Geodetic surface based methods for applications in civil engineering

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Abstract

At the Institute for Structural Engineering at the TU Wien a cost and resource efficient concrete shell construction method called "Pneumatic Forming of Hardened Concrete", was invented. A flat hardened concrete plat is transformed into a double curved concrete shell, by inflating a simple air cushion placed under the concrete plate and stressing post-tensioning tendons at the circumference. Basically the stability of a concrete shell is sensitive against geometric imperfections. As part of the quality assurance, the engineering geodesy audits the geometry during the construction process with point and surface-based metrology. The scanned 3D point cloud is approximated with B-Spline surfaces to assess the shape of the shell by means of a static finite element calculation.
Three different datum definitions for the 3D cartesian coordinate systems are derived from the requirements of the civil engineers, e.g. to assign geometry impacts to different construction steps. Necessary preparation steps of the approximated geometry as main part of the structural analysis, computed with a finite element model, are shown in the workflow from the point cloud to the static behaviour of the dome. The results of the structural analysis shows no significant changes due to the geometric deviations in the static load behaviour compared to nominal finite element model.

Key words: Modelling point cloud, freeform approximation, structural analysis, finite element model, shell structure

1 INTRODUCTION

Surfaced based inspection measurements are one of the main issues in engineering geodesy. During a new construction process of a pneumatic formed hardened concrete shell surfaced based measurements and analysing procedures are realised. The concrete shell is built as a dome and further prepared as a deer pass bridge over a two-track rail. As learning structure a 1:2 model was built where the construction process, the measurement and analyse concept could be tested. The surface based measurements are scanned 3D point clouds performed inside of the dome. They provides the possibility of modelling a freeform surface for structural analysis and the analysis of the deviations between the actual cloud and the CAD model. The analysis concept includes the geometric surface approximation as well as the surface and the point based deformation analysis of the actual geometry during different construction steps.

Designing the construction is part of the Institute for Structural Engineering, while the surface based geometric monitoring is realised by the Research Group Engineering Geodesy, both at the TU Wien. The project is advertised and managed by the ÖBB-Infrastructure AG.
This paper focuses on the datum definition, which is fundamental for both abovementioned parts of the analysis concept, and the surface modelling part in combination with the structural analysis. In the modelling part, the point cloud is approximated by estimating the control points of a B-Spline surface in a least squares adjustment.

In the 2^{nd} chapter, the project and the structure are described. The requirements to the engineering geodesy applications and the planned measurement setup are discussed in the 3^{rd} chapter. Different reference frames and datum definitions are specified in the 4^{th} chapter. The steps of providing geometry information to the structural analysis are presented in the 5^{th} chapter. The paper will close with the conclusion and future tasks.

2 PROJECT AND OBJECT DESCRIPTION

Building a new rail line between Graz and Klagenfurt, the Koralm rail way, is one main infrastructure project of the ÖBB-Infrastruktur AG (federal railway in Austria), managed by the PLK2 team and the technical department SAE / Bautechnik-Brückenbau, (ÖBB-Infrastruktur). In the section Aich – Mittlern, three deer passes are planned over the two-track rail. One of these passes is built as a shell bridge with the method of pneumatic forming of hardened concrete. A flat hardened concrete plat is transformed into a double curved concrete shell, by inflating a simple air cushion placed under the concrete plate and stressing post-tensioning tendons at the circumference, seen in Fig. ***1***. The geometry of the lifted shell is a main-axis symmetric freeform surface with a membrane-stress-state characteristic. This means negligible transversal shearing and bending stress. This dome is mostly used as formwork for the end layer of shotcrete.

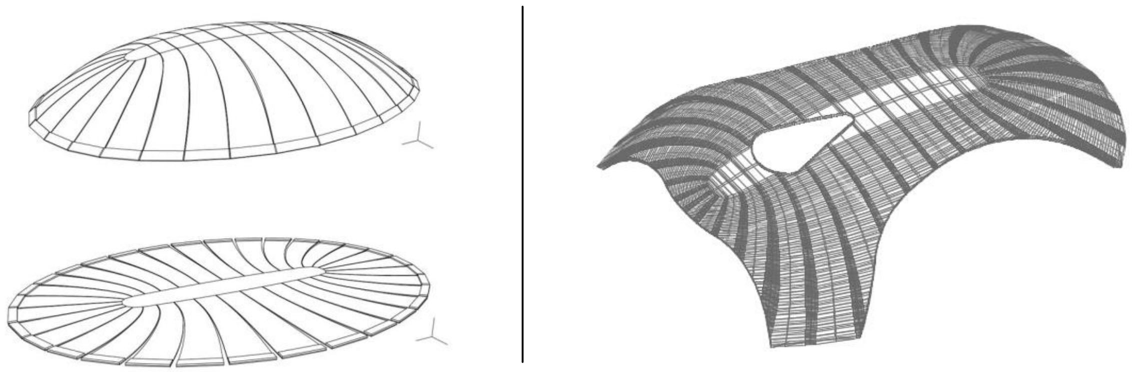

Fig. 1 Schematic sketch before (left, below) and after (left, above) lifting process; CAD plan of the pavilion (right)

