Computer-generated 3D models and digital storage for use in palaeontological collections, tested for xiphosurans of Eocene age from Saxony-Anhalt, Germany

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Keywords: 3D scanning, palaeontological database, palaeontological collections

Zusammenfassung

Geologische und paläontologische Sammlungen sind oft unzureichend elektronisch erfasst, weshalb ein angemessener wissenschaftlicher Austausch oft erschwert wird bzw. nicht möglich ist. Sammlungsdatenbanken von Museen und Universitäten geben teilweise einen guten Überblick über die jeweiligen Sammlungsbestände, liegen jedoch häufig nicht in standardisierter Form vor und verfügen zudem über keine Visualisierungsmöglichkeiten. Ein Ansatz, dieses Problem zu lösen, ist die Erweiterung der Datenbankstruktur von „Specify 6“. Um die Anwendbarkeit zu testen, wurde eine Auswahl von Sammlungsstücken aus den Geologisch-Paläontologischen Sammlungen der Martin-Luther-Universität Halle-Wittenberg, die im Institut für Geowissenschaften und Geographie in Halle (Saale) untergebracht sind und hier wissenschaftlich betreut werden, für diese Studie ausgewählt. Es handelt sich dabei um paläontologische Objekte, wie Xiphosuren (Schwertschwänze) aus dem Eozän von Sachsen-Anhalt, sowie um Teile der „Sammlung Johannes Walther“, die mit Hilfe eines Laserscansystems 3D-digitalisiert und in die modifizierte Datenbank eingepflegt wurden. Erste Ergebnisse zeigen, dass auf diesem Wege Wissenschaftler weltweit sehr schnell auf entsprechende Informationen zugreifen können und dass mit Hilfe der 3D-Scans zugleich erste Messungen und Visualisierungen möglich sind.

Abstract

Geological and palaeontological collections often suffer from an inability to disseminate samples and their scientific background appropriately. Databases of the collections of museums and universities already give good scientific overviews if they are set up properly, but they frequently lack standardization of the structure and visualization possibilities. To solve this problem, a new approach was started to enhance the standardized database structure of "Specify 6" to register geological and palaeontological samples in the collections of the Martin Luther University Halle-Wittenberg. To test the applicability, a subset of only a few samples was taken that comprised some of the most important fossils, including xiphosurans of Eocene age, and samples of the collection of Johannes Walther. To obtain realistic and accurate 3D models, this subset was digitalized with an inexpensive laser scanning technique. The results show that small amout of technical material and the highly differentiated structure of the hierarchical database "Specify 6" lead to a result that helps scientists all over the world to obtain the appropriate scientific background information about the samples and the possibility of obtaining their own measurements and interactive visualization of 3D scans.

1. Introduction

Research nowadays benefits from data availability, data accessibility, and data exchange. In palaeontology and at limited scale in geology research collections also play an important role (e.g. Weber 2012). The capacities for a comparison of fossils, rocks, and minerals are preconditions for a knowledge based research. In the past, the samples had to be sent physically for detailed investigations. But today, modern computers are capable of sufficient registration and visualization capabilities, so that data exchange can substitute for sample exchange in many cases. By now, 3D registration of samples is also available in high resolution for low or medium budgets so that additional sources of samples can contribute to the database, for example, private collections or small museums. The geological and palaeontological collections of Martin Luther University Halle-Wittenberg in Halle (Germany), with about two million objects, are one of the largest and most important university collections of this kind in Germany (HAUSCHKE 2002, 2007, 2013). The history of these collections goes back more than 200 years. Of special value and interest are palaeontological specimens, which are the documentation of scientific work, particularly the type material. In particular, these specimens are in demand by scientists all over the world. To facilitate the decision to study the original specimens in the collections in Halle, 3D images are offered.

Usually, collections are structured hierarchically according to taxonomy (fossils), genesis (rocks), or chemistry (minerals), but most of today's databases have relational database models. The advantage of a hierarchical database model compared to a relational one is that there is no arbitrary entry possible but only a structured step-by-step progress according to meaningful choices and settings. The disadvantage is that the input is not completely free, so that sometimes rocks may not match the investigation results.

2. METHODS

2.1 3D LASER SCANNING

Today, the creation of detailed digital 3D models of real objects is made available instrumentally. A huge number of 3D scanners are offered by different companies and also by a few Open Source projects, which are not suitable for the mentioned purpose at the moment because of their low resolution. In this paper, we introduce a cheap 3D scanning system with a resolution that allows the scanning of detailed objects with textures and a size down to 1 cm.

