

Interactive virtual mummy dissections in a historical anatomic theatre

S. Seipel^{1,2}, M. Lindkvist¹ and L.W. Pettersson¹

¹Department of Information Technology, Uppsala University, Uppsala, Sweden

²Department of Mathematics, Natural and Computer Science, University of Gävle, Gävle, Sweden

Abstract

This paper presents an interactive projection-based application for visual exploration of virtual mummies. It is part of an exposition on the Cultural Heritage of the Egyptian Mummies in the Museum Gustavianum, in Uppsala. We describe a general-purpose projection metaphor for correctly presenting virtual 3D images on the dissection table of a historical anatomic theatre. This method allows for dynamic off-axis perspective viewing situations as well as it provides keystone correction for excessive projection angles as necessitated by the specific installation environment. For the application to reach out beyond the scope of the exhibition, we developed an adaptive image-based rendering approach that scales with the performance of the rendering host. Based on dynamic mesh simplification of the 3D mummy model, it automatically performs re-projections of texture images in order to maintain correct visual results. For interaction purposes with a digitiser tablet we present a means of stroke-based input that provides ease of use to non-expert visitors of the exhibition.

Keywords:

Keystone correction, texture mapping, 3D interaction, virtual reality, anthropology.

1. Introduction

Methods of computer graphics have during the last decade been successfully applied to reconstructions and visualisations of archaeological artefacts. In anthropological research, non-destructive methods as e.g. three-dimensional computed tomography (CT) have created new opportunities to perform studies on precise details of the mummification procedures without destructing invaluable ancient mummies. Most of the paleopathological research presented earlier in this context has focussed on the data acquisition process by using spiral CT [1,2,3]. Recent research has been carried out in post-processing algorithms and tissue classification to enhance visual quality of 3D reconstruction results and to enhance identification of morphological structures [4]. Almost all of these previous efforts have led to methods and tools that are used by experts and researchers in the scientific community. As such, the developed applications are designed to support numerical analysis and scientific visualization of the vast amount of data collected by the various imaging modalities.

In the context of a museum exhibition on ancient Egyptian mummies at the Museum Gustavianum in Uppsala, Sweden, it was the intention to make interactive graphical methods for exploration of virtual mummies accessible to the public. The application should allow for the visitors of the exhibition to study internal structures and artefacts beyond the surface of the linen wrappings. What renders the installation of the virtual mummy application specific is its historical surrounding: The Gustavianum building is among the most distinctive historic buildings in Uppsala. In the middle of the 17th century, the famous professor Olov Rudbeck had an impressive cupola built on top of the Gustavianum. The cupola houses an anatomic theatre where dissections took place at that time. In 1715, this anatomic theatre was hosting the first historically documented exhibition of a mummy in Sweden; and by the end of the 19th century it was popular to perform dissections of Egyptian mummies in these kind of anatomic theatres throughout Europe. 250 years after the first dissection, and in the context of the Mummy Exhibition, virtual dissections were again intended in this particular historical setting.



Figure 1: *The geometric components of the virtual mummy after reconstruction from CT (left). Photographics view upon the actual mummy (right).*

Initially, we investigated the usability of several commercially available software solutions that would allow for exploration of 3D volumetric data sets of the mummy. Among those were e.g. Analyze™ or Amira™, which both are commonly used tools in the scientific community for the purpose of data post-processing, segmentation and 3D surface reconstruction. Very soon we realized that these tools were suitable to recreate 3D models for the virtual mummies from raw data (i.e. CT data) and also for rendering of predefined animation sequences. For the purpose of interactive dissections of a virtual mummy, however, we found those tools to be inappropriate for several reasons: As professional tools, these programs provide a very broad set of powerful image processing operations. These operations and their parameterisation require very specific skills far above the level of most museum visitors. Also, the interaction modalities of those systems are designed for a typical professional desktop workstation situation. In other words, graphical output is presented in several windows on-screen and based on centric perspective projections. User interaction with virtual 3D objects is limited to rotation or scale of entire objects and does not allow for more advanced behaviour of the visualized objects. Also, data entry and interaction is facilitated using standard keyboard and mouse devices, which are no preferable choices for public computer installations. Due to these shortcomings we felt that a naturally appearing implementation of the virtual mummy into the authentic context of the anatomic theatre was only possible by building a customized visualisation application, which addressed the very requirements of the architectural environment and the museum visitors.

