VIRTUAL RECONSTRUCTION OF CULTURAL HERITAGE ARTIFACTS

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ABSTRACT

Museums and other cultural heritage custodians are interested in digitizing their collections, not only for the sake of preserving cultural heritage, but also to make the information content accessible and affordable to researchers and the general public. Once an objects digital model is created it can be digitally reconstructed to its original uneroded or unbroken shape or realistically visualized using different historical materials. Some artifacts are so fragile that they cannot leave the carefully controlled light, humidity, and temperature of their storage facilities, thus they are already inaccessible to the public, and the viable alternative is their exhibition in the form of an augmented reality scene. We present a sophisticated measurement and processing setup, which we have developed, to enable the construction of physically correct virtual models. This setup is illustrated on the reconstruction of one of the best known Celtic artifact from the European Iron Age period to its original uncorrupted form.

***Index Terms*—** Shape reconstruction, surface modeling, bidirectional texture function, virtual reality,

1. INTRODUCTION

While precise shape measurement can be achieved using advanced laser scanners and other commercially available shape measuring devices, an objects surface appearance is much more complicated. Virtual reality applications typically use oversimplified surface material and illumination models that only remotely approximate the appearance of real scenes, meaning human observers can easily differentiate between real and virtual or augmented reality scenes. Real surface material visual appearance is a highly complex physical phenomenon which intricately depends on incident and reflected spherical angles, time, light spectrum and several other physical variables. While recent advances in computer hardware and virtual modelling are finally allowing the view and illumination dependencies of natural surface materials to be taken into account in the form of bidirectional texture function models (BTF) [1], this occurs at the expense of an immense increase in the required number of material sample measurements and the visualization complexity. Several special setups [2, 3, 4] have recently appeared, which are capable to simultaneously capture shape and approximative BRDF or BTF reflectance data.

2. SHAPE MODELING

A precise shape measurement can be achieved using advanced laser scanners or other commercially available shape measuring devices based on stereo vision or structured light. We use the laser scanner Konica Minolta VI-9i. The scanner uses the light-stripe method to emit a horizontal stripe light through a cylindrical lens to the object and a Galvano mirror to repeat this scanning stripe vertically. The reflected light from the object is received by the CCD, and then converted by triangulation into distance information and thus to a 3D image data of the object. The measuring accuracy is in the range $0.05 - 0.2\ [mm]$ depending on the selected lens.

2.1. Shape Reconstruction

A detailed triangulated 3D model of a corrupted shape is the prerequisite for its subsequent reconstruction. Missing or scarred parts of a shape can be reconstructed only by exploiting information from similar parts either from the same object or on some other object. In the former case we can often utilize shape symmetries such as symmetrical parts on human or animal bodies. Scarred parts are removed using the surface spline patches.

The shape reconstruction in an original high resolution model is difficult and requires a lot of manual work in a 3D software (in our case RapidForm www.rapidform.com). Our Celtic druid head has 2 729 228 vertices and 5 458 400 faces, which is too demanding resolution for efficient shape restoration. Therefore, we restore the low resolution model, which contains significantly smaller number of vertices and faces (13%). The complete restored lower resolution model is either up-scaled to the original high resolution or only the corrective parts are up-scaled and inserted to the original corrupted high resolution model. The inserted triangularized partial shapes have to be rescaled to the same scale as the orig-

