DIGITAL 3D RECONSTRUCTION OF ANTONIO GAUDI´S LOST DESIGN FOR A CHURCH NEAR BARCELONA, SPAIN

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ABSTRACT:

Gaudí was not only a visionary architect, but also a great constructing engineer. Creating an analog static method for calculation to design a project, he was far ahead of everybody at his time. The stereostatic model of Colonia Güell amazes not only by its design, but also, for current circumstances, by its dimensions and details (see figure 1.). Due to World War I only the crypt was built. The model and all its documents were unfortunately destroyed.
This research followed several previous reconstructions analysis. For the first time it was possible to evaluate historical photographs photogrammetrically. Through a geometrical reconstruction of the interior orientation from the unknown camera, parts oft the church could be measured three dimensionally. To gain a higher structural density for the calculation a method from the single-image photogrammetry, monoplotting, was used. Using this procedure and an approximate surface model, all visible components of the photographs could be integrated in the three dimensional model. The succeeding modelling and visualisation clarified Gaudí´s design. For uninvolved persons it is very difficult to identify this confusion of cords in the photos and in the three dimensional model. These achievements serve predominantly as a base for further research by Graefe and Demjanov (University of Innsbruck, Institut für Architekturtheorie und Baugeschichte).

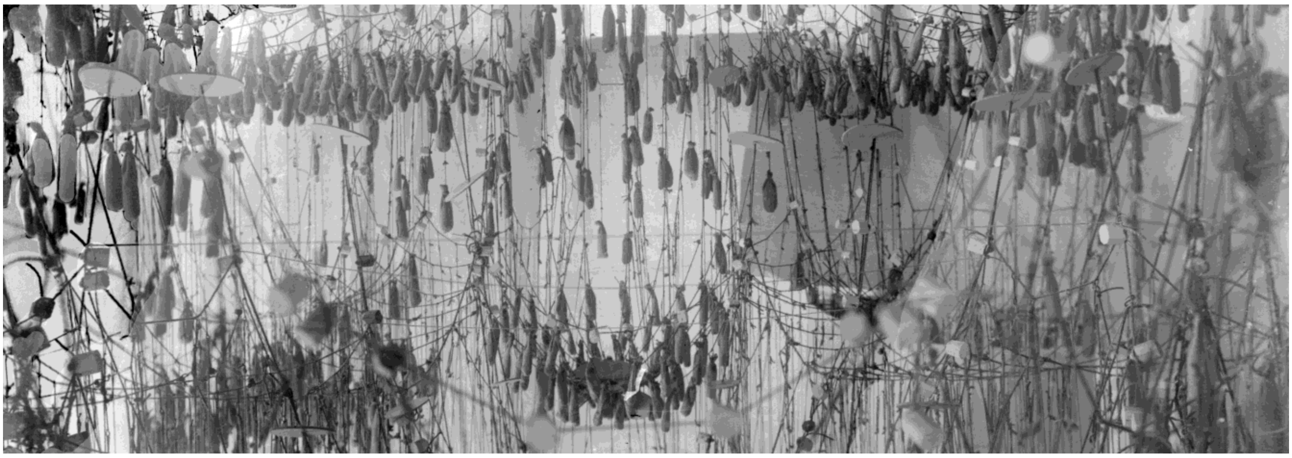

Fig. 1. Image detail of the stereostatic model

1. INTRODUCTION

About 100 years ago the famous Spanish architect Antonio Gaudí spent ten years working on studies for the design, and developing a new method for structural calculation based on a “stereostatic model” built with cords and small sacks of pellets (see figure 2.). The outline of the church was traced on a wooden board (1:10 scale), which was then placed on the ceiling of a small house next to the work site. Cords were hung from the points where columns were to be placed. Small sacks filled with pellets, weighing one ten-thousandth part of the actual weight the arches would have to support, were hung from each catenarian arch formed by the cords.