The manufacturing process of this light weight structure was developed at the Institute for Structural Engineering, further described in (Kromoser B. et al 2014, 2015a, b) and transformed to the industrial realization with the ÖBB-Infrastruktur AG. The dimension of the deer pass is ~53m by ~38m and ~8m high. As learning structure for the construction process a 1:2 scaled learning structure was previously build. The only difference to the deer pass are the cutting areas. According to the subsequent utilization, parts of the domes are cut out, in case of the deer pass the ends with higher curvature, to get a bridge and in case of the learning structure getting a pavilion, seen in Fig. ***2***.

Fig. 2 Pavilion after lifting process (left), planed end state (right)

Because of the high sensitivity of the shell against geometric imperfections, the geometry needs to be monitored after each stress relevant construction step. For the determination of surface based deviations and recalculation of the static load behaviour with the actual geometry. In case of the learning structure after the lifting process, the winter break and the shotcrete layer on top. The tasks by the engineering geodesy at each construction step was first the inspection of the geometry and second the modelling of the actual freeform geometry for the structural analysis.

3 REQUIREMENTS AND GEODETIC IMPLEMENTATION

The engineering geodetic requirements from the ÖBB-Infrastruktur AG for the dome are the surface based geometric inspection by epoch wise measurements. These are the basis for a first assessment of the construction's static behaviour. Using the geodetic measurements, an analytically continuous description of the surface needs to be provided to the FE-processing (finite element-processing) software. The epochs are defined by the construction steps. The geometric model for the structural analysis needs a guaranteed deviation detection of 10cm. This value is derived from the simulated load cases in structural analysis. The available time period for all geodetic tasks in one epoch (from the measurements to the evaluation) is one day in order to not compromise the construction progress.

The challenge in this project is the implementation of the requirements into engineering geodetic tasks. At first, the guaranteed detectable deviation of 10cm, which is interpreted as a tolerance value, needs to be converted into a 1σ accuracy, thus leading to a value of ~2cm (Heunecke O. et al., 2013). Out of that, the decision for the metrology was given to a laser scanner for the surface based acquisition and to total stations for point based measurements with reflectors, the latter as backup and validation opportunity. Because of an expected smooth surface, the object resolution was defined with approximately 3cm, having the available time period for one epoch in mind.

Following analysing steps are defined:

- Point based deformation analysis (reflector points),
- Surface based deformation analysis with raw point clouds and approximated B-Spline surfaces,
- B-Spline surface approximation, for the FE-structural analysis.

In this chapter the basic prerequisites for the geodetic tasks are specified. The last analysing steps are described in detail in the following chapter. As a basic prerequisite, the different definitions of the geodetic datum required in the different analysing steps are introduced separately in chapter 4.

3.1 GEOMETRY FOR THE STRUCTURAL ANALYSIS

The geometric model needed for the structural analysis of the shell is a continuous surface, which represents the intermediate level surface of the construction, oriented to gravity. For getting the actual geometry the surface discretised by the 3D point cloud needs to be scaled with the half of the shell thickness to the intermediate position. Afterwards, the point cloud needs to be approximated by a continuous surface. At this step, the generalisation depending mostly on the object resolution, represents the intermediate surface, relevant for the static load behaviour of the construction. Exemplary the surface texture from the folded air cushion at the inside of the surface of the concrete shell needs to be smoothed. Last, the interface between the geometric and finite element modelling needs to be defined not losing quality on both sides.

3.2 MEASUREMENT SETUP

Covering the entire dome with one 3D laser scan requires a stationing inside the dome. Advantageous is, that it provides a clear view to the surface at each construction step after the lifting process and optimal incidence angles for the reflectorless distance measurements. To accomplish the remaining requirements the reference frame around the object needs to be extended inside the dome. This was done with reference points anchored at the ground concrete plane and connected to the reference frame before starting the formwork of the initial flat shell segments. The measurements were done with three total stations, one of them with a scanning option. The scanning total station was preferred over a conventional TLS as it enables the direct connection to the bottom points and the other stations of the geodetic network by mounted reflectors. Beside the bottom points, 28 reflectors were mounted to the concrete shell and measured with the two total stations. They serve as backup and verification opportunity for the reflectorless scanned 3D point cloud.