2.1.1 SOFTWARE

The software is a very import factor in creating 3D models from real objects. Most scanning systems consist of a special combination of hard- and software. The DAVID Laserscanner pursues a different objective: to offer a cheap but high-performance solution, only scanning software with four main capabilities is provided (DAVID 3D Solutions GbR, 2012). These four capabilities are surface scanning, texture generation, alignment, and merging. Although there is also the possibility of using DAVID for mesh cleaning, MeshLab (CIGNONI et al. 2008) is far more suitable for this task. This Open Source tool was designed for processing unstructured triangular meshes, especially high-poly scan data (CIGNONI et al. 2008). Another interesting functionality is the command line interpreter, which allows automated processing of multiple files. To automate the whole scanning process, a bridge between DAVID, the controlling hardware, and MeshLab was needed. For this reason AutoScan was developed. This program sets up the different scan settings (laser movement speed, lighting, number of partial scans, etc.) and controls the hardware and DAVID via an emulated serial connection. These are the basic programs needed for the fully automated 3D scans within this project. To work with these models some additional software is needed: 3D rendering and animation software (Blender, 3D Studio Max, etc.), imaging software (GIMP, Adobe Photoshop), and a program for creating 3D PDFs (Tex, MikTex, and Adobe Acrobat).

2.1.2 HARDWARE COMPONENTS - CAMERA

In the described setup a Logitech HD Pro Webcam C920 with USB connection is used. The HD Pro Webcam has a 3 MP sensor that allows 30 frames per second at the highest resolution (1920 × 1080 pixels). The camera is used for the geometric data acquisition and the image texture generation.

2.1.3 HARDWARE COMPONENTS - LASER

Even if anything which creates a thin line can be used for triangulation, a line laser seems to perform this task best. The laser used is a 5 mW focusable line laser. The ability to change the focus has the advantage that the same laser can be used for different scaled setups without losing accuracy. Originally, the laser had a 3.3 V battery, but to ensure a stable power supply and the possibility of switching on or off it was retooled with a permanent power supply.

2.1.4 HARDWARE COMPONENTS - MECHANICAL DATA/MECHATRONICS

This component assembly includes two 12 V direct current flow stepper motors and gearing: one stepper motor for object rotation and the other (with gearing) for the laser movement. Stepper motors are used because equal angles are necessary during movement, which cannot be achieved with a standard direct current machine.

2.1.5 HARDWARE COMPONENTS - ELECTRONIC COMPONENTS

The electronic components are used to control the lighting and the stepper motors. The core is an Arduino Duemilanove microcontroller board with two EasyDriver V3 motorshields and one relay circuit board as peripheral devices.

2.1.6 HARDWARE COMPONENTS - LIGHTING

To ensure an optimal stable lighting of the object for texture recording, two 12 V halogen light sources have been installed. One 30 W spotlight with a 30° angle of the reflected beam is used for directional lighting. The other light source (20 W bulb without reflector) helps to reduce shadows or acts as an indirect light.

2.1.7 SETUP

The hardware setup is predefined by the registration technique of the DAVID 3D Laserscanner described in Winkelbach et al. (2006). The laser line triangulation geometry registration requires a basic fixed geometric alignment of the single system parts (Fig. 1) during the scanning process. The setup can be used for nearly every kind of object and also nearly every size. The limitations are only defined by the hardware components used.

The basic scanning system consists of the camera, a focusable line laser, and the calibration background, as shown in Fig. 1. The calibration background consists of two panels with a special calibration pattern which must be arranged at an angle of exactly 90°. The camera, the object, and the laser should be placed on the diagonal of the quadric base and the camera's focus should be aimed at the middle of the calibration background. However, the laser can be positioned either above or below the camera.

