be greater than 2cm.

The time of the field measurements had to be performed during a short maintenance period of one week, when the tower was out of order, thus the inner area of the tower could be approached and no systematic errors due to thermal effects would occur.

PPC wished to obtain the 3D model in order to achieve two targets through the above-mentioned geometric documentation:

- The knowledge of the deviation of the in-situ cooling tower comparing to the theoretical designed shape and the nominal dimensions. The general geometric deviations and the possible deformations of the installation must be investigated. Also local causes such as cracks, hollows etc. could be recognized.

- The use of 3D finite-element analysis in order to perform structural analysis taking into consideration loads, wind pressure, thermal and seismic effects [5], [6]. The processing was planned to be made with ANSYS software, so the output of the 3D model had to be in an appropriate format (i.e IGES).

The geometric documentation of the tower was commissioned to the Lab of Photogrammetry of National Technical University of Athens, by a research project funded by the PPC.

## **2. TERRESTRIAL LASER SCANNING FOR DEFORMATION ANALYSIS**

### **2.1. Selection of method**

The first issue to be decided was the selection of method and the techniques used for the geometric documentation of the cooling tower. Methods that are capable of measuring in a non-contact way a large number of points and provide a complete, detailed and accurate description of the surface, referred to geodetic, photogrammetric and laser scanning techniques.

Geodetic techniques that might be used include the use of reflectorless theodolite equipped with laser. The available conventional instruments of this kind allow the 3D determination of point coordinates with an accuracy better than 1cm, even for measuring from long distances (>500m), which is fully acceptable for this application. Nevertheless, the high point density demanded from the technical specifications, made the use of this method practically impossible. It could be used only for supplementary measurements or for the determination of high accuracy check points. The alternative solution of using a robotic reflectorless theodolite allows the automatic data collection but the method is still very slow. An especially tough parameter was the short time limit restriction for the measurements in the internal side of the tower. An additional problem is the insecurity in data collection at all necessary locations on the shell due to the maximum range of the instrument and the construction material of the tower.

Digital photogrammetric techniques that might be used could be either simple stereo-restitutions from individual image pairs of metric cameras, or photo-triangulation using bundle adjustment, a method that determines 3D coordinates of a large number of points using multiple images [3]. In both cases the use of a mechanical elevator could be used as a platform for the camera, in order to avoid taking pictures with large  $\omega$  orientation angle or with scales smaller than 1:500 at the highest parts of the tower. The available space in its inside though, allows access only within a narrow cement corridor (along a diameter of the circular basis) of a width of 1m. Not even the acquisition of stereo-pairs, which would have full coverage of the shell's surface, was possible from these positions. In addition the illumination conditions (natural or technical) were totally inappropriate for the acquisition of acceptable images, due to the large height of the tower and to the small diameter of its top.

Consequently, the only alternative technique practically applicable was the use of terrestrial laser scanning; this technology is based on active range sensors measuring directly the distance between the sensor and the points over the surveyed object. The ability to collect enormous and very dense 3D data sets, both on the external and on the internal surface of the tower, in short time is achieved by that way. A pulsed time-of-flight scanner, with maximum range 150m, position accuracy better than 1cm and 360° field of view in horizontal angle, consists the appropriate type of laser scanner which should be used, so that the particular technical specifications referring to the coverage, the measurements accuracy, and the density of points, will be met.

## 2.2. Data collection

Laser scanners HDS2500 (FOV  $40^\circ \times 40^\circ$ ) and HDS3000 (FOV  $360^\circ$  horizontal and  $270^\circ$  vertical angle), with spot size of 6mm and position accuracy of 6mm in 50m range, were used for the data collection. The scan point interval was ranging from 6cm to 8cm on the tower's surface. Three flat and/or spherical reflective targets were placed in appropriate locations (on the ground and the surrounding constructions or on the tower's surface up to the external height of 20m) for each scan. The targets were geodetically measured, with an accuracy of 0.6cm, referring to a common local coordinate system. For the outside of the tower, scans from 7 positions were made, at distances which vary between 40÷120m (Figure 2). For the inside, 20 overlapping scans were acquired from 4 positions and by 10 angles resulting to 10 scanworlds, each one of them comprising of two scans: one with the scanner viewing the lower part of the tower, and one more viewing the upper part (these were the only scans in which targets were not used). Approximately 22,000,000 points were collected in total.