4 GEODETIC DATUM DEFINITION

Why is the datum definition so difficult? The main reason is getting the relative deviation of the dome itself without having enough stable areas calculating the parameters for the datum in 3D space. This is equivalent to the rigid-body movement with its three shifting parameters, tX tY, tZ, defining the origin, and its three rotations, defining the orientation rZ and the vertical deflection rX, rY. The only stable object is the ground plate with the foundation underneath, representing the shift in the height component, tZ, and the two rotations of the vertical deflection, rX and rY. The remaining parameters tX, tY, rZ needs to be interpolated from the "deformed" dome to define a quasi datum, like a quasi geoid, describing a relative datum of the geometry itself. Beside that, other definitions are defined separating different influence criteria's in the following sub points:

1. To detect deformations and its direction with respect to the measurement accuracy (the geodetic datum directly influences the deformation values).
2. To separate influences of different construction steps at the dome:
   a. Stake out and formwork.
   b. Rigid body movement during the lifting process.
   c. Geometry distortion during the lifting process.
3. Providing a gravity oriented or foundation oriented geometric model for the structural analysis.

The challenge hereby is defining a reference frame on the deformed dome geometry within the required accuracy.

Out of these ideas four datum definitions are specified. Whereby two are linked to a classic geodetic definition with a point based realisation of the origin and orientation through geodetic network measurements. The other two are defined on the surface geometry itself realized with the iterative closest point (ICP), (Besl P. J. et al, 1992), algorithm on 3D point clouds.

4.1 CLASSIC DEFINITION

4.1.1 Local

The local datum corresponds to the CAD design (nominal) of the dome, with a right hand cartesian coordinate system. The bottom edge of the dome where the foundation connects, defines the vertical Z-plane (Z = 0), the Z component of the origin (height component). The origin in X and Y, is defined as the intersection of the two main axis in the Z-plane, seen in Fig. ***3***. Whereby the major axis defines the X and the minor axis the Y axis of the coordinate system.

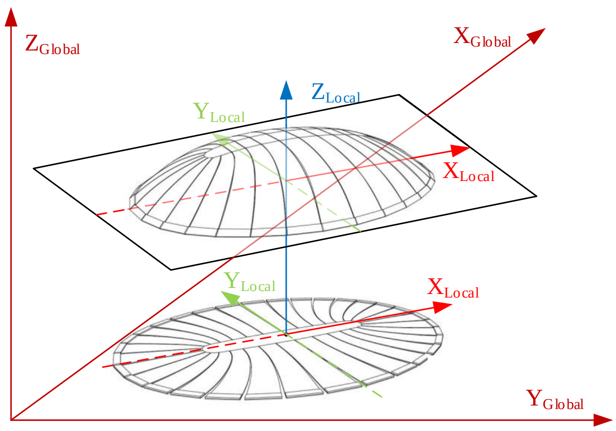

Fig. 3 Schematic sketch of the local and global coordinate system definition

4.1.2 Global

The global system is a left hand local coordinate system at the construction site, derived from the ÖBB reference frame without any applications of reductions and mapping distortions. It is realized through measurement pillars around the dome and used for staking-out the foundations and formwork of the plane shell structure. Detected deviations in the inflated state includes all influences mentioned above. The connection of the local and the global datum is defined through the planed geometry properties of the origin and orientation, seen in the chapter before.

4.2 SURFACE BASED DEFINITION

4.2.1 ICP – ground plate restriction

This definition is characterized through the separation of estimating the right hand coordinate system parameters. The rotation rX and rY (vertical deflection) as well as tZ (height component) of the origin, is realized with a plane approximation of the ground plate, because of the foundation underneath, which suggests a stable behavior during the construction process.

The rotation rZ and the origin component tX and tY results from the ICP algorithm between two point cloud sections of the dome, a horizontal profile with 0.4m thickness from the ground plane. The point clouds are from the actual and the nominal (CAD sampled) cloud with equal point resolution. The 0.4m section is chosen because of its smallest relative deviations to the CAD model. The result can be seen in Figure 4 (left) where the 3D point cloud is mostly lower than the CAD model.

This datum is used within sub points 1, 2.a, 2.b, 2.c, 3 at the beginning of this chapter and especially for thle comparison between the epochs.