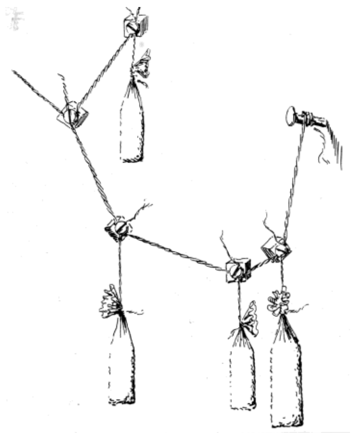

Fig. 2. System of the stereostatic model

Photographs were taken of the resulting model from various angles, and the exact shape of the church's structure was obtained by turning them upside-down. So architect Gaudí could prove vertical sections or elevations of the building.
Only the crypt of the planned church in the Colonia Güell near Barcelona, Spain, itself has been built (see figure 3). Then it had to be stopped because of the outbreak of Word War I. Decades later interest in Gaudí's work and buildings increased again. During the documentation of his work the importance of Colonia Güell was discovered. It is regarded to be a first test for Gaudí's ideas for the church "La Sagrada Familia" (UNESCO World Heritage List) which is still in a building process today (HANKE, MOSER, 2006).

Fig. 3. Entrance facade of the crypt

The original non-metric photographs of Antonio Gaudí's model date back around the year 1900 (see figure 4). They have been detected some years ago in a garret of an old Güell workers settlement in Santa Coloma de Cervello. These are probably the last existing ones because the rest of them had been destroyed during the Spanish Civil War in the 1930s.

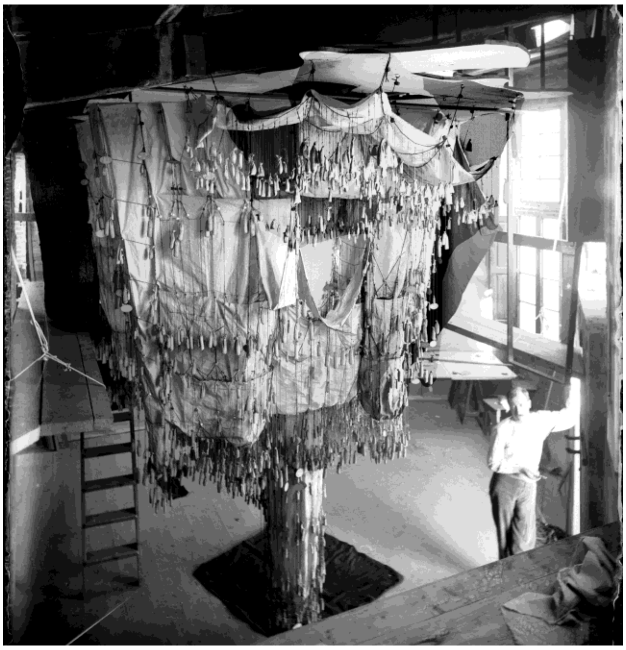

Fig. 4. Entrance facade of the stereostatic model

Various people tried a reconstruction of the church. The so far best approach was an attempt carried out by the German institute for "Flaechentragwerke" of Frei Otto in 1982. The result of this research was a reproduction (scale 1:25) built by the "Gaudí group" (Rainer Graefe, Jos Tomlow and Arnold Walz). To succeed in their work only few details were available. Of course there were publications made and measurements taken, but the use of photogrammetry therefore was not possible at this time and was rejected because of too few and uncompleted data. The photographs were an important part, reserved for comparison and analysis of the stereostatic model (for detail see GRAEFE, TOMLOW, WALZ,).

2. PHOTOGRAMMETRY

Throughout further research of Graefe and Demjanov the development of digital photogrammetry revived the interest in original photographs for an optimal reconstruction.
After the second successful evaluation with temporary results, early problems were under control. Because of the so far unknown camera and its orientation it was essential to measure other factors most precisely.
For the first reconstruction the size of the negatives was unknown. The taken photos had been only reproductions with unknown scale in x and y. This problem was solved by digitizing the original glass plates. Further it was possible to complete the technical details of the used camera in Barcelona. Because of the now known original size and measurements of the negatives a geometric reconstruction of the interior orientation was feasible.

