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Automatic reconstruction of old globes by photogrammetry and its accuracy

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Summary: Virtual 3D model of an old globe can be created automatically using Structure From Motion (SFM) algorithms on an appropriate set of photographs. This convenient new way of globe digitising raises new problems and questions. The texture of the model has to be transformed into equirectangular projection to facilitate further work. The reconstructed model brings new meanings of accuracy: the similarity of the 3D model to the original one; the positional accuracy of the globe map content within its own geographic graticule; the positional accuracy when the globe content is compared to the actual geographical positions.

This paper introduces a possible photogrammetric globe digitising method and discusses the ways of measuring the various aspects of accuracy.

Introduction

Due to the continuous increase of the computing power of an average PC and the emerging Structure From Motion (SFM) algorithms, creating a 3D model based on photographs is easier nowadays than ever. The method is quite simple: the object is photographed from many different angles, ensuring that every detail of the object surface is visible on multiple photos. Then the images are loaded to the SFM application and the result will be a textured 3D mesh. The method is popular in the field of cultural heritage preservation (e.g. Chiabrandu, Donadio, Rinaudo 2015), especially for digitising sculptures or relief models (e.g. Gede, Mészáros 2013), but also widely used in terrain and rock face modelling (e.g. Mészáros 2014).

Using SFM algorithms instead of manually georeferencing globe photos (like in Gede 2010) has several advantages: this solution is much faster; globes (mainly celestial globes) with no or insufficient geographical graticule or damaged map content (Figure 1) can also be processed; not only the globe map, but the globe shape is reconstructed as well. However, the automatic reconstruction will keep the errors of the globe too — particularly the effects of the improperly mounted (overlapping, wrinkled) gores; this feature may be counted either as an advantage or a disadvantage (depending on the intended use of the digitised globe).

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Figure 1: Automatically reconstructed model of a damaged celestial globe of Blaeu in the Virtual Globes Museum

Several SFM software products (desktop product or web service, open-source and commercial) are available. The examples in this paper were created using *Agisoft PhotoScan*, which is probably the most widely used one, but any other software (which is capable of exporting textured VRML models) can be used instead.

Workflow of SFM reconstruction

A successful globe photographing technique was established for the Virtual Globes Museum project several years ago (Gede, Márton 2010) and it has been in use since then. Therefore, we tried to use the same photographs for the automatic reconstruction. Although in most cases the reconstruction was successful, we decided to slightly modify our approach — while keeping all other settings, e.g. the geometric arrangement of the globe, the camera and lighting — by increasing the overlap of the pictures in order to get shapes that are more accurate. Currently, neighbouring photos overlap by approximately 50–55%.

Before starting the reconstruction, images are thoroughly examined, and eventually some parts—like shining surfaces, dismountable parts of the globe frame or other objects that should not appear in the model—are masked out.

The next step is the automatic reconstruction itself, which, depending on the software used, may split up to several sub-steps like creating point cloud by aligning photos, creating mesh and creating the texture. When using *PhotoScan*, the “Build Dense Cloud” step of reconstruction is not necessary if the shape is more or less a sphere; however, it is required when the processing relief globes or when analysing the distortions of the shape is part of the goal of the project.

The optimal texture width and height depend on the resolution of the raw photographs. A good approximation is to use 30 times the number of pixels that cover ten degrees spherical distance. For

example, if the distance between the 10° parallel and the Equator is 200 pixels on the photo, the optimum texture size is ca. 6000*6000 pixels.

When digitising globes, SFM algorithms usually produce a sphere-like, but not perfectly spherical object, which represents the globe in an oblique position (the rotation axis is not parallel to any of the axes of the model coordinate system, Figure 2).

After reconstruction, the model is exported as a VRML model. Only the vertex and the texture are exported (no vertex colours, normals or cameras).

