DOCUMENTATION OF GERMAN EMPEROR MAXIMILIAN I's TOMB

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ABSTRACT:

Innsbruck was the residence of the Habsburg Dynasty between 1420 and 1665. The Hofkirche with its tomb of German Emperor Maximilian I is one of the most famous and outstanding historical monuments, being in the property of the State of Tyrol. It was built between 1555 and 1565 under Ferdinand I (the brother of Emperor Karl V). The cenotaph (i.e.: empty tomb) of Maximilian is located in the center of the church's nave. The cenotaph itself has a base of about 3 m x 5 m. 24 very delicate white marble reliefs are attached to a black marble structure which is decorated by bronze elements. With the kneeling Emperor and four more bronze statues on top of the monument it is about 5 m high. For centuries the tomb was separated from the visitors by a black iron lattice. In addition, the fine caved marble plates were covered by glass. Because of a basic conservation and restoration of the tomb, lattice and glass plates were removed for the first time ever since its construction in the 16th century. For a short period in May 2002 all sides were accessible after the temporary housing of the restoration technicians had been removed from one side and not yet been moved to the other side for the second restoration period. This time slot could be used for a complete metric documentation of the object. Both, close-range photogrammetry and 3D scanning techniques were used. A common geodetic control point system was installed for both methods. Photogrammetric work consisted of stereo pairs and separate color images. 3D scanning was accomplished with a MENSI S25 for the overall structure and a GOM ATOS II at high resolution for the relief plates. Line plots from the photogrammetric stereo models do not really give an adequate representation of the object. 3D visualization using the scanning results can achieve a much better impression of the complicated geometry after the data modelling. In order to model the complex geometry, it is necessary to use huge amounts of data. The project proves the enormous potential of these new technologies, but shows as well that more progress is needed in hardware and software development to accomplish such demanding tasks.

Fig. 1: Total view of the cenotaph during the measurement work – for the first time ever without lattices and glass plates

1. MAXIMILIAN I's CENOTAPH

1.1 Historical background

Between 1420 and 1665 Innsbruck was the residence of one of Europe's most known imperial families, the "Habsburger". The Hofkirche at Innsbruck with the tomb of Emperor Maximilian I probably is the most important art-historical monument, which is possessed by the country of Tyrol. It was built between 1555 and 1565 under Emperor Ferdinand I (the brother of German Emperor Karl V). It contains the most important German emperor grave of Maximilian I. The cenotaph (i.e. technical term for an empty tomb) with the statue of the kneeling Emperor is in the center of the church's nave. The tomb was created by artists from various countries, who cooperated in the production. It is a unique certification of European court art, which was influenced by the personality of the Emperor and its successor as clients. The sarcophagus is surrounded by 28 more than life-sized bronze figures, embodying ancestors and relatives of Maximilian, the so-called "Schwarze Mander" (i.e. black men).

1.2 Description

The cenotaph (fig. 1) comprises about 3 m x 5 m. The top of the Emperor's statue is 4,5 m above the base. The cenotaph consists of a frame of black marble in which the 24 reliefs of white marble (each approx. 82 cm x 55 cm) are embedded in two horizontal rows. These reliefs show scenes from the life of the Emperor Maximilian I. They have a level of detail within the range of 0.1 mm and had to be documented in particular and with highest available precision. On the cover of the tomb the kneeling figure of the Emperor is central, surrounded by representations of the four basic virtues, which are arranged at the four corners. All mentioned figures consist of dark bronze.

1.3 Restoration measures 2000/2003

On the occasion of the preservation and restoration of the tomb a complete art-historical and geometrical documentation was initiated for the first time since the completion around the year 1568. In order to make a continuous access for tourists possible, only in each case one half was concerned by the measures of restoration and covered in a boarding. The other part remained accessible for the public. However, the cenotaph was separated for centuries by a wrought-iron lattice from the visitors (fig. 2). Additionally the white reliefs were hidden by glass plates. In May 2002 the right half was completely restored and it became necessary to dismantle and transfer on the other side. Thus, for ten days for the first time since its establishment the cenotaph was accessible from all sides and unwrapped both from lattices and from windowpanes (fig. 1). This time slot was used for the complete documentation and the measurement work described here.

2. DATA ACQUISITION

2.1 General remarks

The setting of tasks was not clearly defined – as is often the case in comparable projects, and had to be developed in co-operation with the responsible authorities. It stood firmly that the rare chance of accessibility from all sides should be used for documentation by all means. Of course, neither detailed plans nor art-historical documentations of this tomb were available at this time. Because of the preciousness of the object - and the uniqueness of the opportunity for data collection - accordingly a combination of geodetic measuring methods was suggested and carried out in May 2002.