2. Material

The mummy under investigation is from a four years old girl child and it is dated to the period between 0 and 100 A.C. It was previously examined with CT in

the framework of the Uppsala Mummy Survey in spring 2001. CT scanning was performed at 1 mm slice intervals, which resulted in a number of 976 axial slices of the mummy. The image matrix had a resolution of 512 by 512 pixels. In total, the primary raw data comprised approximately 488 megabyte of binary data. These 3D image raw data were subsequently post-processed using commercially available software packages. Eventually, a re-sampled and filtered volume of the size 128x128x488 voxels could be obtained for the purpose of surface reconstruction. Three-dimensional polygonal surface models of relevant structures were reconstructed semi-interactively in local regions of interest, since fully automated segmentation procedures did not yield satisfactory reconstruction results for all regions of the mummy. The data-acquisition procedures were carried out by the radiology department of Uppsala University Hospital (UAS) while the Center for Image Analysis (CBA) of Uppsala University provided the basic set of polygon meshes for interactive visualization. A list of objects with their absolute and relative number of triangles respectively can be found in Tab. 1.

Object	Triangles	Ratio
Skull	5000	4,02%
Arms	9996	8,04%
Leg_upper	4020	3,23%
Knee	1983	1,59%
Leg_lower	5360	4,31%
Chest	19964	16,05%
Spine	20000	16,08%
Liver	3000	2,41%
Heart	500	0,40%
Skin	14988	12,05%
Linnen	39544	31,80%
Total	124355	100,00%

Table 1: *Model complexity of the various model components*

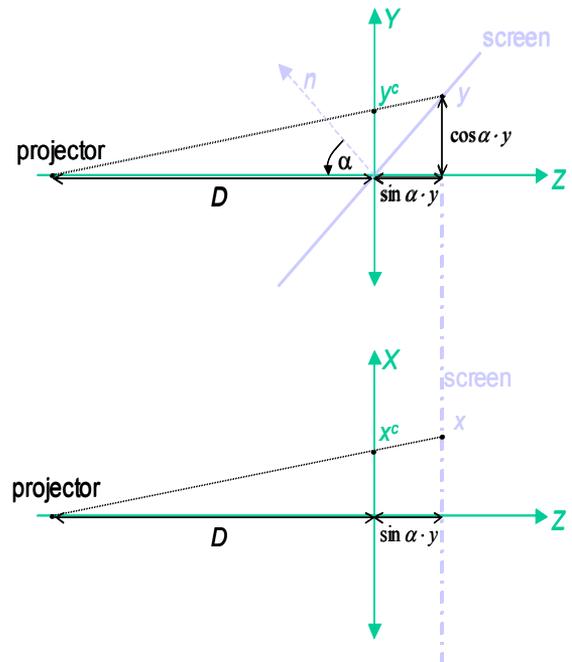


Figure 2: *The historic projection environment (left). Graphical sketch of the relationship between on-screen projected coordinates and pre-distorted coordinates in image space (right).*

In order to improve the visual quality of the virtual mummy we also acquired photographic material of the real mummy. A number of digital photographs were taken from predefined directions by an archaeologist. These digital pictures show the mummy in one frontal and two orthogonal lateral views (Fig. 1 right). The approximate photographic parameters such as focal distance, camera direction, and lens zoom were known.