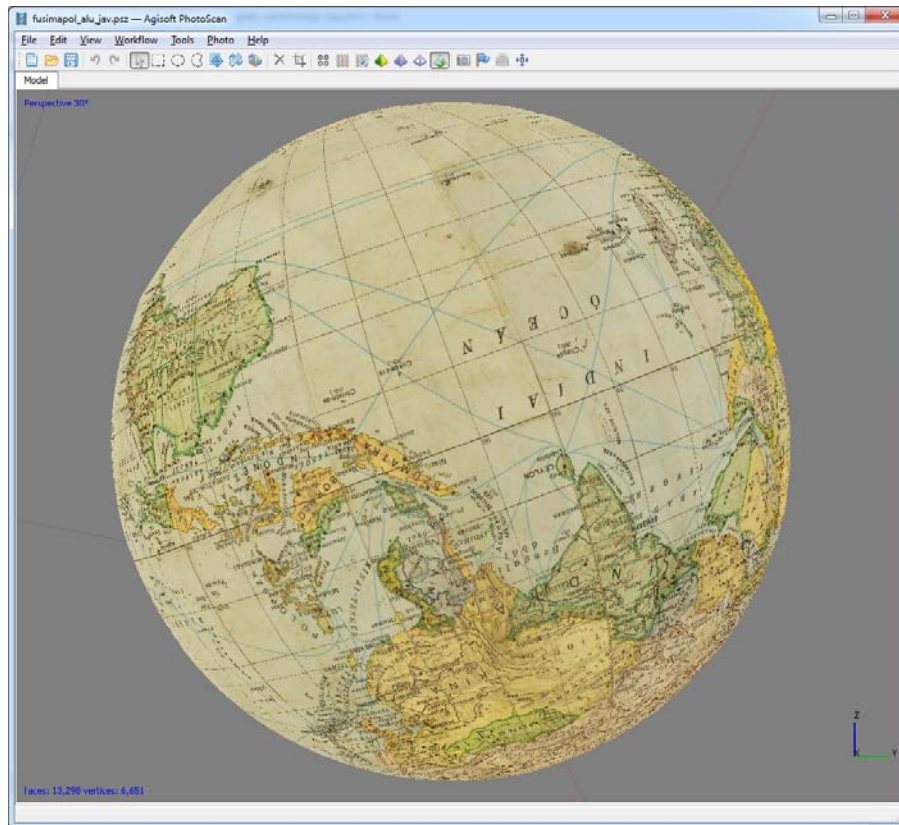


Figure 2: The aspect of an automatically reconstructed globe model is usually oblique (Screenshot taken from Agisoft PhotoScan)

Equirectangular maps from 3D models

The most common representation of textured 3D models is a set of triangles defined by 3D Cartesian coordinates (defining the shape) together with 2D coordinates for mapping the appropriate part of the texture image to the given triangle. The most common 3D interchange formats, VRML and X3D implement this structure by *IndexedFaceSet* geometry structures (Web3D Consortium 2013).

In this structure, the mesh is defined by a list of the coordinates of the vertices, and another list defining the faces (mostly triangles) of the mesh by giving an ordered list of the indices of the vertices for each face. The texture mapping rules are defined in a similar way: another set of vertices in the texture plane, and polygons given as a list of indices. The number of mesh faces must match the number of texture polygons and the i^{th} face is draped by the part of the texture image defined by the i^{th} poly-

gon. The triangles in the texture image may be arranged arbitrarily, but they usually form two or three continuous patches (Figure 3).