In parallel, a geodetic network of 26 stations (3 were placed inside the tower) was established for the measurement of the targets, of the pedestals and the part on the inside of the shell extending from the lintel up to the doorway (part that could not be acquired by the scanner) and of approx. 2,900 check points smoothly scattered on the shell's surface. This check-point network provides sufficient security for the accuracy control of the final 3D model.

In total, a group of 4 persons has worked on the field for 6 days.

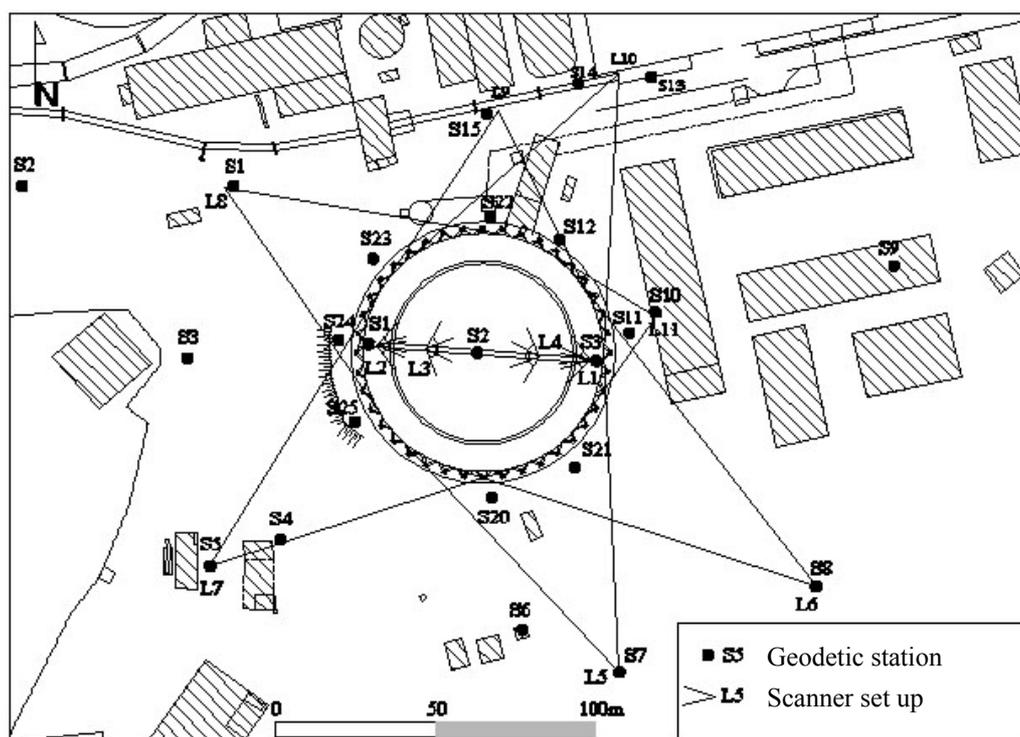


Figure 2: Plan view of the tower, showing scanner set ups and geodetic stations

## 3. POINT CLOUD REGISTRATION

The registration process was carried out in Cyclone software. The most difficult part of this process was the registration of the inside, because of the absence of targets for the upper part of the tower. Under such circumstances and especially in cases of objects such as this tower, whose surface appears unvarying, the selection of homologous points that would normally

result to a good registration is impossible. The solution was given by an algorithm developed by the authors. This algorithm brings each scan of the upper part of the tower to its approximate correct position relative to the corresponding scan of the lower part by taking advantage of the shape of the tower, i.e. the top of the tower forms a ring that is horizontal (as was proved by surveying measurements), and if a plane is fitted on points that belong on that ring, the rotations that must be applied are derived from the coefficients of the equation of the plane. Another algorithm corrects for the remaining rotations and offset by comparing the two scans (i.e. upper and lower) and brings all of the scans of the upper part are at their approximate correct position relative to the corresponding scans of the lower part.