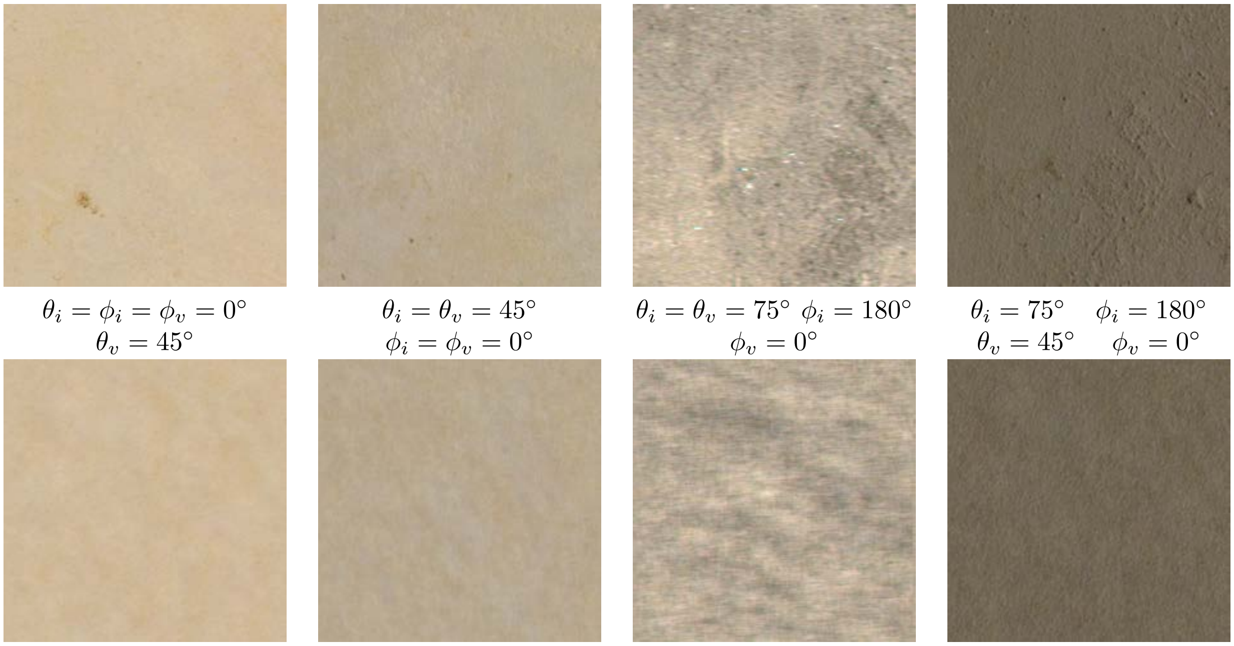

Fig. 1. BTF plaener texture measurements (upper row), their synthetic counterparts (bottom row) for various elevation (θ_i, θ_v) and azimuthal (ϕ_i, ϕ_v) illumination and viewing angles.

inal reconstructed shape model. In the case of down-scaling this means simple triangular mesh decimation. The opposite up-scaling process is more complicated because we have to estimate unobserved shape data. We start with dividing rough scale triangles into several embedded smaller ones and their newly created vertices are subsequently modified using additive Gaussian noise.

3. SURFACE MATERIAL MODELING

Real surface material visual appearance is a highly complex physical phenomenon [1] which intricately depends on incident and reflected spherical angles, time, light spectrum and other physical variables. The best current measurable BTF representation of a material appearance requires tens of thousands of images using a sophisticated high precision automatic measuring device. This results in a huge amount of data which can easily reach tens of tera-bytes for a single measured material. Nevertheless, these data have insufficient spatial extent for any real virtual reality applications and have to be further enlarged using advanced modelling techniques.

3.1. Surface Material Acquisition

Within the Pattern Recognition department of UTIA, we have built a high precision robotic gonioreflectometer [1]. The setup consists of independently controlled arms with camera and light. Its parameters, such as angular precision (to 0.03 degrees), spatial resolution (1000 DPI), and selective spatial measurement qualify this gonioreflectometer as a state-of-the-art device. The typical resolution of an area of interest is around 2000 x 2000 pixels, each of which is represented by at least 16-bit floating point values to achieve reasonable representation of high-dynamic-range visual information. The memory requirements for storage of a single material sample amount to 360 giga-bytes per spectral channel but more precise spectral measurements with a moderate visible spectrum (400-700nm) sampling further increase the amount of data to five tera-bytes or more. BTF acquisition setup requires a planar material sample, which can be a problem for general shaped and too precise artifacts. The Celtic druid head, we modeled, is made from plaener a type of marlite or marlstone, which is a calcium carbonate containing variable amounts of clays and silt. The type of plaener used for the Celtic druid head by an unknown artist two thousand year ago is fortunately known and we were able to obtain the corresponding planar tile for measurement.

3.2. BTF Material Modeling

Although a BTF material representation assumes several strong simplifying assumptions [1, 5, 6] its measurement, compression and synthesis is on the leading edge of current mathematical modelling and technological capabilities. BTF is a seven-dimensional function [1] which considers not only measurement dependency on planar material position and spectral channel but also its dependence on illumination and viewing angles.