In the scope of automating the scanning process, an enhanced scanning system based on a maximal object size of 20 cm was developed. This includes the following aspects:

- ensuring constant lighting conditions during the scanning process
- constant lighting conditions for texture images

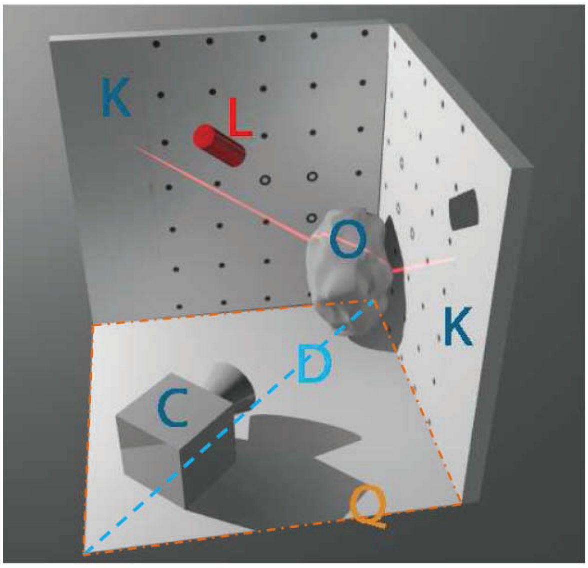

Figure 1: Basic setup of the scanning system camera (C), laser (L), calibration background (K), diagonal (D), object (O), and quadric base (Q).