For the presentation of the virtual mummy there were a number of specific pre-conditions: In the very centre of the anatomic theatre the historical dissection table is situated. It is elevated approximately 80 cm above the floor, and has a length of approximately 160 cm. The board of the table can be turned about 360 degrees. It is on top of the table were a front projection of virtual imagery was intended. Due to the historic value of this inventory, we could not permanently affix special screen material upon the table. Therefore we used fine woven white cotton linen to cover the dissection table (see also Fig. 2).

The historic environment put several constraints to the arrangement of the image projection source. In order to avoid distortions of projected images, it is generally desirable to locate the projector perpendicular to

and above the display area (here the board of dissection table) or, if that is not possible, as close as possible to the central line of the projection. In the anatomic theatre, there is about 9 meters clearance above the dissection table up to the roof of the cupola, where a projector most suitably could be affixed. Though, several issues made this option impractical. The projection distance to the table would be very long in comparison to the relative small projection picture desired. This would call for a projector model with very long throw length, which are available, but at very high costs and to the expense of heavy weight. The latter implies also solid fixation points in the antique interior that are not feasible. Another aspect is that the entire structure of the cupola is made from wood. Wind under normal weather conditions introduces significant motion to the entire building structure of the cupola and hence to the projection image. Given all practical circumstances, the preferred solution for front projection was a low cost LCD projector with a native resolution of 1024 by 768 pixels mounted to a metal stud on the stairs upwards the gallery of the anatomic theatre. All involved people felt, that the solution as shown in Fig. 2 suited most inconspicuously into the historical environment of the anatomic theatre.

3. Method

Starting from the initial material and situation described in the previous section, it was a challenging task to accomplish a realistic three-dimensional effect of the graphics depicted on the dissection table. Stereoscopic imagery is a strong visual 3D cue commonly used in virtual reality and interactive graphical systems [5]. It is relatively easy to implement in software, but due to the fragility of the required technical hardware stereoscopy is critical in the context of public installations. The chosen projection technique described above does generally not permit stereoscopic presentations. Alternative strong 3D cues that create strong illusions of three-dimensional imagery are motion parallax [6] and correct off-axis perspective projections [7]. The combination of both is often referred to as dynamic perspective displays and is often found in multiple screen VR environments [6] and horizontal stereoscopic displays [8, 9] that represent the same display conditions as in our application. In order to successfully implement viewpoint adapted perspective projections in the specific context, we needed to develop a projection metaphor that accommodates all parameters that render the actual display environment specific such as viewing position, off-axis projection angle, and size and orientation of the projection image.

3.1 Keystone corrected projections for off-axis 3D viewing

General methods for orthoscopic projection of 3D objects have been published before by different authors [10, 11]. While allowing for off-axis perspective projections, they make specific assumptions either in regard to the centre of projection or in regard to the orientation of the projection plane. Implementations of arbitrarily definable window-on-world viewing metaphors are meanwhile publicly available in a number of high level VR development libraries (e.g. CAVELib™, VR Juggler), but they do not support arbitrary manipulations of the projection matrix by the application developer. Based on similar projective methods presented in the literature [10], we developed a projection metaphor, which is parameterised with metric parameters for the users current head position, the centre and dimensions of the virtual viewing window, and two vectors that denote the orientation in the real environment. This method which is described in detail in [12], calculates a parameter set to pre-configure the OpenGL projection matrix and the model-view matrix in order to obtain a viewpoint dependent oblique projection. As is indicated in Fig. 2, the low projection angle of the projector leads to a trapezoid distorted image in the projection plane that coincides with the dissection table. In the actual situation, this distortion is excessive such that it cannot be compensated for by the built-in keystone correction functions of the projector. Therefore, the trapezoid projection image must be corrected by a 2D warping of the computed imagery. This operation is most suitably

performed posterior to all other vertex transformations of the 3D projection pipeline. We achieve this final image transformation by manipulating the projection matrix stack by invoking a *PostProjectionTransform* function.

```
glMatrixMode(GL_PROJECTION);
glLoadIdentity();
PostProjectionTransform();
glFrustum(left, right, bottom, top, near, far);
glMatrixMode(GL_MODELVIEW);
glLoadIdentity();
glMultMatrix(T);
```