2.1 Geometric reconstruction of the interior orientation

As base for the reconstruction a few parallels like the wooden board's joints and the vertical strings were taken, as well as a circular point pattern. Because of the parallelism of the loading strings the horizontation of the camera could be controlled. The horizontal wooden boards in combination with the circular point pattern enabled an approach to the focal length and the principal point of the image.
With Pascal's doctrine the point pattern was connected and refined to an ellipse (well known as a circle's perspective description). With the conjugate diameter of the ellipse the principal point of the photo was determined.
This enabled the construction of a square. Using its diagonal the focal length could be constructed. Besides the results fit with a former dogma, that the shorter side of the negative correlates with the focal length.

2.2 Multi-image photogrammetry

Due to the high resolution of the images technical details could be precised. It enabled a better analysis of the stereostatic model's structure and the different periods of its construction. A small change in the stereostatic model causes a general change in its entire structure. The exact position and the direction of the load determine the extent of the deviation. Only a few photos date from the same period of time. On each image small changes of the stereostatic model's structure are visible. For precise results of the photogrammetric evaluation deviations must be reduced to a minimum.
The remaining camera positions were reduced to three points of view. Two of them were on the main axis of the church. Due to the bad orientation conditions the number of control points had to be increased and improved. The circular point pattern enabled a rectification of the control points on the wooden

boards of the altar. In combination with an old plan of the cryptas's column positions an optimal orientation of the three images could be reached.
For the following photogrammetric bundle block adjustment all data could be assembled. Compared to the first try the numbers of details were augmented. The results were surprisingly stabile and enabled the involvement of two exterior images.
Despite their low resolution the illustrations of the former publications (early 20th century) were useful. In a following step the altar was completed in its structure (see figures 5 – 6). Gaudí used these images for his over-paintings. The camera positions of the exterior images enabled an inclusion of Gaudí's preserved over-paintings.

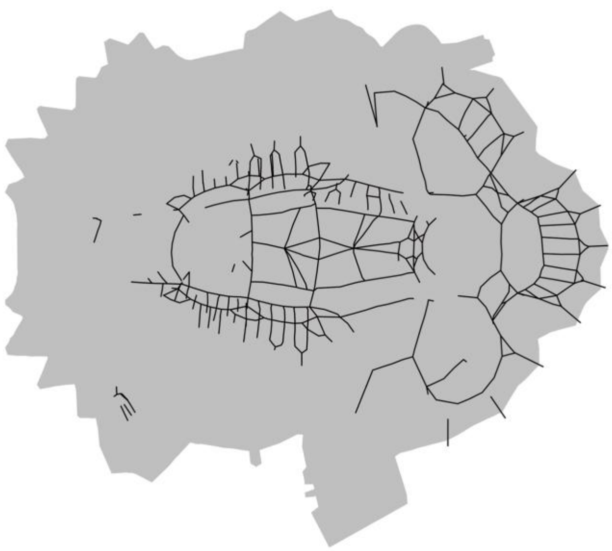

Fig. 5. Ground view - results of multi-image photogrammetry

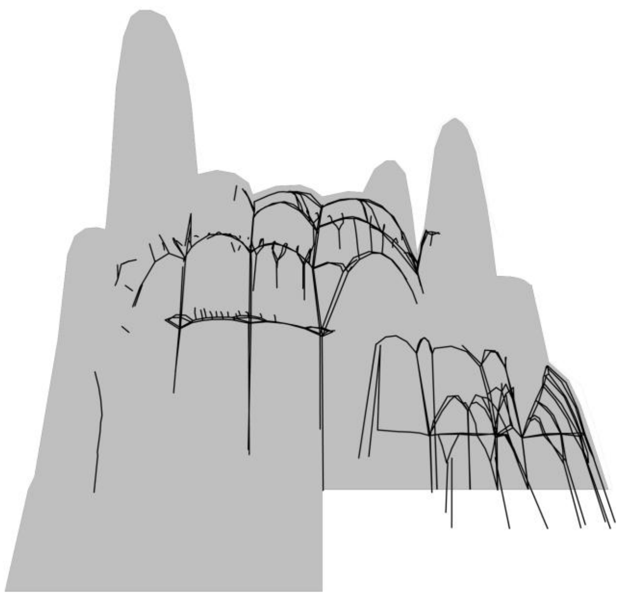

Fig. 6. Side view - results of multi-image photogrammetry

2.3 Single-image photogrammetry

2.3.1 Approximation of the shape: Up to now many parts of the stereostatic model could not be evaluated by multi-image photogrammetry, because important details were displayed on one photo only. To reconstruct an approximate cord model from only one photograph monoplotting turned out to be a reasonable method. This approach allows a complete integration of the available information of the image into the three dimensional model of the church.