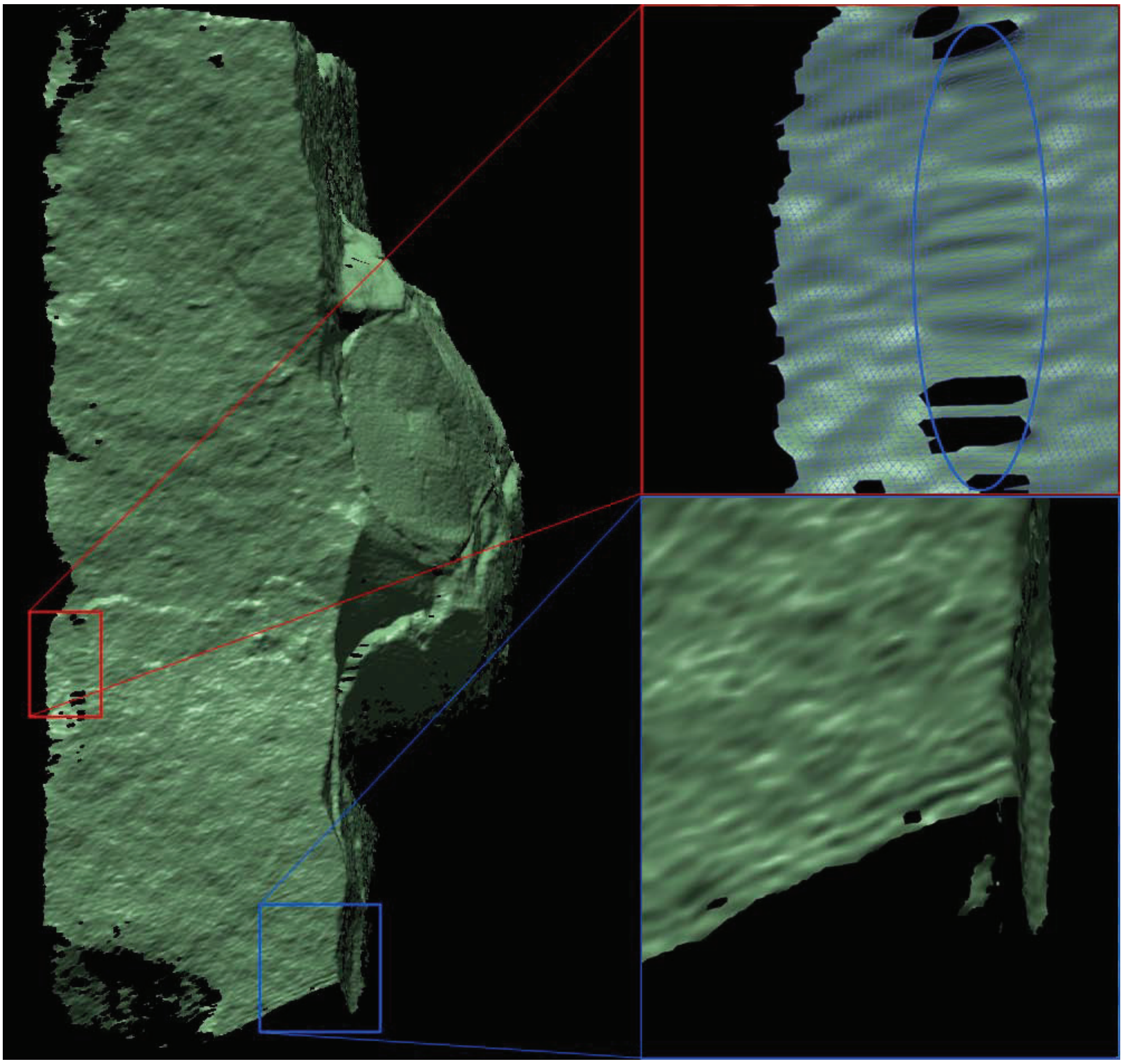

Figure 2: Deformations of a 3D scan. Left: complete partial scan of *Limulus decheni* without texture; height: 344.6 mm. Upper right: polygons with a surface area up to ten times bigger than the mesh average, caused by shadows cast and interpolation. Lower right: "waves" in the lower part of the mesh, caused by a defocused (too broad) laser-line. Amplitude of the "waves": ca. 2.2 mm.

• automated laser movement and object rotation

• easy and fast camera, laser, and turntable adjustment.

To achieve the lighting requirements, a closable casing with two independent halogen light sources (spot and indirect) was built. The movement of the laser was realized using a stepper motor with gearing mounted on a slide which can be moved along a rail lying on the top diagonal. The camera and the stepper-motor-driven turntable are also mounted on slides but here the rail is on the bottom diagonal. The controlling hardware is placed in a separate case on top of the scanner casing.

2.1.8 CREATING THE MODEL

The model creation process itself consists of 1 to n single steps, depending on the needs and, of course, the complexity of the scanned surface. Each step can be considered as a partial scan. Partial scans are necessary because of the geometric data registration of the DAVID software. The triangulation method (described in WINKELBACH et al., 2006) does not allow movement of the object during the scanning process. Also, texturing of the model

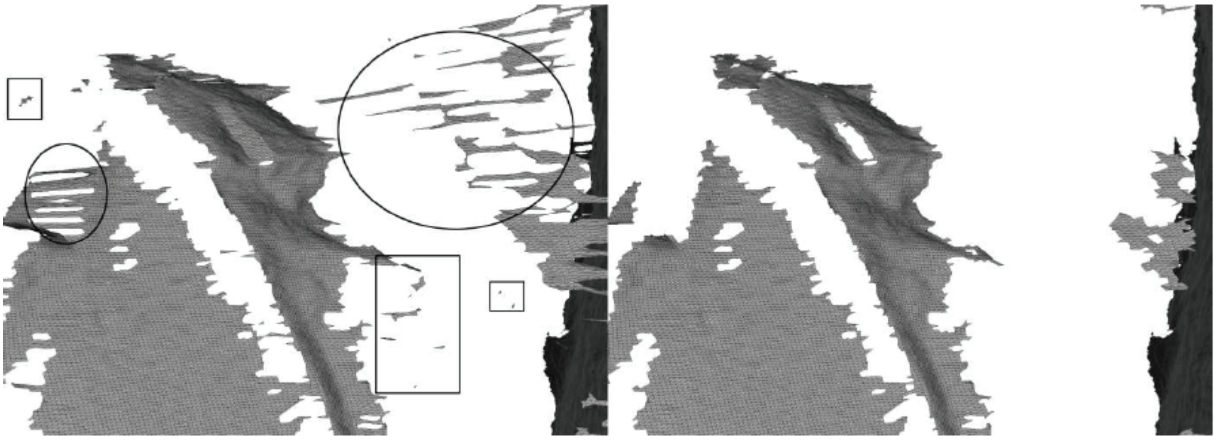

Figure 3: Detail of a partial scan of *Limulus decheni*: before (left) and after (right) removing polygons with edges that are too long (oval) and "island polygons" (rectangle).

requires an image texture, in contrast to other laser-scanning techniques, where the colour of each vertex is calculated from the reflected and received laser beams. The quality of the resulting mesh depends on the object itself (complex surface, colour, glossiness, etc.), the hardware components used (camera resolution, laser line thickness), and the interpolation of "holes" inside the mesh. Fig. 2 shows a partial scan of *Limulus decheni* without texture and some deformation of the mesh.

A lot of these deformations can be automatically removed using the Open Source tool MeshLab or by hand. Without this important step (mesh cleaning or post-processing), the alignment of the partial scans and the fusion to complete the waterproof mesh certainly result in bad quality and incorrectness. Proper mesh cleaning should always include the deletion of faces with edges which are too long, "island polygons", and areas which are not part of the object itself (fixing and stabilization). The result of a cleaning process can be seen in Fig. 3.