The problem of compensating geometric errors in projection VR has been addressed earlier e.g. in the Office of the Future by Raskar et al. [13] or in other place by Sukthankar et al. [14]. The solutions presented there are based on camera registration of projected reference images and intend to automatically generate calibration functions for arbitrary projection surfaces. In our virtual mummy application, the projection situation is not so elaborated and we wish to parameterise our software by simply using two variables that can easily be measured by the technical personal in the anatomic theatre. Those variables are the distance D between the projection lens and the centre of the projection screen, and the projection angle α upon the planar projection surface.

Fig. 2 (right) depicts graphically the relation between the variables involved in the calibration procedure where X , and Y mean intended screen coordinates as appearing in the trapezoidal distorted image, and X^c and Y^c the required pre-calibrated coordinates. The mathematical relation is straightforwardly given by:

$$\frac{y^c}{\cos \alpha \cdot y} = \frac{D}{D + \sin \alpha \cdot y} \Rightarrow y^c = \frac{D \cdot \cos \alpha \cdot y}{D + \sin \alpha \cdot y} \quad (1)$$

and

$$\frac{x^c}{x} = \frac{D}{D + \sin \alpha \cdot y} \Rightarrow x^c = \frac{D \cdot x}{D + \sin \alpha \cdot y} \quad (2)$$

The formulas in (1) and (2) can be denoted in form of a homogenous transformation matrix such as to be pre-concatenated with the viewing matrix:

$$C = \begin{bmatrix} D & 0 & 0 & 0 \\ 0 & D \cdot \cos \alpha & 0 & \sin \alpha \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & D \end{bmatrix} \quad (3)$$

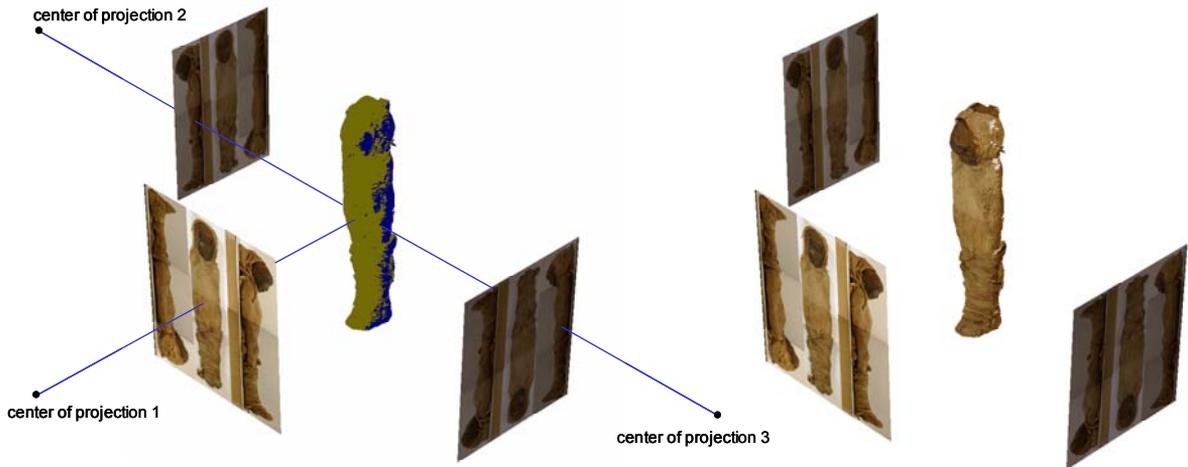


Figure 3: *An interactive editor allowed for fine-tuning the spatial relation between the virtual mummy and anticipated real world camera position (left). The picture to the right illustrates the resulting mummy after texture re-projection.*

The procedure *PostProjectionTransform()* for keystone correction of the projection comprises therefore calculation of C and multiplying the result with the current matrix on the OpenGL projection matrix stack.