The next step involved the registration of all of the scans of the inside. Given the fact that both the inside and the outside part of the tower should be expressed in a common coordinate system, a scanworld with the geodetic coordinates of the targets must be created and used as reference for all the registrations. A reference scanworld was created first for the inside. All of the scans of the lower part were first registered using the reference scanworld and afterwards, in order to obtain a better and more reliable solution, all of scans that overlapped were related with cloud constraints, something that is possible in the Cyclone software and does not require the selection of homologous points when two overlapping scans are already in their approximate correct position in a common reference system. This was used onwards in order to register the scans of the upper part. However, these scans first had to be expressed in the geodetic coordinate system. Therefore for each one of them the coordinates of the targets of their respective scan of the lower part were imported. Each one of these new scanworlds was registered with the reference scanworld and point clouds derived were registered with the point cloud that resulted from the registration of the scans of the lower part (Figure 3) and which was used as a reference. For each scan of the upper part a cloud constraint was added until all of these scans were attached to the lower part and, finally, cloud constraints were added for all of the scans that overlapped.

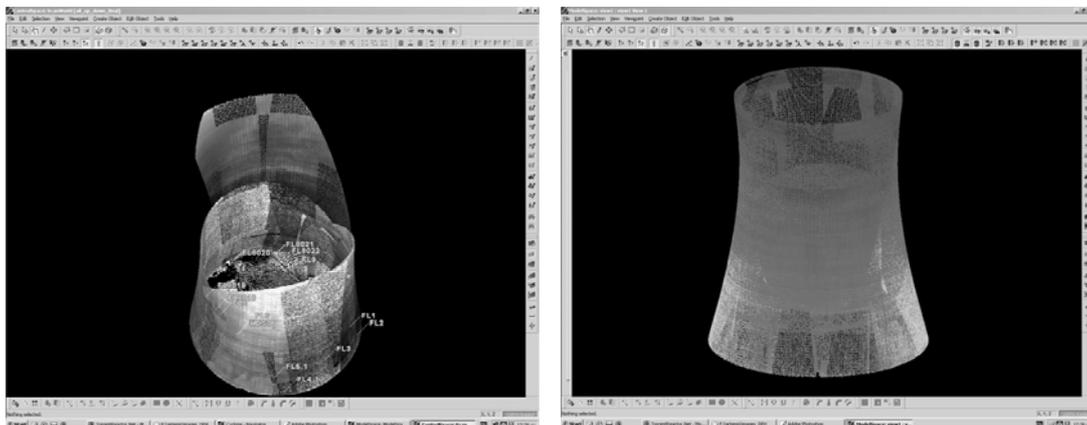


Figure 3: Intermediate phase of the registration of the inside (left). Registered pointclouds of the inside (right)

This process, as described in the above, leads to the complete registration of the inside part of the tower (Figure 3). The registration of the external part of the tower presented no particular difficulties. The exterior comprised of 7 scans that were registered one by one using a reference scanworld of the geodetic coordinates of the targets and once again cloud constraints were added for the overlapping scans.

Finally, in order to register the inside and the outside part of the tower, a scanworld that contained all of the targets in the geodetic coordinate system was used as reference. This registration had no residuals as the geodetic system was used as a reference in all cases and there were no common targets between the inside and the external scans of the tower. It is worth mentioning, that for the registration of the scans of the inside the mean absolute error was 5mm and for the outside the error was 4mm.