If enough partial scans are available, the final model can be created. This is done in two single steps: aligning all partial scans with each other and merging them into a "waterproof" mesh. These two steps are described in Winkelbach et al. (2006).

Putting everything together results in the so-called scan-pipeline (Fig. 4). The demonstrated pipeline can deviate from the effective one, depending on the usage of the AutoScan-Core functionality and the particular needs and complexity of an object.

2.1.9 WORKING WITH THE MODEL

The final textured model can be used in many different ways. However, it needs to be adapted to different purposes, because it is only possible to use the export format of DAVID (OBJ- or STL-format) to transfer it into other software (Blender, 3D Studio Max, etc.). But these programs are often not capable of working with a high number of polygon objects and a scanned model can easily achieve millions of polygons. Another limiting fact is that, because of its complexity, 3D modelling software is not practical for non-experts. Nevertheless, 3D modelling and rendering software is indispensable for creating high-end linear contents like images and animated videos. But in contrast to linear contents, interactive contents have become more and more important because of permanent developments in computer technology. So, it was necessary to find a solution for exchanging the model combined with interactive usage in one data format. The very popular Adobe Portable Document Format (PDF) can be seen as an (unofficial) international standard for exchanging and publishing digital contents on the World Wide Web by now. It also has a lot of 3D functionality implemented. For this reason and due to its easy handling, the Adobe PDF seems to be the best format for digital publishing of the