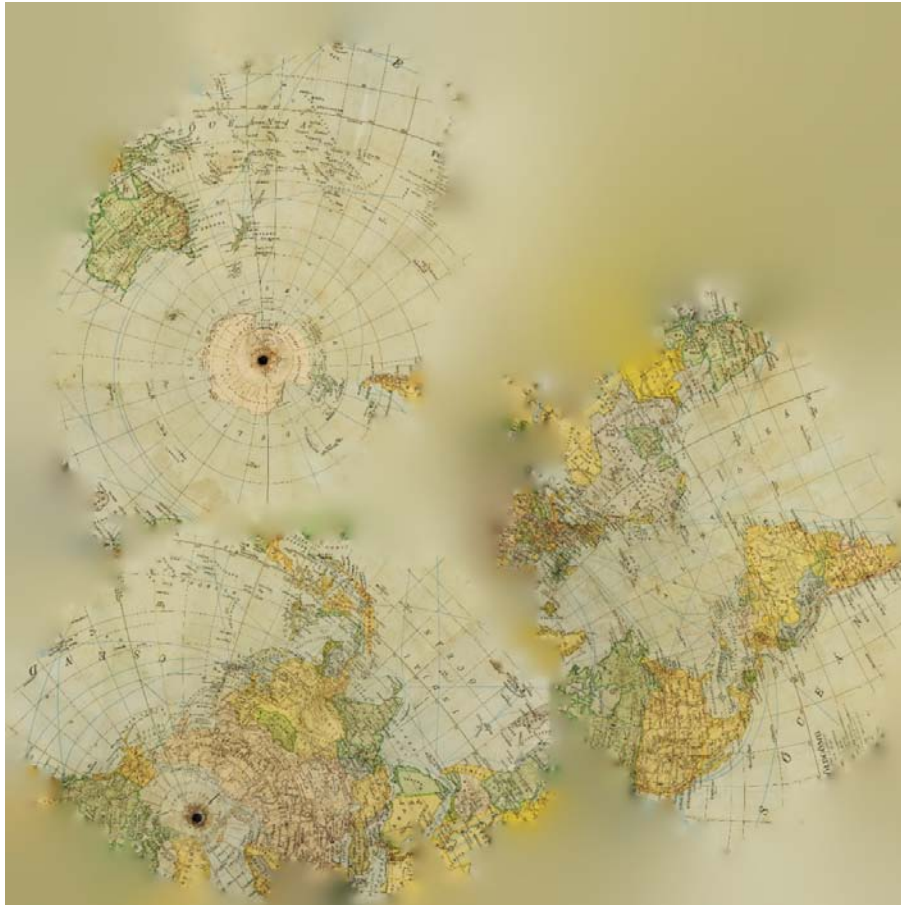


Figure 3: Typical texture image of a photogrammetrically reconstructed globe model

For further analysis, however, we need the globe map in some standard (most preferably in Equirectangular) projection. To help this task, the author developed a program (see at <https://github.com/samanbey/VRML2Equirect>), which performs this transformation (Figure 4). The program reads a VRML file consisting of one single shape with IndexedFaceSet geometry, containing triangle faces only. Its output is a raster bitmap with the equirectangular globe map.

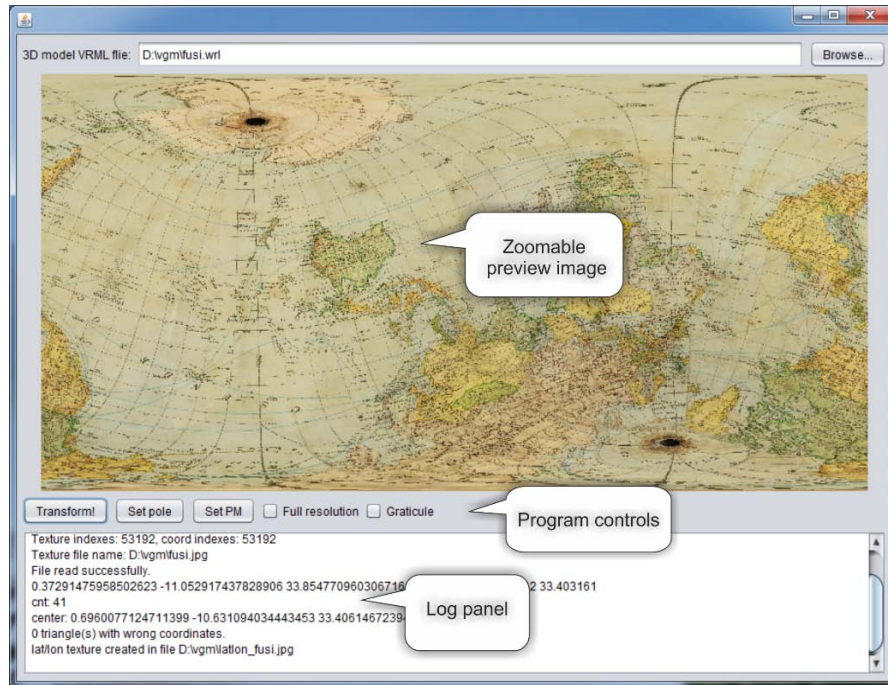


Figure 4: User interface of the transformation program

The algorithm is as follows:

- Read all (x_i, y_i, z_i) mesh vertices and (tx_i, ty_i) texture coordinates as well as mesh triangle vertex indices $(tm_{i1}, tm_{i2}, tm_{i3})$ and the corresponding texture triangle vertex indices $(tt_{i1}, tt_{i2}, tt_{i3})$ from the VRML file.
- Find the best fitting sphere for the loaded vertices: find (x_c, y_c, z_c, R) values for minimizing the following expression:

$$\sum_{i=1}^n \{ (x_i - x_c)^2 + (y_i - y_c)^2 + (z_i - z_c)^2 + R^2 \}$$

- Calculate spherical coordinates relative to (x_c, y_c, z_c) for all vertices:

$$r_i = \sqrt{(x_i - x_c)^2 + (y_i - y_c)^2 + (z_i - z_c)^2}$$

$$\lambda_i = \text{atan2}(y_i - y_c, x_i - x_c)$$

$$\varphi_i = \arcsin \frac{z_i}{r_i}$$

- Load the texture image (*TexImage*).
- Create a new image for storing the Equirectangular map (*EqImage*) and two additional images for creating the texture near the poles in Azimuthal Equidistant projection (*NpImage*, *SpImage*).
- Iterate over all the triangles of the shape (texture vertex indices for the i^{th} triangle are tt_{i1} , tt_{i2} and tt_{i3}):

- Find the linear (1st order) transformation that maps the texture coordinates of the current triangle to the respective spherical coordinates so that:

$$(tx_{tt_{i1}}, ty_{tt_{i1}}) \rightarrow (\varphi_{tm_{i1}}, \lambda_{tm_{i1}})$$

$$\begin{aligned} (tx_{tt_{12}}, ty_{tt_{12}}) &\rightarrow (\varphi_{tm_{12}}, \lambda_{tm_{12}}) \\ (tx_{tt_{13}}, ty_{tt_{13}}) &\rightarrow (\varphi_{tm_{13}}, \lambda_{tm_{13}}) \end{aligned}$$

- Copy the given triangular part of *TexImage* to the triangle defined by the spherical coordinates in *EqImage* using the linear transformation just calculated.
- If the triangle stretches over the 45th latitude (any of $\varphi_{tm_{11}}, \varphi_{tm_{12}}, \varphi_{tm_{13}}$ is greater than 45° or less than -45°), transform the spherical coordinates to Azimuthal Equidistant projection (with the projection centre at the North Pole in the first case or the South Pole otherwise); find the transformation that maps the texture coordinates to the transformed Azimuthal Equidistant coordinates; using this transformation, copy the current triangle of *TexImage* to *NpImage* or *SpImage* depending on which pole is near.
- Merge *NpImage* and *SpImage* to *EqImage* using the appropriate projection transformation. (At this point, we have the equirectangular map of the globe in *EqImage*, but in an oblique, rotated aspect, as axis Z of the original model's coordinate system is usually not parallel to the rotation axis of the globe).
- Display *EqImage*, and ask user to mark the place of the North Pole, and another point along the prime meridian (preferably somewhere near the Equator).
- Based on the coordinates of these two points, calculate the parameters of the oblique aspect, and transform the image into normal aspect.
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Figure 5: Texture of Figure 3 after transformation into Equirectangular projection

A typical result of this transformation is in Figure 5. The noticeable deflection of the meridians from the vertical straight lines (especially near the poles) indicate the improper mounting of the globe gores.

The software was written in Java language so it can be used on several various platforms, if the Java Runtime Environment (JRE) is installed.