Fig. 2: Total view of the cenotaph - behind lattices – before the restoration work

On the one hand classical close range photogrammetry was used for the complete measurement of the cenotaph and on the other hand - due to the high detail of the reliefs – the 3D documentation should be carried out by use of 3D scanning techniques. The geometrical survey of the object by the 3D scanners also would be combinable in the future with the radiometric information from the photos when both methods were used in one operation. The measurements were accomplished by three independent teams. In order to avoid interference during the short time available, all measurements had to be coordinated exactly and scheduled accurately in advance.

Since the surveying methods for the geometric documentation of the cenotaph have been described in earlier publications (Marbs 2002, Hanke 2003), only a brief outline is given in the following sections.

2.2 Geodetic survey and photogrammetric densification

A general requirement for all surveys was a common coordinate reference. A precise network of eight observation points around the cenotaph was established and vertical and horizontal angles were observed to the reference targets for the scans and the photogrammetric images (spheres and self-adhesive flat targets). An accuracy of better than 0.5 mm (standard deviation of spatial location) could be achieved. Additional targets which were necessary for the detail scans of the reliefs were stuck onto transparent adhesive tape which was fixed in front of the reliefs without touching them. The coordinates for those targets were derived from photo triangulation using GOM's widely automatic TRITOP system (GOM, 2003).

2.3 3D structural scanning with a MENSI S25

A complete scan of the cenotaph was achieved with a MENSI S25 triangulation type laser scanner (MENSI, 2003). A point density of about 2 mm was chosen. This resulted in 20 observation locations from where a total of about 10 million points were recorded in about 60 hours of scanning time. As long as a scanning range of 5 m is not exceeded, the MENSI S25 will achieve a point accuracy of better than 1 mm.

2.4 3D detail scanning with a GOM ATOS II

Because the marble reliefs show very fine details, it was necessary to use a high precision scanner for their documentation. A GOM ATOS II scannner was chosen. This scanner projects fringe patterns onto the object and uses two cameras to analyze the resulting images (GOM 2003). Since high resolution was important, the version with a 400 mm base and 35 mm cameras was selected. In this configuration, the scanner yields about 1.3 million points in a field of view of 175 mm x 140 mm. Thus, twelve scans would cover one relief (not counting numerous additional scans which were needed to reduce the hidden areas due to occlusions). The raw data for one single relief amounted to about 450 – 700 Mbytes.

2.5 Photogrammetric imaging

A photogrammetric documentation of the whole object was carried out by a private surveying company experienced in the documentation of cultural heritage. A Zeiss UMK metric camera was used. In addition, stereo images were acquired for each relief on high resolution b/w film. Also, orthogonal images were exposed on color film for later rectification and/or texturing.

3. HARD- AND SOFTWARE FOR PROCESSING

3.1 Hardware

Since very large amounts of data have to be handled and visualized, a 2.667 GHz PC with 1.5 Gbyte RAM, including a GeForce4 4600 video board with 128 MB RAM, was acquired for data processing.

3.2 Software

As reported earlier (Marbs, 2002), software requirements for large 3D models consisting of irregular meshed surfaces are very demanding. Some products will not even load more than 1 million 3D points let alone meshing and editing of such data. From all programs tested for this task, Raindrop Geomagic Studio (which was used in the latest Versions 4.1 and 5) proved to be the most versatile (Geomagic, 2003). Nevertheless, even with this software it is not possible to run all processing steps (see following section) when a complete model for one of the 82 cm x 55 cm reliefs is loaded.

Thus, for the time being, the following proceeding had to be chosen for the 3D representation of the whole cenotaph:
- one coarse model with 2 mm sampling for the whole object using Mensi S25 data
- one fine model based on GOM ATOS data with 0.3 mm basic sampling (further reduced by about 40% using a curvature based algorithm) for every one of the 24 reliefs
- five to six very fine partial models for every one of the 24 reliefs with 0.1 mm sampling using the full resolution available from the GOM ATOS II data

4. DATA PROCESSING

4.1 High resolution model (one model per relief)

Merging. In a first step, all (up to 35) scans available for one relief are imported into Geomagic Raindrop Studio. After all points outside the relief area are deleted, the various scans are merged into one single data set. This does not include any transformations since the registration was already completed earlier in the GOM software using the targets which were determined in the photogrammetric densification process described in section 2.2.