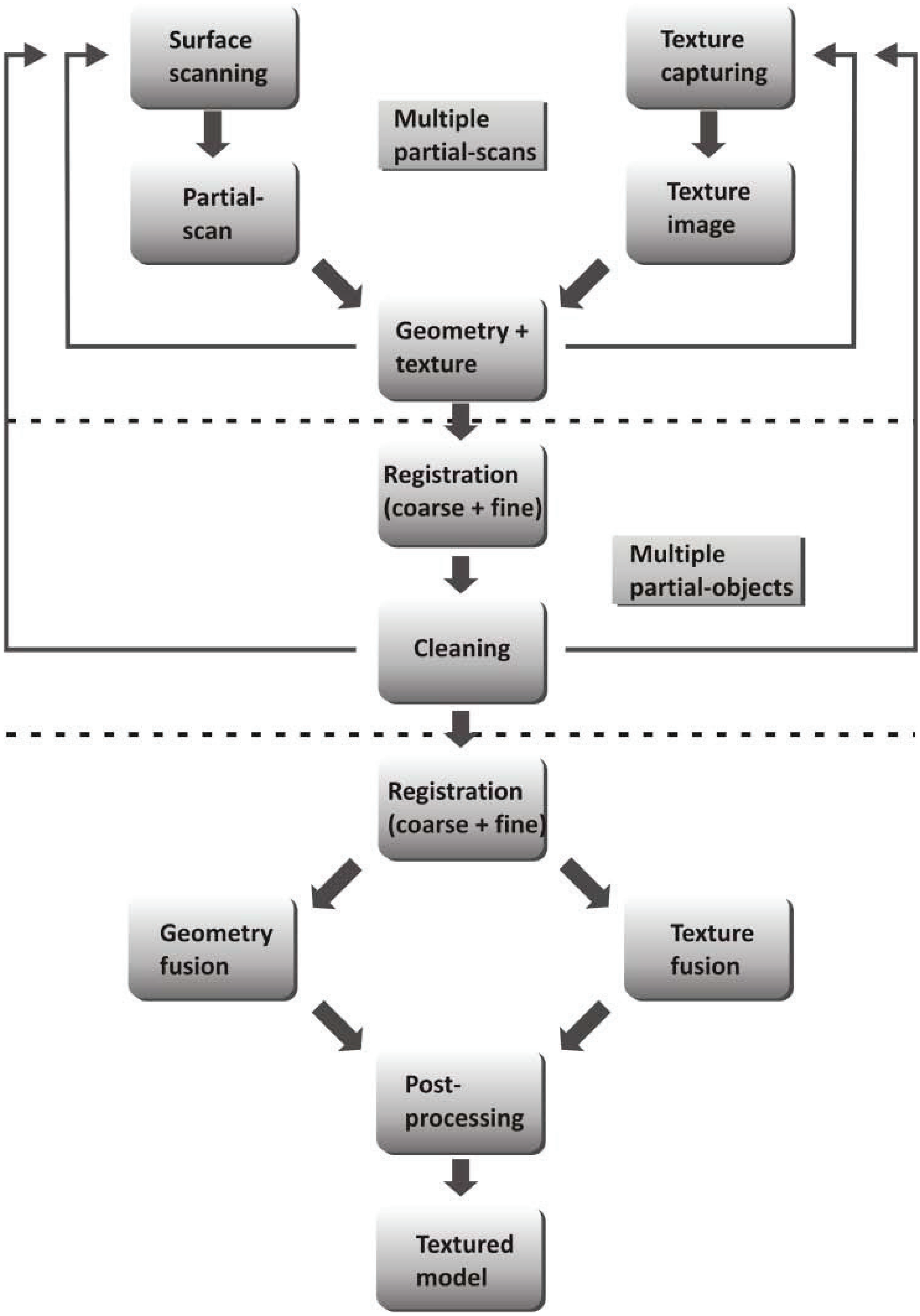

Figure 4: Workflow showing the idealized scan pipeline.

generated 3D models, but there are, of course, many other possibilities, such as the VRML format. To use the generated 3D models in 3D PDFs, the number of polygons had to be reduced from a few million to 150,000 using the quadric edge collapse decimation with the texture filter of MeshLab.

2.1.10 IMPROVEMENT OF DATABASE STRUCTURE AND IMPLEMENTATION OF VISUALIZATION TECHNIQUES

Since the beginnings of computer sciences, databases have played an important role in software development. In parallel with the rapid increase in the efficiency of hardware components, different database models have been developed. One of the first was the hierarchical model using a simple parent–child (1:n) relationship. Due to the lack of flexibility, especially in consideration of attribution, relational or object-oriented database-models were established as an informal standard. However, in spite of its flexibility, the relational database-model does not completely fulfill the needs of archiving natural science collections.

2.2 RELATIONAL VERSUS HIERARCHICAL DATABASE MODEL

One of the main advantages of the relational database model is of course its flexibility. It is very easy to add different contents or new relations to the database scheme. The same task inside a hierarchical model can be much harder just because of the relation. Whereas the relational database model supports the many-to-many (m:n) relationship between two entities, hierarchical models support only one-to-many (1:n) or one-to-one (1:1) relationships. On the other hand, this constraint of the relationship leads to an improvement in the clarity inside the database. In consideration of the fact that every object is present only once in a collection, the common problem of redundancies in hierarchical databases can be neglected. In addition, university collections are usually organized hierarchically. So, the use of a hierarchical database model suggests itself.

2.2.1 SPECIFY 6

The Specify 6 project is developed by the Biodiversity Informatics Research Centre of the University of Kansas. It is geared to natural science collections, especially biodiversity collections, and this is represented by the structure, the contents, and the database scheme of Specify 6. The project's aim is to support the handling of specimen information and a better and easier scientific data exchange (Specify Software Project, 2013). The database management system (DBMS)

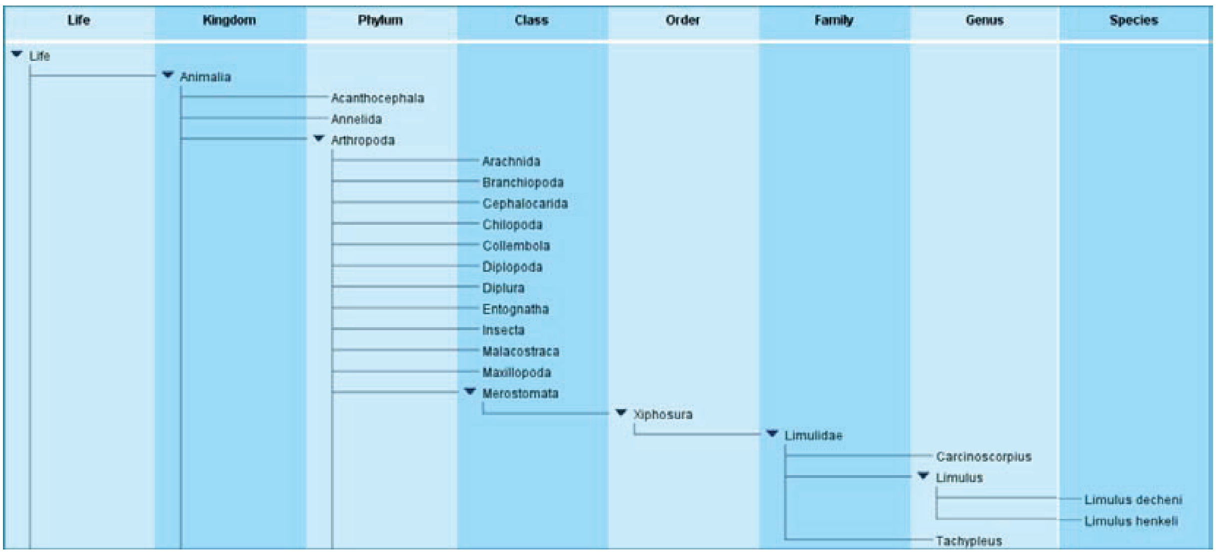

Figure 5: Excerpt from the taxonomic classification scheme showing *Limulus decheni* and *L. henkeli* in Specify 6.