Various measures of accuracy

When examining the 3D model of a globe, accuracy may refer to several aspects:

- *Modelling accuracy* means the similarity of the 3D model with the original object. For photogrammetrically reconstructed globes, this cannot be directly measured, but good modelling accuracy always requires a relatively high vertex point density all over the surface of the model, because between these points the object surface is modelled by flat faces; therefore large distances between the points result in larger “flattened” parts on the reconstructed globe model. Unfortunately, the high density of vertex points does not automatically provide the high accuracy of the model – it largely depends on the quality of the SFM algorithm.
- *Positional accuracy of the original globe content* refers to the relation between the position of any particular object on the map and its position in the real world. Unless the globe map was directly painted to the spherical surface, it depends on at least two factors: first, the accuracy of the original unmounted globe map gores; second, how accurate the gores were mounted onto the sphere. Such measure can be the average distance of grid intersections on the globe from their intended position.
- *Positional accuracy of the model* refers to the relation between the position of any particular object on the surface of the reconstructed model and its position in the real world. Naturally, this kind of accuracy is affected by the two previous factors. The different types of inaccuracies, however, may not only increase the positional inaccuracy of the model but also eliminate each other’s effect. For example, if the gores were mounted inaccurately, but during the creation of the 3D model the content is moved to its intended place (e.g. by using all graticule intersections as control points), positions on the 3D model become more accurate, even though the modelling was not accurate as the model does not reflect the gore mounting errors.

Depending on the purpose of modelling, different types of accuracy may have priority. For example, if the goal is the documentation of the present state of a globe, the modelling accuracy is most important. If we want to compare the content of the globe to other contemporary maps, a positionally accurate model is needed.

Visualizing modelling accuracy

To exactly measure the accuracy a photogrammetrically reconstructed model, another, accurately created model (e.g. by laser scanning) is needed. In most cases, however, such models are not available. The author’s approach is to map the difference of the model and the best fitting sphere. (A similar method is used in Adami 2009 and Menna et al. 2012.) This approach can be used when the globe is a sphere (not a relief globe, where height differences are intended parts of the globe content). The spherical coordinates of the model vertices are treated as points with height (the radius becomes height). Then a DEM is generated based on these points. If the overlap of the photographs was insufficient, it is indicated by a systematic height distortion pattern geometrically correlated to the location of the photographs (Figure 6).

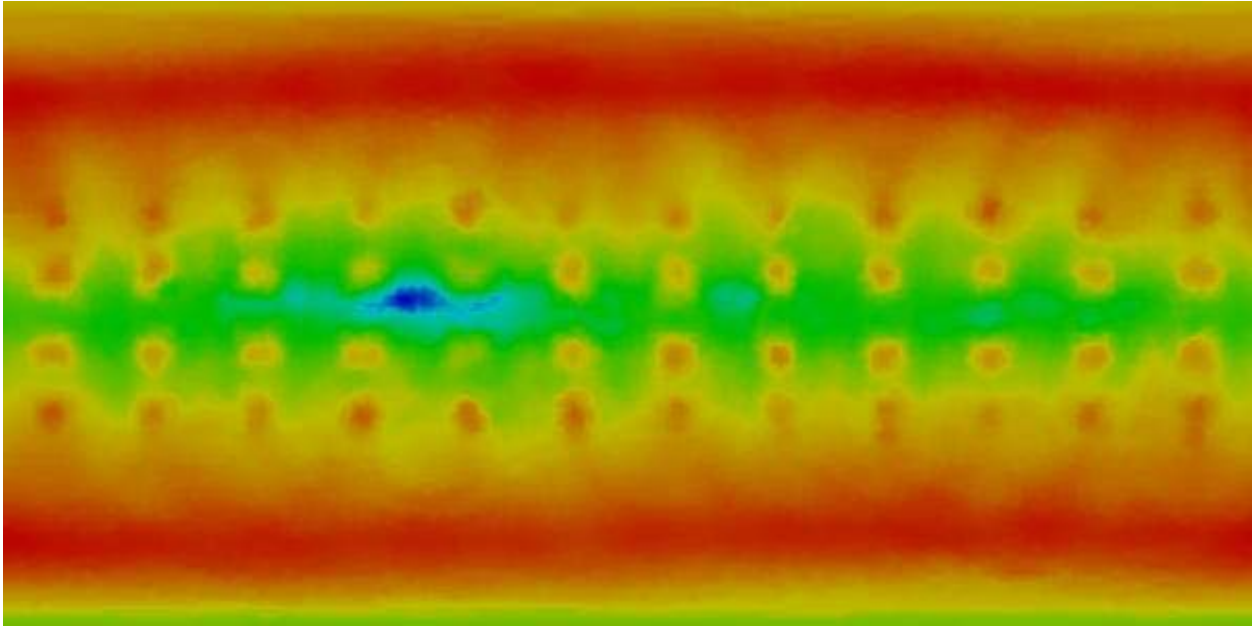


Figure 6: Height distortion pattern correlated to photo locations indicates inaccurately reconstructed surface due to the insufficient overlap between photographs