Thinning. Point density in the object varies considerably. Areas in the foreground may be registered in many scans taken from different viewing angles whereas areas in the background may have been scanned only once (or even been missed completely). The aim of the thinning procedure is to delete surplus points in repeatedly scanned areas. At the same time, the total number of points has to be reduced below 4 million points which is a critical value for some of the following procedures, especially the reunion procedure following the hole filling ('Merge Polygon Objects', see below). After some experiments, the best solutions could be achieved when the points were first thinned to a uniform sample width of 0.3 mm and subsequently the sampling rate of a curvature based algorithm was changed until the required threshold of 4 million points was reached. This could be accomplished by deleting about 35 to 45 % of the 0.3 mm sample.

Meshing. The automatic meshing procedure creates about 8 million triangles from of the 4 million points. With the hard- and software used, this will take about 10 to 15 minutes of processing time.

Checking manifold meshes. At the end of modeling, the object should be covered by one continuous mesh only. After the first meshing, several isolated meshed surfaces can result, however. For example, the surface of a shield held by a hidden knight's arm may result in such a separate surface. If the surface is significant (as in the case of the shield) it has to be connected manually to the main mesh by introducing suitable triangles. The result should be checked again for manifold surfaces. Accordingly, the examination for manifold meshes should be repeated after any manipulation of the data as described in the following steps.

Cleaning. The cleaning procedure of Geomagic Raindrop re-adjusts neighboring triangles which show large orientation differences. It applies a sophisticated shape-cleaning algorithm that alters the triangulation of the point data and results in a certain extent of relaxation of the mesh. The cleaning procedure can handle 6 million triangles only. Therefore the relief has to be split in two parts which are processed separately.

Hole filling. Even with many scans from different angles, some parts of the reliefs remain unrecorded. This is due to the very detailed structure of the reliefs which contain very sharp edges and even free standing figures and objects whose rear sides cannot be inspected from any observation point. The recording method of the scanner requires any surface area to be visible from the light projector as well as from the two cameras at the end of the instrument's base. This fact results in additional inevitable holes in the object.

Before the holes are filled, the relief is divided into six parts because the filling procedure may prove problematic if more than 2 million triangles are loaded.

Geomagic Raindrop offers an automatic hole filling procedure which interpolates new points based on the curvature of the surrounding area. This works well when the area is flat and curvature is changing smoothly. Often the last points recorded at the edge of a hole show large deviations, however, because they have already been partially occluded by the object parts
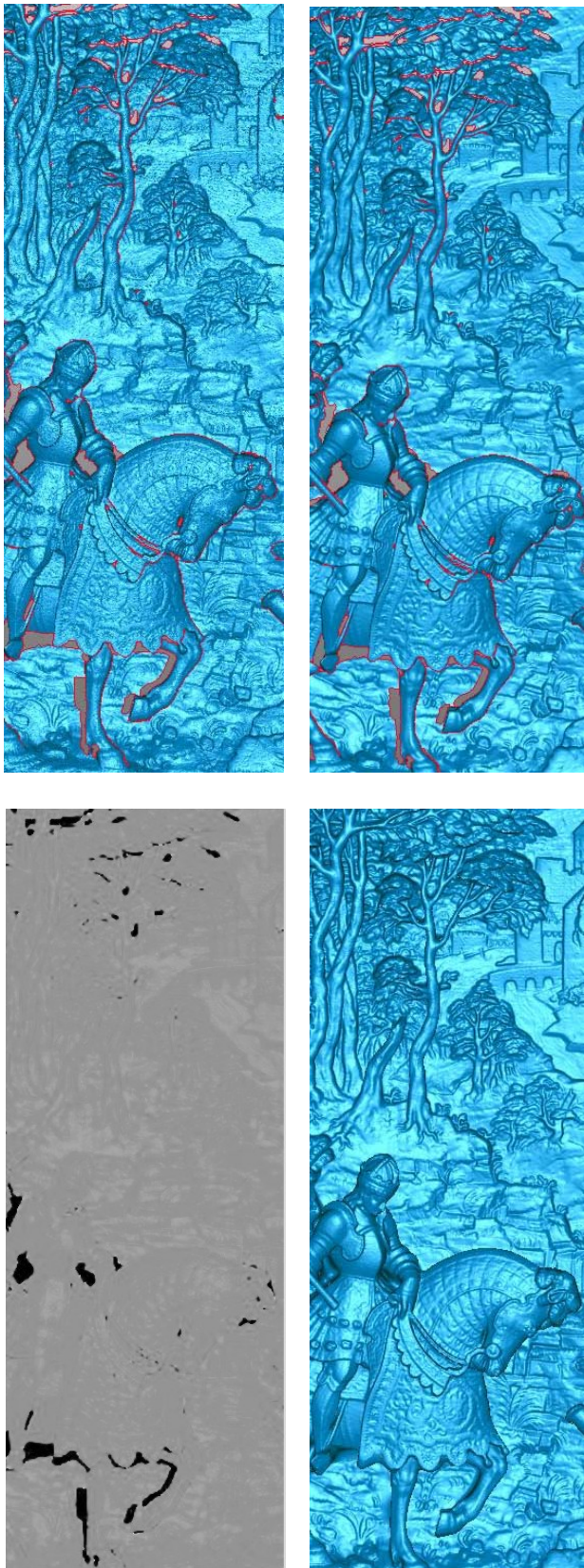
Fig. 3: Processing steps in Geomagic Raindrop Software.