We have developed several multidimensional probabilistic models based either on a set of underlying Markov random fields (Fig.1) or probabilistic mixtures, which allow physically correct surface lossless representation and modelling, huge measurement space compression (so far unbeaten at up to 1:1 000 000), and even modelling of previously unseen surface data or their editing. These methods are parametric, so they do not require original measurements to be stored. Fig.1 illustrates four selected plaener measurements from the 7000 BTF space measurements and their synthesis using the BTF Markovian parametric model which uses three-dimensional auto-regressive causal Gaussian factorial sub-models [1, 7]. However, such models are nontrivial and suffer from several challenging theoretical problems such as stability, parameter estimation and noniterative synthesis, which must be circumvented. Alternative approaches using physical reflectance models [8] or sophisticated sampling methods [9, 10] were also developed.

BTF materials modeling in this paper uses our fully automatic sampling method - the BTF roller [9], which is based on the overlapping tiling and subsequent minimum error boundary cut. The main idea of this nonparametric multi-scale algorithm is to automatically extract several optimal mutually interchangeable double-toroid-shaped data patches. These patches can be then randomly tiled to generate a seamless BTF data space enlargement.

A further problem is that of physically correct material visualization, because there are no professional systems which allow rendering of such complex data. Therefore, we were forced also to develop the novel Blender plugin [11] for the purpose of realistic material appearance model mapping and rendering. Blender is a free open source 3D graphics application for creation 3D models, visualizations and animations and is available for all major operating systems under the GNU General Public License.

4. CELTIC DRUID HEAD

We applied this technique for the best known Celtic artifact from the European Iron Age period (450 - 50 B.C.) owned by the National Museum in Prague - the Celtic druid head. This plaener Celtic druid head (Fig. 2) is so precious that it has only been exhibited three times since its discovery at a sandpit in Mšecké Žehrovice, Czechia in 1943, and each time only for a few days under tight security. Its exact digital model Fig. 2 with 0.1 mm accuracy created from our laser scanner measurements allows us not only to create a high quality copy for permanent exhibition, but art historians can study in detail its chiseling style by an ancient artist, its ritual smashing when Celts had to abandon their sanctuary, and even allows researchers to look for alternative materials (Fig. 3 – D) of that era. Visual techniques are non-invasive and thus ideal for documentation and assessment of cultural objects directly in their workroom computers. The plaener material was measured on

Fig. 2. Celtic druid head (300 BC, National Museum in Prague) precise digital current shape and BTF plaener model.

our robotic gonioreflectometer using 7000 different combinations of illumination and viewing angles, 14 bits per channel spectral resolution, and the spatial resolution 350 DPI.

Unfortunately some parts of this precious sculpture were never recovered (see the right part of the head digital model on Fig. 2). These missing parts, as well as numerous deep stone scars being the result of its ritual smashing and the damage done subsequently by ploughing, can be reconstructed using shape prediction-based image processing methods. We exploit the assumed shape symmetries on the Celtic druid head.

Fig. 3 - A-C illustrate such shape reconstruction results in the original plaener and possible alternative wooden (Fig. 3 – D) materials. The up-scaled corrective patches insertion (Fig. 3 – A) provides more realistic reconstruction results but it requires precise corrective patch localization and manual corrections in the patch border areas, while the reconstructed low resolution model up-scaling is done fully automatically. The later approach (Fig. 3 – B) can suffice for objects with limited sharp edges and covered with surface materials which do not contain low frequency patterns.

Once the accurate shape and material models are developed, we can insert such a model into an augmented reality scene (Fig. 3- C) in a way which respects physically correct illumination and viewing conditions derived from the real environment. For example, to insert this Celtic druid head into a true Celtic sanctuary if archaeologists were to find one.