4.2.2 ICP – dome

The difference to the definition in 4.2.1, where the datum is restricted to the ground plane, is deriving the ICP – dome datum from the entire dome clouds. This is done by the ICP by using the full actual cloud within the datum from 4.2.1 and the nominal cloud (CAD sampled), both with equal resolution. The idea is to get the best relative definition of the actual and the nominal point cloud to each other (smallest residuals from the ICP).

It provides the smallest deviations of the actual cloud against the CAD model, seen in Fig. ***1*** (right), where the point cloud is shifted in the Z component compared to 4.2.1. Further, it is used within the sub statements 1, 2.a, 2.c at the beginning of this chapter.

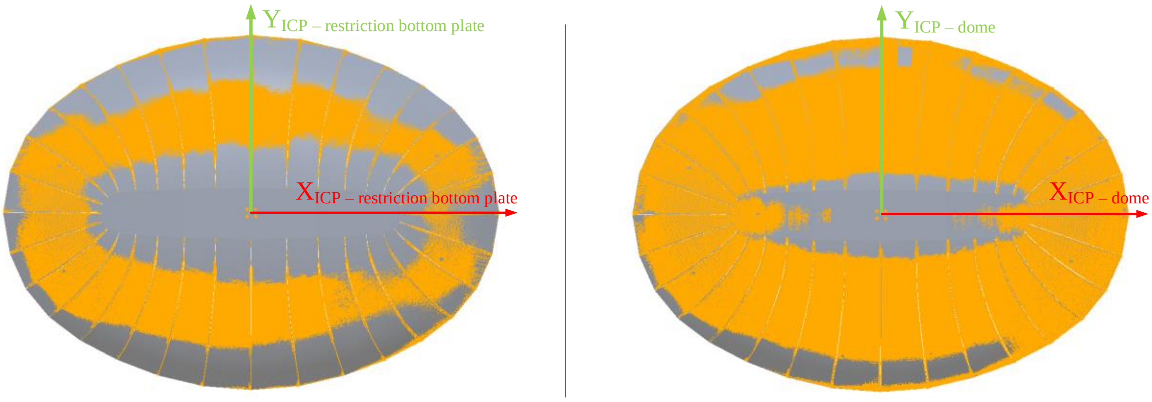

Figure 4: ICP datum differences. ICP – ground plate restriction (left, see 4.1.1); ICP - dome (right, 4.1.2); grey: CAD model; brown: the scanned 3D point cloud

5 STRUCTURAL ANALYSIS

5.1 DESIGNED GEOMETRY

A concrete shell is a favourable supporting structure if the geometry is properly chosen. A very important part of the design process is therefore the form finding of the shell. The optimum shape of a shell-like structure is found if the applied loads induce mainly compressive normal force. The form finding for the presented project was done by using a particle spring system (Kromoser B. et al 2017). Mainly three different types of boundary conditions were taken into consideration: usability, economic and procedural. All external forces were applied at a mesh with an elastic behaviour in opposite direction. The result was assessed by accompanying finite element calculations and steadily improved within a special designed feed-back loop until the optimal shell shape was found. The stability of the final shape of the shells was proven within extensive static calculations supported by finite element simulations with a number of different load conditions.

5.2 ACTUAL GEOMETRY

The basis of the actual geometry is the 3D point cloud. The cloud was obtained with a Leica MS50, which was placed inside the dome scanning with an object resolution of ~ 3cm for ~7h. This point cloud is approximated by a B-Spline surface with the aid of a linear Gauß Markov model, minimizing the residual sum of squares. (Niemeier W., 2008).
B-Spline surfaces are part of the freeform surfaces with the flexibility to describe a continuous surface regarding to local artefacts (Bureick J. et al., 2016). It consists of two parameter sets, the knots and the control points. With the knots the basis functions $N_{i,\, pu}$, $N_{j,\, pv}$ are calculated recursively at a surface point. These basis functions are defined in the function space in u and v direction, linear independent to each other. The degree p_u, p_v of the basis function can be defined separately and is set to $p_u = 3$, $p_v = 3$, having the opportunity of a C2 surface continuity. The total number of basis functions n and m in u and v direction produces with the value 30 of each the best results for the approximated surface. The control points $P_{i,j}$ defined with X, Y, Z values, project the function space (u, v) to the cartesian coordinate system (X, Y, Z) (Piegl L. A. et al, 1997).

$$C(u_C, v_C) = \sum_{i=1}^{n} \sum_{j=1}^{m} N_{i,p_u}(u_C) N_{i,p_v}(v_C) P_{i,j}$$

C are the points on the B-Spline surface in cartesian coordinates (X, Y, Z) at the function space position (u_C, v_C). This definition of the B-Spline surface function requires (u_C, v_C) the parameter values of observations homologous to the 3D points (X, Y, Z). These parameters of the observations are estimated by a projection of the observations (3D points) to the nominal B-Spline surface.
In the Gauß Markov model the unknowns are the control points and the observations are the 3D points from the scanned point cloud (Schmitt C. et al., 2014). The system is linear and can be solved directly.

