3D Reconstruction and Accuracy Analysis of Historical Relief Models

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ABSTRACT

The relief of Franz Ludwig Pfyffer, constructed between 1762 and 1786, is considered the world's oldest large landscape model and a pioneering work of Swiss cartography. Based on Pfyffer's own measurements, the 26 m^2 big work represents topographically an area of almost 4100 km^2. The relief, which served as a basis for several printed maps issued at the end of the 18th century, is now a subject of the first quantitative evaluation. Applying principles of aerial photogrammetry, a precise 3D model of Pfyffer's relief is created for the documentation of cultural heritage. As a main research aim, several methods for the comparison of the virtual model with current map information are developed: planar and spatial transformations of identical points and an analysis of digital surface models. Suggested approaches consider object distortions in all three directions and allow making statements about relief accuracy as well as reconstructing Pfyffer's model building strategy.

1. INTRODUCTION

Old maps, charts and 3D models have traditionally been a subject of study by the historians. These masterpieces combining art and a great knowledge of surveying and cartography currently receive deserved attention of scientists as well. In particular, photogrammetry and digital image processing are being used to extract metrical and semantic characteristics of historical maps (for example see Baletti, 2000 and Rickenbacher, 1995). This paper addresses a three-dimensional aspect of historical cartography and focuses on the image-based reconstruction and geometrical evaluation of one of the most remarkable landscape models in the history – the relief of Franz Ludwig Pfyffer.

2. PFYFFER'S RELIEF

Lieutenant general Franz Ludwig Pfyffer von Wyher (1716-1802) devoted 20 years of his life to the construction of a relief of Central Switzerland (Figure 1). The result of his surveying and cartographic work – a 6.7 x 3.9 m^2 big model of Lake Lucerne and neighboring cantons – displays as much as 1/10 of the country in a scale of about 1:12500. Finished in 1786, Pfyffer's relief attracted numerous visitors from all over Europe to Lucerne. This masterpiece is not only a fascinating three-dimensional representation of the mountainous area of Switzerland, but also a significant improvement of existing maps at that time. A detailed study of Pfyffer's relief probably played an important role in the victorious battle of French troops against the Russian field marshal Alexander Suvorov in the topographically complicated St. Gotthard region in 1799. As a strategic cartographic object, the French commander Napoleon Bonaparte planned to buy the relief in 1805 (Imhof, 1981). Fortunately, at that time better map information was already available and the model stayed Swiss property. Today it can be admired in the Gletschergarten Museum in Lucerne as the world's probably oldest large landscape model.

The model is constructed from pieces of timber, bricks, charcoal and cardboard with a mixture of gypsum, sand and beeswax as a top layer. Thin cords and chenille indicate roads, rivers and railway lines. Other landscape objects such as churches, houses and bridges are thoroughly modeled using colored beeswax. The relief surface is painted with tempera and oil colors.

The project goals include:

- 3D reconstruction of the relief for the documentation of the cultural heritage
- Analysis of the relief accuracy for the purpose of research in the history of cartography
- Investigation on Pfyffer's surveying and modeling procedures

Figure 1 A view on the Pfyffer's relief

3. 3D MODELING AND VISUALIZATION

The project objectives require a high quality 3D model of Pfyffer's relief. Therefore great attention has to be paid to the selection of optimal procedures and instruments. Moreover a narrow room without natural light where the relief is situated makes the image acquisition as well as control point measurement fairly difficult. From a 185 cm high construction, 87 analog and 50 digital "aerial" images were taken in a scale of about 1:22. Both cameras were calibrated using a close-range photogrammetric reference field. The three-dimensional position of control points in a local coordinate system was determined by theodolite measurements with an accuracy of 0.09 mm. Analog images, selected as a basis for the photogrammetric processing, were triangulated manually on an analytical plotter. The achieved block accuracy of 7.62 microns corresponding to 0.17 mm in object space is very satisfactory. Currently, the DSM measurement is in work.

Within a previously finished pilot project, a part of the relief (220x150 cm^2) was reconstructed in both manual and automated mode. The comparison of a manually measured reference DSM and automatically derived models shows that the matching procedures cause unacceptable errors in the derived surface. That is the reason why we decided to resort to manual measurements in the main project phase. For the results of visualization see a texture-mapped 3D model in Figure 2.

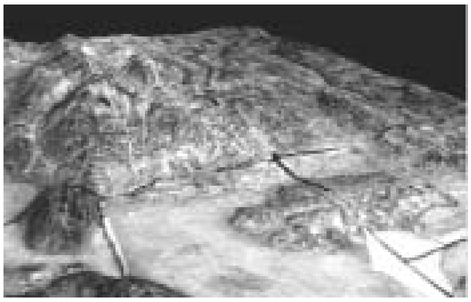

Figure 2 The reconstructed part of the relief

4. ACCURACY ANALYSIS

Photogrammetric processing of Pfyffer's relief resulted in a pilot data set (DSM, orthoimage and structured 3D vectors such as roads, rivers, settlements etc.) maintained in a GIS together with actual map information of the area (digital terrain model DHM25, digital map 1:25000 and vector data VECTOR25). The accuracy analysis of the relief is based on a number of identical points selected according to principles of historical cartography. Each point is assigned to one of three categories quantitatively estimating its reliability. Several methods for the comparison of historical and actual data sets are developed:

- Global planar and spatial transformations. In this step, identical points are transformed using non-polynomial transformations with weighted observations, such as planar Helmert and affine transformations and spatial 7- and 9-parameter (3 shifts, 3 rotations and 3 scales) transformations. Global transformations allow statements about absolute relief accuracy. The best results, achieved by means of the last mentioned transformation are as follows: planar vector of relief's identical points deviates from actual data of 182 m and a height vector of 65 m in average of absolute values, represented by 1.6 cm and 0.6 cm in the relief. Differences on the background of the 3D model are depicted in Figure 3.
- Local transformations. In order to improve relief planimetry for a height analysis, local transformations are performed. For this purpose, a Delaunay triangulation mesh is created on identical points. All the points within a triangle are transformed using its vertices as reference. In this way, vector data of Pfyffer's relief can be superimposed and compared with actual map information.
- DSM analysis. DSM analysis of historical reliefs addresses a question of comparing two 3D models showing up differences in all three directions. The historical reliefs are distorted and their height scale is often magnified on purpose. Two approaches are used to solve these problems. The actual terrain model DHM25 is compared with an irregular point cloud obtained by transformation of historical relief using identical points (a) in space or (b) in the plane either directly or mesh-wise. The first

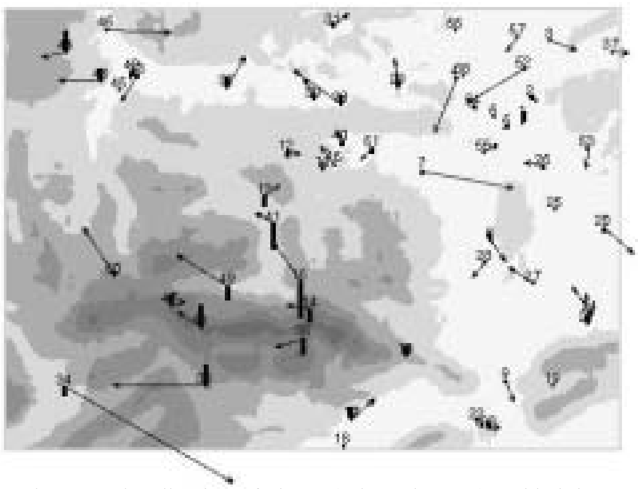

Figure 3 Visualization of planar (oriented arrow) and height (vertical bar) differences on identical points of Pfyffer's relief after spatial 9-parameter transformation

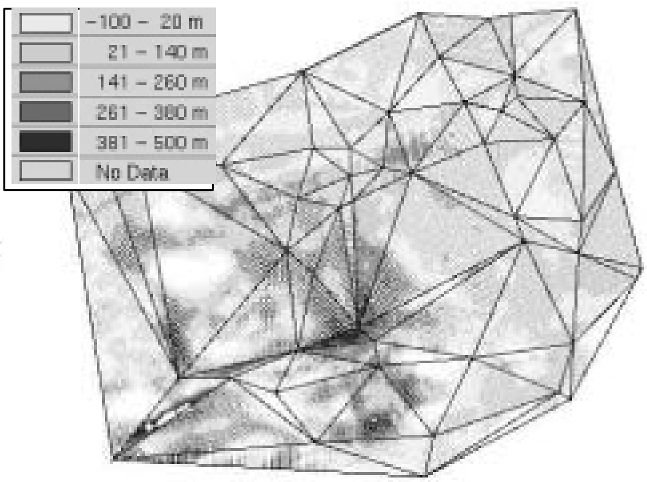

Figure 4 Difference DSM: 3D model of Pfyffer's relief was transformed on the actual map data using mesh-wise affine transformation and afterwards compared with the DHM25

procedure includes a simultaneous determination of the height scale and achieves good results - 108 m average absolute height difference and 150 m standard deviation (0.9 and 1.3 cm in relief). In the second approach local relief distortions are decreased and heights can be compared by any given scale – even a changing one – in the next step. This method allows a separate consideration of planar and height accuracy and as such it respects model building strategy of most historical reliefs. Find an example of planar mesh-wise DSM transformation and a height comparison of Pfyffer's relief with the DHM25 in Figure 4.

For the first time the relief of Franz Ludwig Pfyffer has been quantitatively evaluated. The a-posteriori standard deviation of the spatial vector on identical points, reaching 1.7 cm within the 26 m^2 big relief as well as the average height error less than 1 cm show a surprising accuracy of the relief constructed long time before the first Swiss national triangulation network. Moreover, these numbers consider not only the accuracy of Pfyffer's surveying, but also include an influence of model construction.

5. CONCLUSIONS

On an example of the relief model of Switzerland, constructed by Franz Ludwig Pfyffer in 1762-1786, methods for 3D reconstruction and accuracy analysis of historical reliefs were shown. A remarkable feature of the photogrammetric part of the project is an unusual combination of aerial and close-range applications: a big landscape mapping process is performed in an artificial environment of a cellar room of the museum. For the accuracy analysis approaches are suggested that allow meaningful evaluation of old 3D models, taking into account a probable way of their creation according to research in history of cartography.

After finishing the photogrammetric reconstruction of the overall Pfyffer's work, the developed methods for accuracy analysis will be applied. Further project steps include investigation on surveying process for the relief construction. Finally, procedures for visibility analysis of preserved topographic sketches of Franz Ludwig Pfyffer will be implemented.

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