3.2 Adaptive texture re-projection on geometric objects

The interactive visualization of the mummy was based on the geometric objects that were subsequently acquired from the initial CT raw data. A list of the objects with their respective number of polygons is shown in Tab. 1. A graphical representation of the objects is given in Fig. 1. As can be seen, the visual quality of these polygon meshes is more than satisfactory. However, we found some drawbacks after trying to visualize those models interactively. One big obstacle was the large number of independent polygons, which caused frame rates clearly below 15 frames per second, even with state of the art graphics hardware. Another problem was the colour representation. The bones and also dried skin can be rendered with sufficient degree of realism by using appropriate material definitions. However, for the outer shell of the mummy, the use of the photo realistic textures was crucial in order to depict details of facial expression and woven linen wrappings. The model, which represents the outer layer of the mummy represents almost one third of the total number of polygons. In textured rendering mode, we encountered that significant performance increases were easier to accomplish by reducing moderately the number of textured polygons rather than decimating rigorously the number of non-textured polygons. While to our experience the texture performance in terms of fill rate never

was a critical issue, we believe that expenses for texturing in the triangle set-up can explain the described phenomenon.

In order to find an optimally balanced configuration on various computer systems with different performances, we employed dynamic mesh simplification and decimation at program start up, to find an acceptable number of polygons for the textured part of the model. Our iterative mesh decimation algorithm utilises surface curvature parameters to identify and eliminate redundant polygons in the object. We will not expand the details of the algorithm in this place, because it is quite similar to approaches described earlier in the literature [15,16,17,18]. However, we address the question of how texture coordinates must be treated in the mesh simplification procedure in order to avoid excessive texture warping artefacts.

We tackle this problem utilising the fact that we have a-priori knowledge about how the textured object looks in the real world, and under which circumstances the photographic pictures were taken that form the texture image. We implemented a small interactive graphical editor program, which allowed us, starting from the initial photographic parameters, to define the position of one frontal and two lateral focal points of projections in relation to the 3D model of the virtual mummy. Projecting the virtual mummy towards these focal points creates two-dimensional silhouettes of the mummy, which naturally should coincide with the respective photographic pictures represented in the tex-

ture image. The purpose of the editor program was to shift the 2D texture images and to interactively fine-tune the spatial relation between mummy, texture images and focal points such that the original photographic configuration was optimally reconstructed. In this configuration, a nearly perfect match between the silhouettes in the texture image and the contours of the projected virtual mummy object can be accomplished. This configuration was stored in an external file for later use.

Subsequently, whenever the mesh topology of the outer mummy layer has changed as a consequence of mesh simplification, the configuration data in the external file is reused. A process is started that identifies for each triangle in the mummy geometry the most suitable out of the three texture images. It then projects the vertex towards the corresponding center of projection and calculates the coordinates in the corresponding texture image. The resulting 2D texture coordinate is written back into the vertex buffer for the mummy geometry.

Fig. 3 illustrates the spatial configuration between the three texture images, the focal points and the geometrical model of the external layer of the mummy. In the left picture, different colours on the mummy surface indicate that different focal points apply for respective surface points. The right side of Fig. 3 shows the result of the automatic texture coordinate generation. The advantage of the described procedure is that the chosen mesh decimation strategy can be optimised exclusively in terms of geometric optimisation criteria and does not need to be compromised by parametric constraints in texture and colour coordinate space.