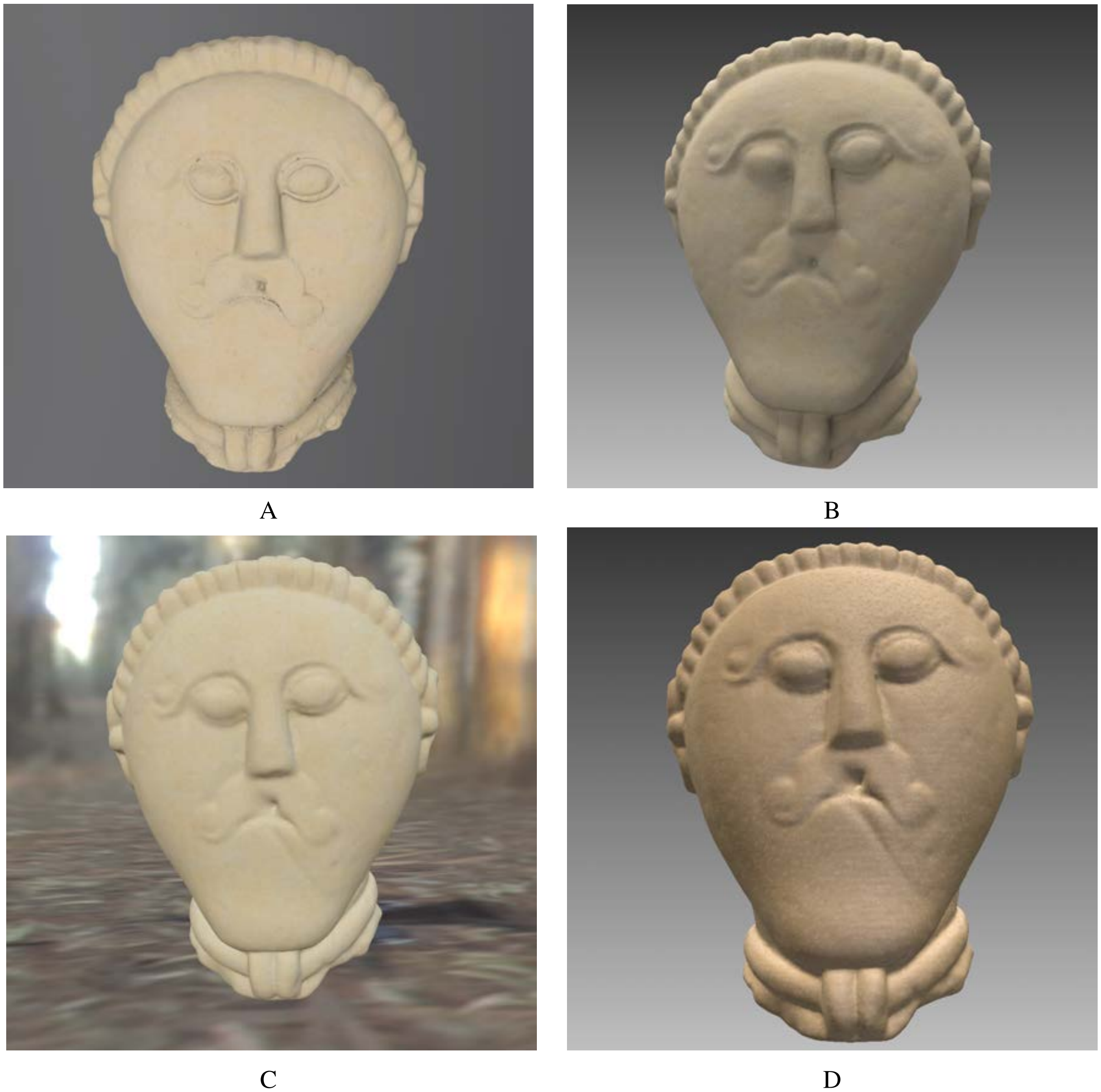

Fig. 3. Reconstructed Celtic druid head shape and the BTF plaener model. A - high resolution model with inserted correction patches, B - enlarged reconstructed low resolution model with additive noise, C - reconstructed low resolution model with environmental lighting, D - the alternative linden wood material BTF model.

5. CONCLUSIONS

The proposed reconstruction approach for three-dimensional cultural heritage objects allows to produce physically correct virtual models which imitate the original appearance of such objects as the were created by ancient artists. The shape reconstruction cannot be fully automatized. The amount of interactive work involved depends of the shape symmetries which can be used for reconstruction. For example in our case - the well preserved left part of the Celtic druid head. The state-of-the-art BTF surface material representation requires planar material sample for efficient measurement. The Celtic druid head plaener material required demanding search to find similar plaener specimen to built our material model. An objects digital model is digitally reconstructed to its original uneroded or unbroken shape or it can be realistically visualized using different alternative historical materials. Once a reconstructed objects digital model is created it can be printed on a 3D printed to create a high quality copy for exhibition or study purposes if the original is too precise or fragile to be exhibited.

Thanks to the Czech Science Foundation Project No. GAČR 14-10911S for funding.

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