#### **4. CREATION OF 3D MODEL**

Finite Element Analysis (FEA) is a computer-based numerical technique for calculating the strength and behavior of engineering structures. In order to perform FEA a structure is broken down into many small simple blocks or elements, the behavior of each individual element is described with a relatively simple set of equations and all the equations describing the behaviors of the individual elements are joined into an extremely large set of equations that describe the behavior of the whole structure. The CAD model required for such an application must meet certain standards. The geometry of a structure must be described by a mesh and a method well suited for FEA is NURBS surface modeling. A simple polygonal mesh is seldom adequate for FEA, as this kind of analysis is extremely sensitive and attempts to use CAD geometry directly for FEA often result in huge and expensive models or, worse, in models violating basic laws of mechanics. Some file formats suitable for 3-D solid models are ACIS, IGES, STEP and STL.

The original data of the cooling tower comprised of point clouds and supplementary geodetic measurements, and the modeling process was carried out using Raindrop Geomagic software. Originally, the point clouds were manually processed so as to remove the noise and partition the body of the tower, so as to facilitate the next stages of modeling. In particular, the shell of the tower was exported from Cyclone into two files: one for the point-clouds of the external surface of the shell that extended from the upper circumference of the lintel to the cornice and another file for the point clouds of the inner surface that extended from the doorway up until the top. During the wrapping phase polygon meshes of an approximate density of 10cm were created. The lintel at the lower part of the shell was exported separately and more detailed mesh was created for that area. The shape of the pedestals and the part on the inside of the shell extending from the lintel up to the doorway (parts where only geodetic measurements were acquired) was constructed with 3D faces in AutoCAD. The diagonals were also treated separately because for all of them only a part of their front face was possible to acquire. Eventually the acquired part of each one of the diagonals was adequate for fitting a cylinder to use for the model (cylinders were fitted with a  $\sigma_0$  of about 6mm - approximately the accuracy of the scanner used). The cylinders were created in Cyclone and extended both ways so as to be trimmed later in Geomagic, up at the section with the lintel and down at the section with the pedestals.

Afterwards the surfaces were cleaned from intersecting triangles, wholes were filled, floating triangles were deleted etc, because such faults create problems at later stages, and are often the cause for distorted and twisted grids that lead to severe faults on the NURBS surface of the final product, something that definitely leads FEA to computationally expensive solutions and erroneous results etc. The next step was to assemble the parts of the tower beginning with the diagonals that were unified with the pedestals. Next, the diagonals were attached to the lintel, and the lintel was attached to the external surface of the shell (Figure 4). Another area that was impossible to acquire using the scanner was the part of the external side of the shell that extended from the cornice level to the top. In order to have a full model, the inside part of

the shell was offset 14cm on the outside and used to complete the model. For the top circumference of the cornice, a plane was fitted and used to cover the gap between the cornice and the offset part of the shell (Figure 4). This process involved extending and trimming the parts to be assembled. The inside part of the shell, was attached to the 3D faces model that were created in AutoCAD for the lower part. The inside shell was trimmed with the lintel that was extended to the inside. The model finally closed by covering with triangles the gap between the inside and external surface of the shell on the top.