behind Specify 6 is the Open Source DBMS MySQL. Every Specify database, which represents a single collection, is organized by a hierarchical database model. There are also lots of different hierarchical attributes implemented like taxonomy, bio- or lithostratigraphy, and storage location. The particular nodes can be set up before the database creation to conform to the data format of external attribute resources like the Integrated Taxonomic Information System (ITIS 2013) or the Catalogue of Life (CoL 2013), shown in Fig. 5. To ease the usage of the database, Specify 6 comes with a graphical user interface with customizable data forms. The software itself is also Open Source and this enables a potential user group to customize it for its special needs and purposes.

2.2.2 IMPLEMENTING OWN CONTENTS IN SPECIFY 6

The implemented 161 attribute tables of Specify 6 allow a huge amount of information depending on a biological collection object. However, these attributes do not fulfill the requirements of this project. The tested objects are of course fossils and could be described by the relevant implemented attributes (taxonomy), but as a part of the geological and palaeontological collections of the Martin Luther University Halle-Wittenberg some of the important information about geological characteristics cannot be recorded properly. To accomplish this, some fundamental enhancement of the database scheme and the user interface had to be made. This enhancement basically contained the development of a new hierarchical attribute, the encapsulation of this attribute in the Specify database scheme, and the corresponding modification of the Specify 6 user interface. The most important characteristic of geological specimens is their petrography. So the new attribute should give the ability to determine the rock itself. Furthermore, this hierarchical petrographical structure (petrography tree) is also suitable as a classification of rocks. The petrography tree is developed to contain the entirety of all rocks. The first layer (origin group) of the tree is defined by three nodes: sedimentary, magmatic, and metamorphic rocks. Each of these nodes has five sub-levels determining the different characteristics of the rocks: genesis, composition/educt, assemblage, official representative, and typical sample (Fig. 6). All included rocks are based on the following references: DIN – Deutsches Institut für Normung (2004), MARKL (2008), GILLESPIE & STYLES (1999), HALLWORTH & KNOX (1999), ROBERTSON (1999), STRECKEISEN (1976), and PREUSS (2010). The newly developed contents

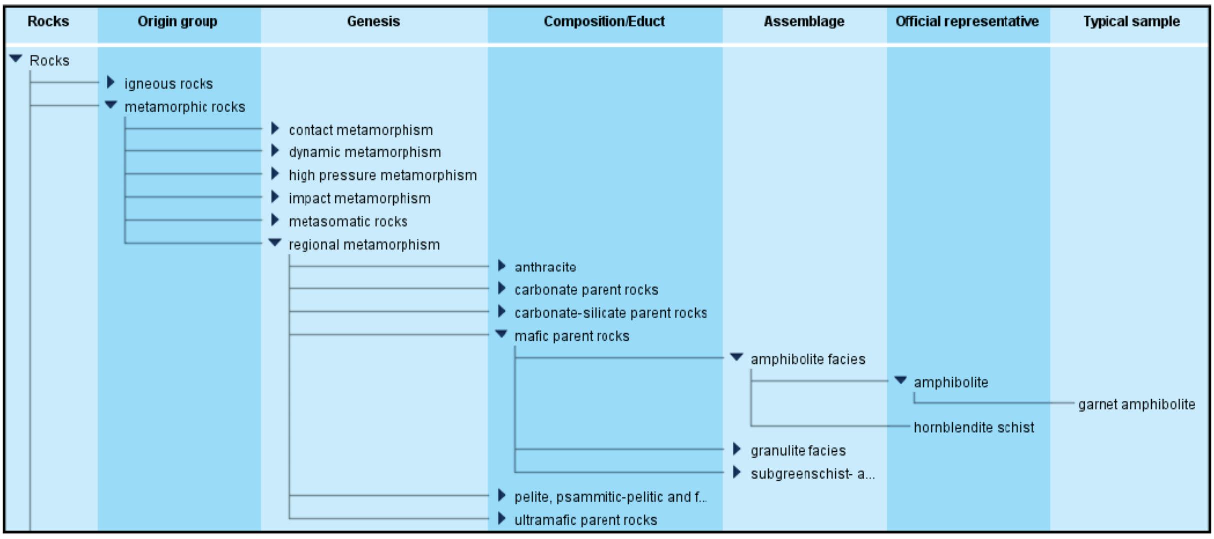

Figure 6: Hierarchical view of the metamorphic rock node showing a garnet-bearing amphibolite.