UL: Result of first meshing.
UR: After checking for manifold meshes and cleaning.
LL: Positions of holes. LR: Final result.

Approx. Scale 1:4

that in the end caused the adjacent hole. These holes remain after the automatic filling. In these cases, the last row of triangles around the holes is removed and the automatic filling procedure, when applied again, will be successful for further holes. If the object structure is very complex, which is not unusual in the neighborhood of holes, the hole filling has to be accomplished in an interactive manual process which is very time-consuming. The hole filling treatment for one single relief may require up to four working days!

When all holes are removed from the six separate parts, a complete model of the relief is merged again. As mentioned above, this 'Merge Polygon Objects' process can handle only about 4 million points. This is the reason why a very high resolution model cannot be produced for one whole relief. If any holes are left that extend from one previously separated part to an other one, this area, including the complete hole, has to be selected now, the holes have to be filled and the separated area has to be merged again with the rest of the model.

All points and triangles created in the hole filling process are also stored in a separate file, since they can be used again when the very high resolution model is created (see section 4.2).

4.2 Very high resolution model (5 to 6 models per relief)

A point distance of 0.1 mm is aimed at for the very high resolution model. All scanned points as merged for the fine model (see 4.1, merging) plus all points resulting from the hole filling process as described in section 4.1 are introduced. Then the points are thinned to a uniform 0.1 mm point width. In order to make data handling possible, the relief is now divided into 5 to 6 sub-models which should contain not more than 3 million points each.

The following procedures are much the same as described above for the fine model: The points are meshed and cleaned. Manifold checks are applied after every procedure that results in data changes. New holes appearing in the model because of the more sensible meshing parameters must be filled. This has to be done in subsets which have to be merged again afterwards.

4.3 Coarse resolution model (one model for the cenothaph)

Fig. 4: Coarse resolution model (shaded view of point cloud)

Fig. 5: Plot from stereophotogrammetric images (photographed and plotted by Linsinger Vermessung). Screenshot, scale about 1:5.

Fig. 6: Shaded view from high resolution scanning data. Screenshot, scale about 1:5.

Because of the processing limitations caused by the hard- and software which have been mentioned above, the 3D model of the whole cenotaph structure will remain relatively coarse as compared to the relief models. The 2 mm sampling as well as the poorer accuracy of the 3D points result in a good geometric model for the whole structure; detail resolution and neighborhood accuracy are not satisfactory, however. The procedures to be carried out are much the same as described for the high resolution model (section 4.1). A combination of all scanned and meshed information is not possible presently. There is little doubt that this can be accomplished in the near future.

Fig. 7: Detail of figure 6. Scale about 1:1

Fig. 8: Same detail as in figure 7, but seen from different angle.

5. RESULTS AND CONCLUSIONS

Results of the documentation project are presented in figures 4 through 8. The full value of the data can only be judged when evaluated in 3D on a computer monitor, however. 3D scanning yields results that have not been possible in the past for objects with extensive and complicated 3D surfaces as in the case of the cenotaph and the associated reliefs. Photogrammetric matching methods to achieve a digital object model do not work in this case as the white marble reliefs do not show enough texture. Orthophotos or line drawings from stereo pairs can be useful for some purposes but do not contain the information for the creation of a complete virtual (or real) model.

The processing of the laser scanner data is very time-consuming, however, when high model quality is aimed at. Presently, it also suffers from many restrictions. Even with the latest computers and software products, certain processing steps are only possible when the number of meshed triangles is less than some millions. If the development in hard- and software continues as rapidly as in the past, these problems should be overcome in a few years. Even a combination of laser scanner (geometric) and photogrammetric (texture) data may become available for such large and complicated objects. Since all the original cenotaph data are archived, improved results may be created in the future.

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