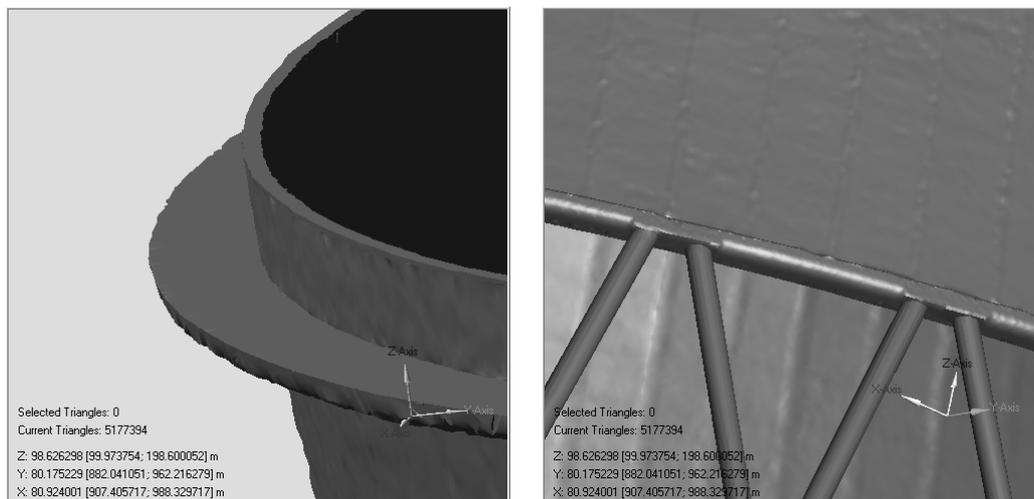


Figure 4: Details of the model of the tower: the cornice (left) and part of the lintel and the diagonals (right)

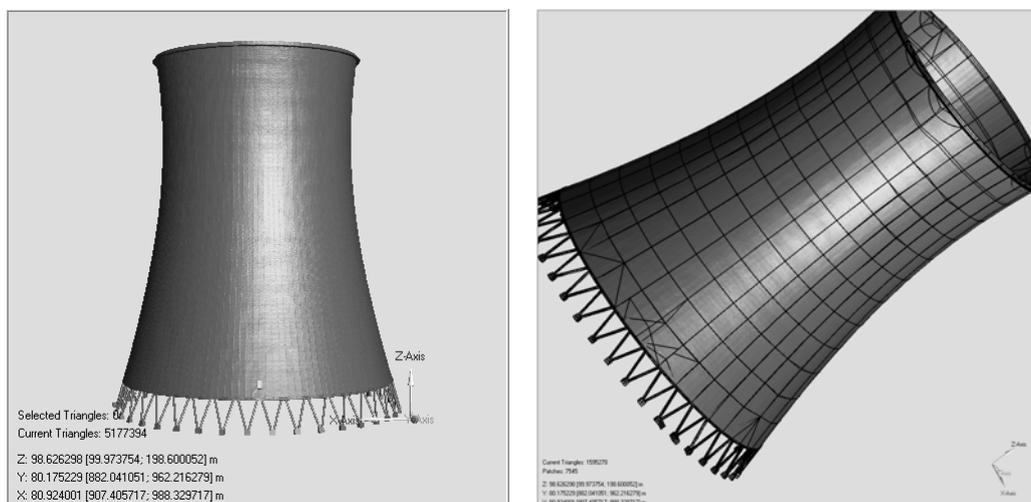


Figure 5: Final polygonal model (left). Patches created for the creation of the NURBS model

The final polygonal model (Figure 5) was subdued to thorough control i.e. spikes were relaxed or removed, floating and intersecting triangles deleted, holes filled, edges were straightened etc. as it has been found that such faults cause problems to the next stages, i.e. the model becomes heavy and processing demands great computational effort as each faulty area is modelled and modelling is much more difficult for such cases. Another important fact is that in order to go through the next steps (patch creation etc.) it was found that the number of triangles had to be reduced. Therefore, it was preferred to decimate the triangles on the surface of the shell and retain the triangles on other areas such as the lintel where decimation

would lead to distortions. Eventually, instead of 5,000,000 triangles, the model used finally held approximately 1,500,000 triangles (about 1/3 of the original amount).

The next step is to create boundaries on the model so as to retain edges, facilitate the detection of curvature on the model surface and eventually produce well defined patches. Boundaries were created on all of the edges (pedestals, cornice, top of the shell, doorway) and several vertical and horizontal sections were also used for the creation of boundaries onto the shell surface. The most difficult part to model however was the lintel, where all of the diagonals meet the shell. For all of the diagonals, boundaries were created at the intersection with the pedestals and the lintel, a boundary line was also defined along each diagonal, several boundaries created on the lintel between the diagonals also facilitated the next steps. Without the use of boundaries and during the creation of the patches, the program has no knowledge of the shape of the object and the areas of high curvature are detected automatically, leading to patches that are not suitable for the description of the structure, grids that are distorted and eventually deformed NURBS patches that are practically useless to FEA.