3.3 Stroke based interaction with digitiser tablet

As was the intention with the development of this virtual mummy, interaction i.e. virtual dissection should be easy and intuitively to be used by non-expert users. A physically correct simulation of a dissection process does not really pose a problem. However, it would require advanced motion capture devices to recognise the user's gestures and body expression, and more importantly, due to its physical correctness it would demand much more trained perfection in the interaction behaviour of the user. We therefore decided to provide simpler tools for the user to peel off layer by layer and thus to uncover the inner structures of the mummy. This virtual peeler was technically accomplished by definition of a number of clipping planes that were associated with the different layers. We let the clipping planes be locked with the anatomical transversal direction, and allow the user to interactively manipulate the trans-axial positions of these planes.

To control these positions, we felt that a digitiser tablet was the most intuitive device to use. It features a pen as main input utensil and it allows affixing tem-

plates with self-explaining illustrations to the spot of the actual input.

Input is based on strokes with the pen of the digitiser tablet. They are interpreted by the software and transformed into parameters to calibrate clipping planes or to activate other functions. Fig. 4 illustrates the graphical template affixed to the digitiser tablet. Peeling of the outer layer or the skin of the mummy is accomplished by striking along the central line of the respective mummy icon on the digitiser layout. Hereby, accurate input is not required. As long as the pen is guided in a certain distance to the central line, the software automatically projects the current position of the pen upon the central line and determines the proportion of the clipped area of the respective geometric object (see also top left area of Fig. 4).

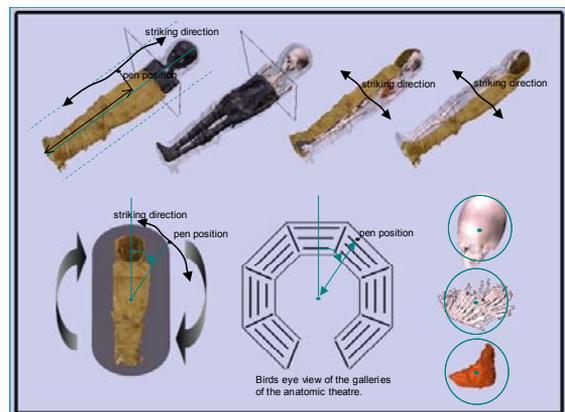


Figure 4: Graphical template for digitiser tablet based interaction. The bold arrows indicate strokes performed by the user. Green lines are mathematical lines of reference.

Another way of slicing the mummy is to manipulate a clipping plane, which is simultaneously affecting rendering of both the linen lay and the skin layer of the mummy. The navigation of this clipping plane is similar to the previously described procedure, where the striking direction goes laterally to the mummy icon on the digitiser layout (top right icons on the digitiser table). In order to make the interaction more fetching, particle animation effects accompany the change of a clipping plane (see Fig. 5). In addition, it is possible to horizontally turn the entire virtual mummy on top of the dissection table. This is due to the fact that the real dissection table, upon which the virtual mummy is recreated, can be turned. To change current turn angle, any point in the neighbourhood of the turntable icon on the digitiser may be hit. The program subsequently calculates the angle between the line from the hit point to the centroid of the icon and the vertical line of the digitiser template. A similar modality is used to interac-

tively adjust the observer's current viewing position in the galleries of the anatomic theatre. To this end, the balconies of the theatre are represented in an iconic picture from a birds eye view. After pointing into the respective area in this icon, the angle and distance to the centre of the anatomic theatre is retrieved by the program. The viewing position is directly fed into the projection pipeline of the application. Finally, pointing to their corresponding icon in the digitiser layout activates an animation sequence for specific parts of the mummy. The animation lets anatomic structures (e.g. chest, liver and skull) pop up out of the mummy and enlarges them for further inspection. Here, the hit-point on the digitiser tablet must be situated within a specific circular area that contains the corresponding anatomic structure.