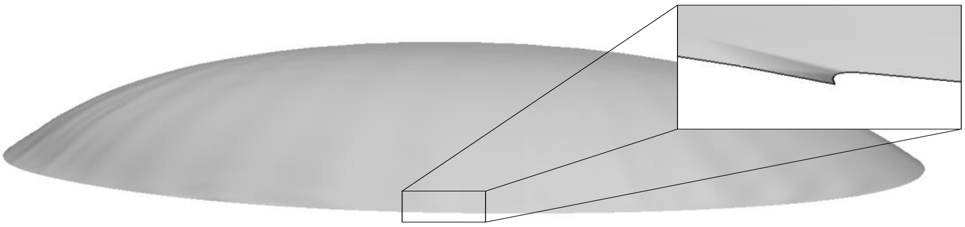

Fig. 5 Approximation of the B-Spline surface with artefact on the bottom edge

Fig. ***5*** shows a result of the fully approximated point cloud as one continuous B-Spline surface. The single stripes of the shell are slightly visible, perspectively seen best at the left side of the surface in Fig. ***5***. The artefact on the bottom edge is caused by the definition of the function space and the knot parameter definition at this position in combination with the sparse density of the point cloud.

This caused mostly from the datum definition. The datum "ICP – ground plate restriction" is chosen with the reason that the dome directly connects the ground plate with the foundations. Out of that, the function space of the B-Spline is defined at this bottom edge curve. The restriction to this bottom edge curve and the sparse density of the point cloud causes this artefact and needs to be optimized.

Transforming the approximated B-Spline surface to the intermediate FEM level surface is not necessary at this step because the half of the shell thickness is smaller than the required accuracy. For the later geometry with the shotcrete layer, it is appropriate. As exchange format to the FEM program the B-Spline surface was prepared for the *.iges/igs file definition. The advantage of this exchange format is saving the functional definition of the B-Spline with its knot and control points directly to the file, instead to an *.stl format where a mesh is interpolated on top of the surface definition and stored in the file.

5.3 GEOMETRY POST PROCESSING

Basically, the measurements explained above have two different purposes. On the one hand, the target to predict the load bearing behaviour of the final structure right after the inflation of the dome and on the other hand monitoring the structure during the further work steps to measure the influence of additionally applied loads on top of the thin shell structure. For the first purpose, the*.iges file serves as basis data. This complete cupola from measured data is then cut out to the final structure by using a nurbs modelling software. The obtained model serves afterwards as basis for static finite element calculations. A particular challenge is the import into the finite element calculation software. In most of the cases automated interfaces are used, which modify the initial geometry into the program's data type. Within first tests strong deviations from the initial file to the transformed file occurred due to conversion errors. Sometimes the interface was even not able to transform the data into useable data. Within the current project, a fitted solution could be found by customizing the number of control points of the B-spline surface to the interface.

5.4 ASSESSMENT OF THE BUILT GEOMETRY

The comparison of the finite element calculations between the designed geometry and the modified measured geometry, with datum from 4.2.1, seen in Figure 4 (left), of the learning structure showed, that the minor form deviations to the designed structure concern only non-critical areas. Consequently, the stress results of the shell were only modified marginally and the stability of the structure could be proved for further working steps.

5.5 CONCLUSION AND FUTURE WORK

All requirements could be reached for the learning structure. Therefore, a reference frame was design and different datum definitions were introduced. The used metrology collects point and surface based dataset with the desired accuracy. Point and especially surface based evaluation methods were developed for the approximation of 3D point clouds, prepared for the structural analysing step. Although optimizations at these steps needs to be satisfied for the 1:1 scenario, the deer pass. Exemplary for this is the reduction of the bottom edge artefact of the approximated surface to provide a direct supported geometric model for the FEM software. The actual structure was proven by the FEM and shows no critical areas. Beside that, the evaluation methods and the testing program will be intensified, reaching reliable the one day measurement time slot.

Further work will be to complete the implementation of a monitoring system with the applied metrology on the hardware side. On the analyzing approach, the detection of deformations on the approximated surface is planned.

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