2.3.2 Monoplotting: This method enables a spatial determination of a certain point from a single photograph. A desired point is calculated by the intersection of the projected rays with a digital surface model (see figure 7). The interior and exterior orientation is taken by multi-image photogrammetry (for detail see LUHMANN). The reconstructed wire frame model of the church served as a base for the required surface model.

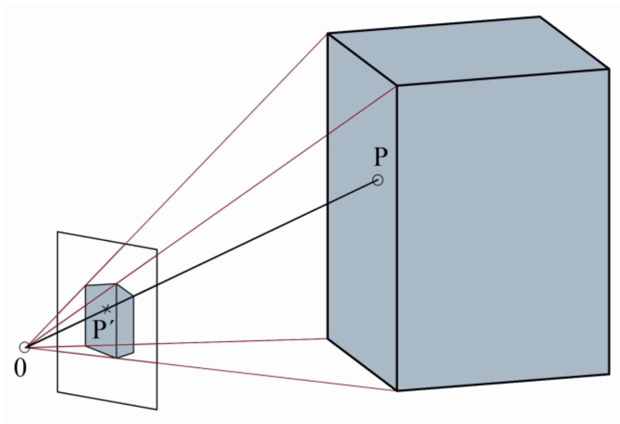

Fig. 7. Monoplotting

2.4 Initial situation - improved structural analysis and targeting of structural pieces

The results of the photogrammetric evaluation were imported to a CAD software. The upgraded image quality by digitalizing the original glass plates enabled a control of the antecedent structural analysis. In addition the number of assignable components could be increased. Furthermore the construction system of the church could be investigated more precisely. Hidden and diffuse areas in the photos of the cord structure could be reconstructed.

2.5 Digital surface model with geometric estimates

For further processing the wire frame model of the church's evaluated structure could not be used as a surface model. The advanced structure and system analysis of the stereostatic model enabled a better initial situation for geometric estimates. It could be precisely considered how the surfaces between the cords were created. The intention of the single-image photogrammetry was not to gain an exact reconstruction, but to achieve the best possible approximation to the original design. Using the available photos for an exact reconstruction was not the aim, because several regions of the cord model were displayed on only one photograph and a couple of cords were in different design stages. In every image minor differences have been detected. Especially the exterior photograph of the church caused problems. Some cords of the stereostatic model in this image were missing or differently arranged. In addition the internal space was covered with cloths for a better view. Unfortunately all these factors had an effect on the stereostatic model. Our main interest was focused on two inside photos of the church.

2.6 Surface for intersection

2.6.1 Single unknown points: In the calculated structure not all points of a constructional element could be referenced. They were covered or cut off on the photo. The intersection surface served as connecting line, or spline, of the proximate and already calculated points in ground or side views.

2.6.2 Several unknown points in a constructional element with large or similar load: Depending on the type of weight, cords in a stereostatic model can generate very homogeneously compared to proximate cords. At constant load, identical length of the strings, depending on the connecting line of the endpoints of the cords, a homogenous form can be generated. An alternative would be vertically charged heavy weights. The surfaces between the boundaries are approximate plane. The user coordinate system for the cutting plane is defined by three vertices of the bordering structure.

2.6.3 Vertical intersection surface: A special form in the model are free-standing arches. They are fixed only on their bases and are vertically loaded (see figure 8). The arches are basically elements of galleries and single wall segments. In general, for a reconstruction both root points are used. With only one base the direction must be known. It can be overtaken by analog elements in similar situations.