4. Results

The specific installation of the interactive virtual mummy in its historical context of the anatomic theatre can be seen in Fig. 6. It shows the projection of the virtual imagery on a cotton cloth that covers the top of the dissection table. Even though the application has functionally been developed for dual-piped projection with dynamic head tracking in mind, it has for reasons of practicality been decided not to install specific motion tracking equipment. Instead, users may occupy any position in the gallery of the anatomic theatre, and by pointing on the digitiser layout chose their current viewing position. In that way, visitors can indeed also explore the significance of a correctly projected individual 3D image in comparison to the imagery generated for an alternate user with a different viewing position.

The picture in Fig. 6 also shows the actual digitiser tablet with the graphical layout. The digitiser is connected to an extension cord that allows the visitors to pick up and take along the digitiser when walking up the gallery. An information panel explains to the visitors in few concise statements how to use the digitiser-based interface for interaction.

In Fig. 5 upper part, the sequence of a typical interaction scenario is shown. For the purpose of clarity, the pictures have been projected and rendered for on screen presentation. As is evident, the different outer object layers of linen wrapping and subsequently the skin layer can be peeled off to uncover the interior constituents of the mummy. The dynamic motion of the clipping plane is supported by an animation of a colourful particle system. Runtime performance of the system is an important issue not only for real-time update of the observer's head position, which though was not enabled in the actual installation. But also for the animation of the particle system and for an immediate and smooth response in the interactive peeling procedure, high rendering speed is vital.

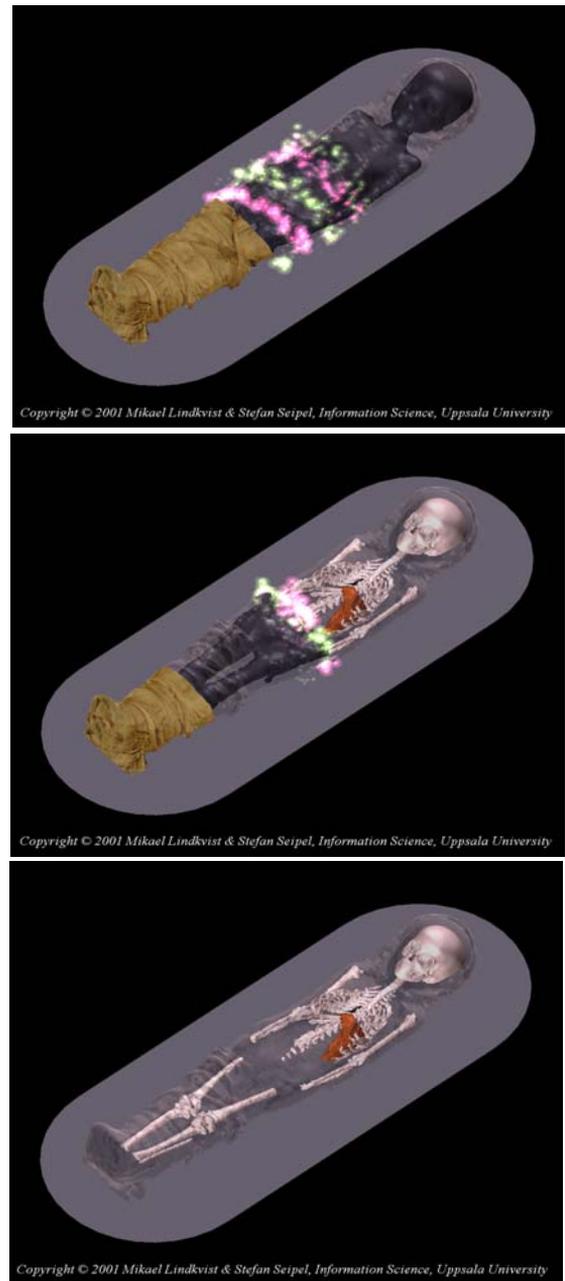


Figure 5: Resulting graphical effects of the virtual mummy.

In the actual exhibition, a Pentium III based computer with 1200MHz clock frequency and 128 MB of RAM is used to render the simulation. It is equipped with a no-name graphics card that is based on GeForce2TM technology, and which is equipped with 32 MB of on-board memory.