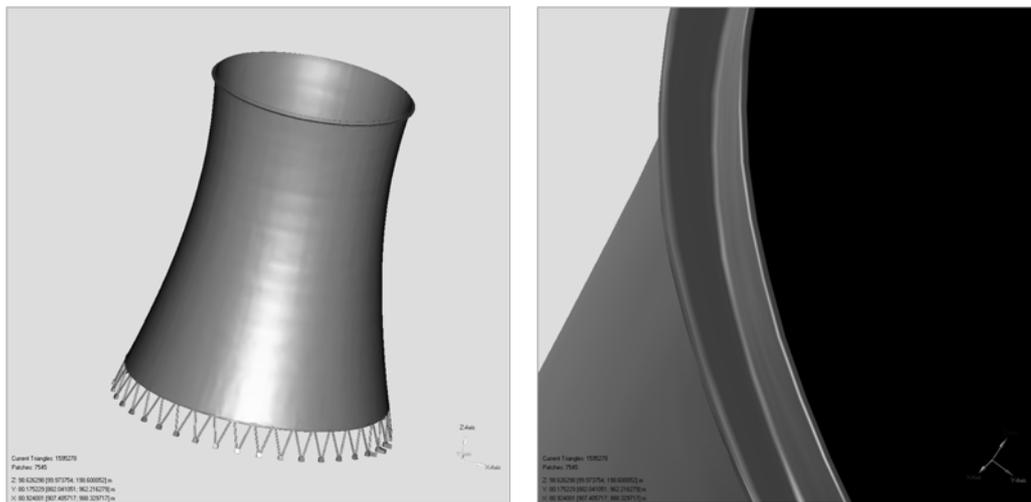


Figure 6: Final NURBS model of the tower (left) and detail of the NURBS model (right)

After the model has been cleaned and the boundaries have been defined, patches can be created (Figure 5). The first stage is the detection of curvature. If boundaries are found, they are named as contours, retained and used for the definition of patches. After the patches have been created several corrections have to be applied so as to fix intersecting patches and high degree angles, something that is also carried out manually. Onwards grids are created and NURBS patches are fitted. At this point, it is possible to make some more corrections, i.e. relax grids, relax NURBS patches etc. When the NURBS model is ready (Figure 6) it can be exported in a suitable format such as IGES. The NURBS model for this case comprised of 7500 patches.

The whole process for the creation of the NURBS model is pretty straight forward. However, the corrections that have to be applied during each one of the stages described are very important. If no corrections are applied, it is almost certain that one will have to step backwards in the process losing time and most importantly information as it is impossible to retain all of the information of the model between different phases such as polygon phase and shape phase (i.e. stage of creation of patches etc.)

## 5. COMPARISONS

In order to evaluate the accuracy of the process, a number of experiments were carried out. First, the polygonal model that was created was compared with the geodetically collected data. As already mentioned approximately 1250 points were acquired geodetically for the external surface of the tower. For each one of these points, the distance along the gradient vector of the nearest triangle of the object surface was calculated. The majority of the geodetically acquired points are within 3 cm from the model surface (only 146 points deviate more than 3 cm from the model surface), with a mean distance of approximately -1cm and a respective standard deviation of  $\pm 1.5$  cm. The results are considered to be quite satisfying considering that the surface model has been subdued to some serious processing, that involved data thinning (a sampling spacing of 10 cm was selected for the wrapping phase) and a great deal of corrections both manual and automatic.

Another control was carried out so as to see whether a less processed model would yield better results. In order to perform such a test a part of the model was created from scratch, i.e. using one quarter of the points of the scanner point cloud a new model was created for part of the surface. The new partial model comprised of approximately 3,3 millions triangles (the model of the external surface that was created and used for the project comprised of 2,2 millions triangles). For the new model, no corrections were applied and the results were immediately compared with the geodetically controlled points of the area, i.e. 322 points that covered the detailed model surface. Once again, the results were analogous with the majority of the geodetically acquired points within 3 cm from the model surface (only 40 points deviate more than 3 cm from the model surface), a mean distance of approximately -1cm and a respective standard deviation of  $\pm 1.5$  cm. This strongly suggests that the less detailed model (average density of 10cm) that was created for the project was as precise as a model of full detail would be. This is very important, as a lighter model is easier to manage in such cases where there are several parts to assemble and/or the creation of a NURBS model is required.