Fig. 8. Free-standing arches

2.6.4 Section with a level curve or altitude reference: Gaudí used approximately horizontal supporting cords to adjust the shape of the model or for an equal form of the wall. These cords are found mainly in the wall at the bases of the galleries and as horizontal rings for the towers. A possibility to reconstruct the shape of the level curve is further a horizontal supposition with an altitude reference to the photogrammetric evaluation. This temporary result will be completed, if possible, by further details. In search of an optimal form of the wall, all points are connected with a spline. A good approximation of the supporting cords in their different levels can be achieved by removing the obvious bends in the line.

2.6.5 Intersection surface on the basis of boundary lines: With complex shapes and known boundary lines it is possible to complete the missing points with a cut of an edge defined surface. For the entrance facade the level curves for the crypt and the roof level were reconstructed. The right edge of the wall was already known from the evaluation of the stair tower (see figure 9). The surface generated by the available edges served as slice plane for the rays of the wanted points.

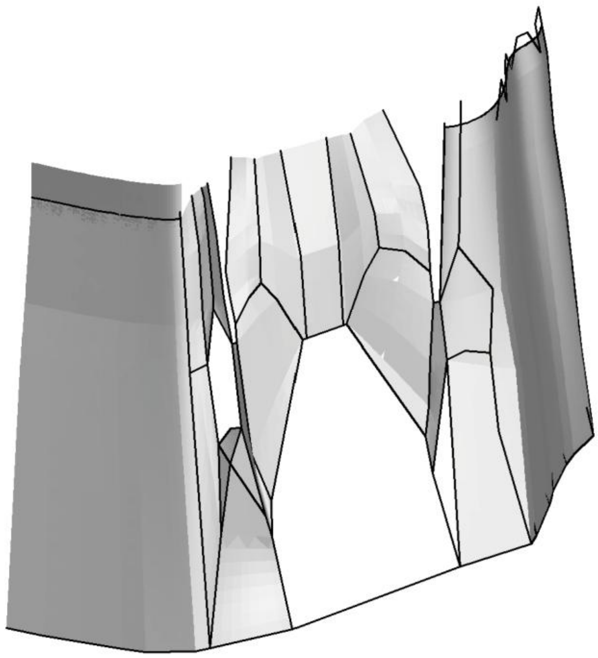

Fig. 9. Surface model of the entrance facade

2.6.6 Takeover of silhouettes: Using multi-image photogrammetry two exterior photographs with poor image quality could be orientated, but the visibility of the cords was very limited. For referencing only the back wall of the altar area was useful. Although silhouettes were visible, an integration to the 3D model was not possible. Using monoplotting it is possible to reconstruct contours of certain components. The intersection surface is parallel to the image plane and arranged through a known point. The devolved shape to the 3D model was the base to construct the component.

2.7 Reprojection

The first control of monoplotting is a reprojection of reconstructed components. The mentioned exterior photographs, with poor quality, qualify for a comparison of outside edges and proportions. An augmentation of precision in the 3D model of the church is feasible.

A further application is an adaptation of constructed components without an integration of projection rays. For the right stair tower only a few edges, near the spire, could be measured by photogrammetry. From a pocketbook of Gaudis assistant the hanging basis coordinates of the stereostatic model in the crypt are known, as a consequence the ground plan of the stairs, too. With an altitude reference of the multi-image photogrammetry the highest ring of the stairs helix could be determined. Comparing the edges from the photogrammetry, an equal gradient of the helix was noticed. The initial situation for the construction of the stair tower was an estimate of a constant helix in the model and the two ground plans of the crypt and the roof level. Using the re projection of the stairs the confusion of cords could be unscrambled and reference points were found. Through this a further alignment and correction was possible.

2.8 Evaluation of results

Considering all available measurement methods a three dimensional surveying is seen to be best qualified. Without exact information of the section level, such a complex shape of a church is very hard to read in a 2D plan. A subsequent modelling would create a lot of work and would not be as precise.