Figure 6: *The virtual mummy as projected into it's historical context of the anatomic theatre. In front: The digitiser based interface to the application..*

For rendering purposes we use the models listed in Tab.1. However, to accomplish higher frame rates, the textured model of the outer layer has been reduced by 19614 polygons. Therefore the total number of polygons for the mummy sums up to 104741 polygons. Fig. 5 exhibits the simplified geometric objects. In this model configuration, we could on average achieve a frame-rate of approximately 23 Hz.

5. Discussion

The keystone correction of the OpenGL projection pipeline has proved to be a straightforward instrument to quickly set-up projection based VR applications in new environments that are not and cannot be adapted to the technical equipment commonly used in VR. The parameterisation of this viewing metaphor allows to model virtual objects and real world display components in the same spatial context. It allows for easy on-site measurements of the projector's position, the viewer's location, and the situation of the projection screen to correctly calibrate the software with the real world situation. Being an intrinsic part of the projection pipeline, the keystone compensation function enabled us to overcome the excessive distortions that could not

be handled by the projector's build-in compensation mechanisms. Modelling of equidistant regular patterns that were to appear on the projection surface, allowed us to verify the correct function of the algorithm on site. It should be noticed that in practice, the parameterisation of the projector's position usually must be adjusted by a vertical positional offset that is known and specific for the model of the projector. This is due to the fact that most available projectors today automatically create a correct rectangular projection image at a certain given limited off-axis position. This does however not invalidate the generalised keystone correction method according to (3) and as illustrated in Fig. 2.

With regard to the automatic generation of texture coordinates based on photographic re-projection of texture images we can state, that this method creates very satisfactory visual results and that it helped to overcome our rendering bottleneck. The method is generally applicable to many other application fields of image-based rendering. In combination with our mesh decimation algorithm, the results of the re-texturing procedure for various resolutions of the same object were more than satisfactory. This is mainly thanks to

the fact that the mesh decimation procedure chosen does not introduce significant artefacts to the projection silhouette of the object.

The means of object manipulation and input as described above provide an appropriate degree of freedom in interaction to the user. Satisfying our initial requirement, the virtual dissection is intuitively to understand and the carefully selected interaction paths do not confuse the users. As a proof of our interaction method we account, that during the opening ceremony of the exhibition the vice-chancellor of Uppsala University off-hand performed an impeccable debut dissection of the virtual mummy in front of the spectators. Sporadic observations of visitors of the exhibition under a three-month period showed, that visitors in all ages and regardless of their gender quickly interacted with and performed a virtual dissection of the mummy on their own.

Despite the scepticism of the involved technical experts in this project, the effect of the installation in the authentic environment is enormous, even though dynamic head tracking and stereoscopic projection using dual pipe polarized light projections were not used as foreseen with the software.

6. Conclusion and future work

We have presented a computer graphics application in the cultural heritage of the ancient Egyptian mummies. It provides a powerful tool for non-expert users to interactively uncover internal features of the mummies that are otherwise difficult to appreciate. That, beyond this, the virtual dissection application has been installed in one of the few preserved historical anatomical theatres, excites an experience of a historic kind to the visitors of the museum. The practical requirements of the installation environment required development of a viewing metaphor for arbitrary viewer-to-screen relations with built-in keystone correction was developed. Our method is vital for all projection based VR applications that have to cope with extreme off-axis projection conditions and arbitrary viewer and screen configurations.

Our continued research in this project will look into the networked aspects of this application in order to accomplish distributed collaborative experiences of the virtual mummy. We have engagements in the development of protocols for propagation of shared states in a distributed VR environment. They have been applied successfully in the context of distributed virtual learning environments and their application in the virtual mummy project would make this historic content available to a wider community. Other planned activities are to use parts of the virtual mummy as a platform to implement virtual excavations as an advanced learning tool in education of students in Archaeology.

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