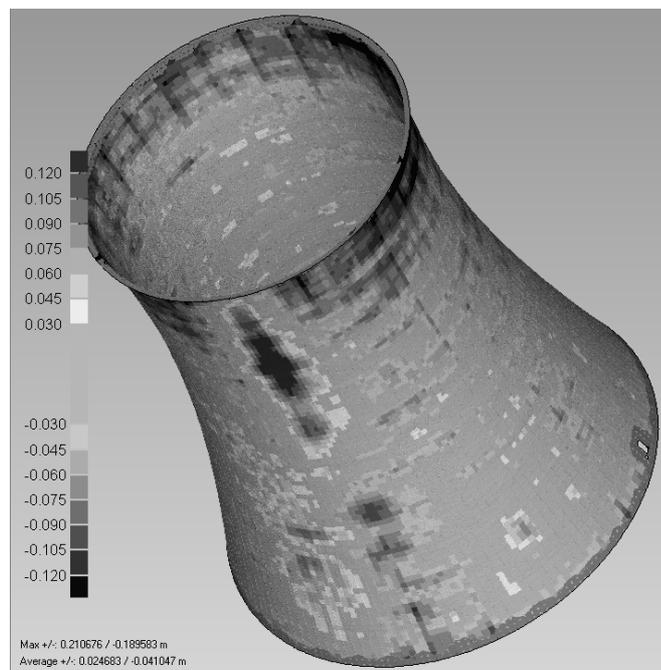


Figure 7: 3D comparison of the actual tower model and the theoretical (mathematical) surface

Another check was performed so as to see if the geometry that was created accorded with the theoretical shape of the tower. First, using data from the construction plan of the tower a mathematical model of the surface was derived. In particular, it was found that the mathematical surface that best describes the shape of the tower is that of a one-sheeted hyperboloid. The one-sheeted hyperboloid is a surface of revolution obtained by rotating a hyperbola about the perpendicular bisector to the line between the foci. A least squares fitting process that yielded the parameters of the model was developed in Matlab, along with a function that created approximately 18,000 simulation data points. The points of the mathematical model surface were used for the comparison with the model surface that was created and used for the project. As it turns out there are deviations of  $\pm 20\text{cm}$  between the mathematical surface and the actual model surface. However, as it can be seen in Figure 7, the deviations are within  $\pm 3\text{cm}$  for most of the surface, with a mean of  $-2.4\text{cm}$  and a respective standard deviation of  $\pm 4\text{cm}$ . These figures, suggest that the tower is in pretty good shape, and the deviations are regarded acceptable as they are within construction tolerance.

## 6. CONCLUDING REMARKS

The results of this application showed that the selection of a time-of-flight terrestrial laser scanner, in order to create a 3D model of the cooling tower, was a successful one. The use of a scanner with FOV (horizontal angle)  $360^\circ$ , in the internal side of the tower, combines speed and completeness in field data collection with easy registration of scans during data processing. This is a critical factor when working in the field especially under similar conditions. The quality of the data acquired (density and accuracy) is considered to be adequate for the application described.

Regarding to the 3d model, it is stressed that if a model is to be used for FEA, it should be both as abstract as possible and as detailed as necessary. Raindrop Geomagic, definitely succeeds in producing a polygonal model that forms an excellent basis for the creation of the CAD model. If the appropriate corrections are applied and if boundaries are chosen in a strategic manner, then the creation of the CAD model is a pretty straightforward process and the remaining corrections are as few as possible. The model created for this project was used to control the structure for deformations. It has been found that the tower is in a rather good state and some small deviation that was detected can be attributed to construction methods.

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