The measurement is simply a control for the three dimensional model. It was only used for one determination of a base, a column in the entrance area, during the reconstruction. The conformity of the various results (see figure 10 and 11) of comparable areas is surprisingly good, considering all potential sources of error from surveying of the original model, to the building of the crypt and at least the measurement and reconstruction of the church itself. The constant corkscrew staircase shows only a little deviation, too. Errors occur, if, at the estimated beginning and end of the stair tower's helix.

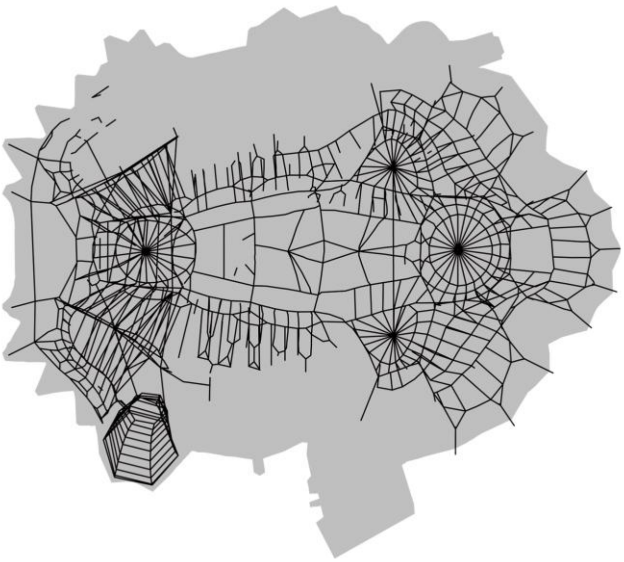

Fig. 10: Ground view - results of monoplotting

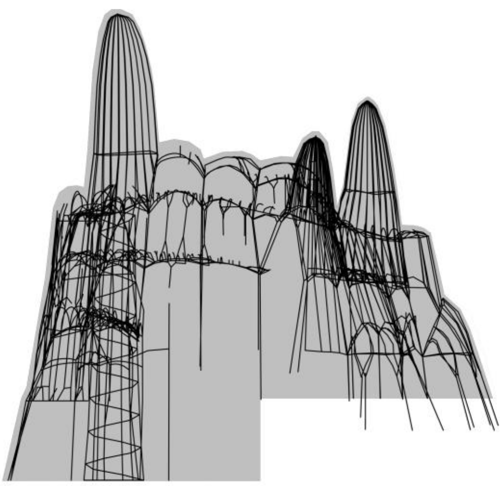

Fig. 11. Side view - results of monoplotting

2.9 Modelling and visualisation

The results of the photogrammetry served as skeletal structure. The diameter of columns could be determined by monoplotting. All further dimensions of components were taken from the datas of Graefe and Demjanov. Although modelling does not provide further research results, it is an important instrument to understand Gaudí's concept. To look through a "chaos of cords" on the images, or the three dimensional wire frame model, much time and patience is necessary. However it is difficult to imagine the form and especially the details of the church.

Fig. 12: "Chaos of cords"

Some original over-paintings are preserved, but they cannot give an overall impression. A three dimensional model features a sequence of applications, that are very useful in this complex construction, especially for further research for Graefe and Demjanov, their current models' construction and following publications. Various sections can be shown without big time efforts. This advantage can only be realized by a 3D method.

3. CONCLUSIONS

The result of this research was surprisingly good for all involved groups. Although an approximation method was used, it is currently the most precise possibility for a reconstruction of the church. An essential advantage of monoplotting is the small deviation in the height. The closer a wanted point on a photograph is to the imagine horizon, the smaller is the tolerance in the model. A reason for this method was also the position of unsolved details after the multi-image photogrammetry. Most of the wanted components were in the middle of the image.

Because of photogrammetry many detailed questions could be answered. One of the most frequently discussed problems was the level curve of the gallery and the respective hights of their arches, the connection of the stair tower to the church and the possible entry or exit of the stairs and a confirmation of Graefe and Demjanov's supposition of a level grid in the stairs helix. The photogrammetry answered the difficult question about the shape of the altar area with its three towers and the entrance`s facade with its complex structure. At the moment there is no other method available which leads to comparable results. At the beginning only planned as a supporting method, photogrammetry turned out to be the most important part for this research project.

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