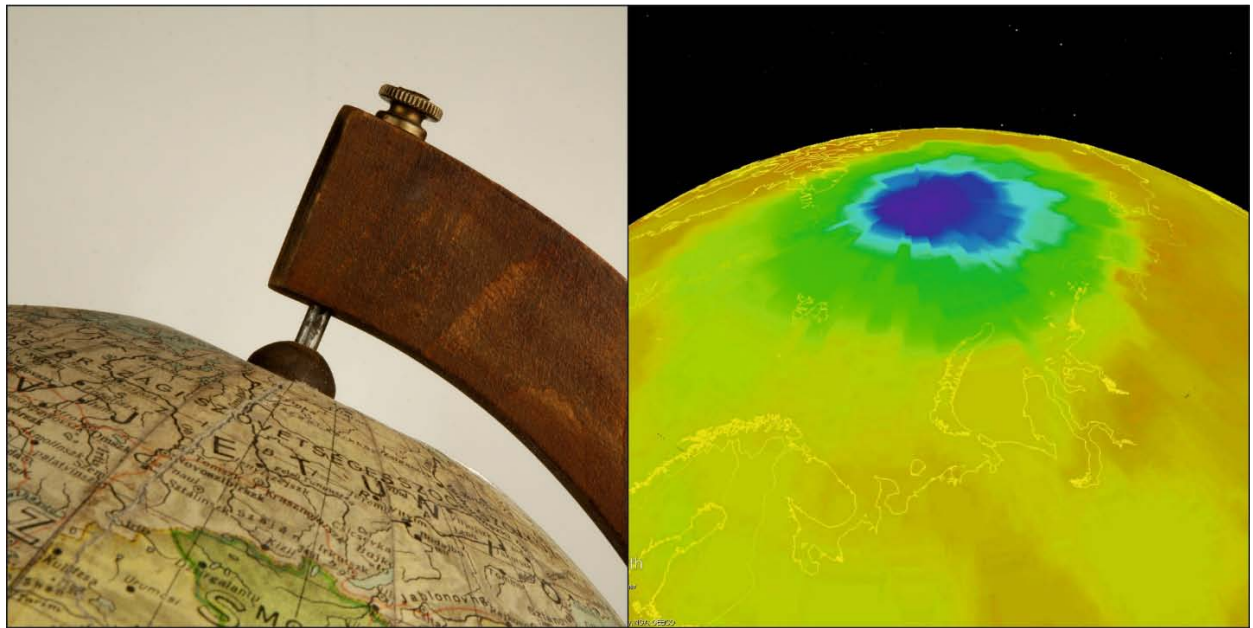


Figure 7: Depression on a globe around the pole (left) and its representation on the DEM (right)

In this case, further analysis of the DEM is pointless, because the model does not represent the real object shape. Otherwise, the most significant differences should match bumps or depressions on the globe. Greatest depressions usually occur around the poles (Figure 7).

Conclusions

Globes can be digitized using an SFM algorithm on an appropriate set of photographs. This solution requires further processing. The author developed a program that creates Equirectangular globe maps from photogrammetrically reconstructed globe models in VRML format.

Using this program together with an appropriate SFM software will significantly reduce the time of globe digitising as well as the human interaction required for the process.

Due to this new solution, various measures of accuracy can be specified. When speaking of the accuracy of a globe model, one always should keep in mind the main goal of the modelling in order to know which type of accuracy should be maximized.

Further plans

Currently the oblique aspect model is rotated to normal aspect based on the user-marked position of the North Pole and another point on the Prime meridian. For some globes, however, the position of the pole cannot be marked accurately as there is a hole for the axis, or the axis itself. In future versions of the transforming program, users should be able optionally to mark points along the Equator instead.

Plans also include a comparison of models created by SFM to laser-scanned models of the same objects. This comparison would reveal the real modelling accuracy of SFM.

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