must now be implemented in the source code (Java) of the Specify 6 main program and also the database scheme must be changed.

3. XIPHOSURANS OF EOCENE AGE: A CASE STUDY

Xiphosurans are a subclass of arthropods. In the fossil record, xiphosurans are normally very rare (e.g., Størmer 1955). In particular, this is true for genera and species of the superfamily Limulacea ("limulids"), which remained in the Mesozoic and Tertiary (Hauschke & Wilde 1991). Extant xiphosurans can be subdivided into three genera: *Limulus*, *Tachypleus*, and *Carcinoscorpius*. Whereas *Tachypleus* can be subdivided into the two species *T. gigas* and *T. tridentatus*, the genera *Limulus* and *Carcinoscorpius* are monospecific. The natural habitats of extant xiphosurans are shallow marine coastal areas. *L. polyphemus* lives in near-shore waters along the eastern coast of the USA and around Yucatan in Mexico. On the other hand, *Carcinoscorpius rotundicauda* and the two species of *Tachypleus* live in coastal environments in southeast Asia (Hauschke & Wilde 1987 and references therein).

The only limulids known from the Tertiary worldwide were recovered in the nineteenth and early twentieth centuries in the Upper Eocene Domsen Sands of the Weißelster Basin near Teuchern in Saxony-Anhalt, Germany (Hauschke & Wilde 2004). The still verifiable specimens are hosted in the Geologisch-Paläontologische Sammlungen of Martin Luther University in Halle (Saale), among them also the holotype of *Limulus decheni* Zincken, 1862, and one specimen in the collections of the Institut für Geophysik und Geologie of the University of Leipzig. The specimens that formerly formed part of the collections of Preußische Geologische Landesanstalt in Berlin are regarded as loss due to the aftermath of World War II (Hauschke & Wilde 2004). No more than about ten limulid specimens have been found since then (Fiebelkorn, 1895; Vetter 1933; Bellmann 1997). Only four specimens, among them the holotype with external cast and imprint, remained in collections down to the present day. Several authors referred to these finds in the past (e.g. Zincken 1862; Giebel 1863; Fritsch 1901; Böhm 1908; Vetter 1931; Størmer 1952, Størmer (1952) assigned *Limulus decheni* Zincken, 1862, to the extant southeast Asian genus *Tachypleus*. The most recent description on this Palaeogene xiphosuran was given by Hauschke & Wilde (2004). Comparing the type material with carapaces of extant limulids in the zoological collection of the University in Halle (Saale) and with regard to phylogenetic relationships and present day distribution, these authors came to the conclusion that "*Limulus*" *decheni* could serve as a "missing link" between the North American species and the southeast Asian clade (see also Shishikura & Sekiguchi 1979; Sekiguchi & Sugita 1980; Shishikura et al. 1982; Iwanaga & Kawabata 1998; Xia 2000; Obst et al. 2012).

The limulids from the Upper Eocene of Germany are bridging a stratigraphic gap of about 70 million years from the Upper Cretaceous to date (Hauschke & Wilde 2004). Three of only five proofs from the Cretaceous worldwide were found in the USA, two of them from the uppermost Cretaceous (Reeside & Harris 1952; Holland et al. 1975). Limulids from the Lower Cretaceous were published from the Lebanon by Woodward (1879), from Australia by Rieck & Gill (1971), and from the USA by Feldmann et al. (2011).

Obst et al. (2012) focused on the molecular phylogeny of extant limulids and deduced the three extant Asian species from a monophyletic genus *Tachypleus*. These authors postulated diversification during the Palaeogene. At the moment, a definite generic assignment of the limulids from the Tertiary is not yet possible. Further investigations taking into account specimens of fossil and extant species could help to solve the problem of relationship on a generic level.

During the last few years, several objects from the geological and palaeontological col-

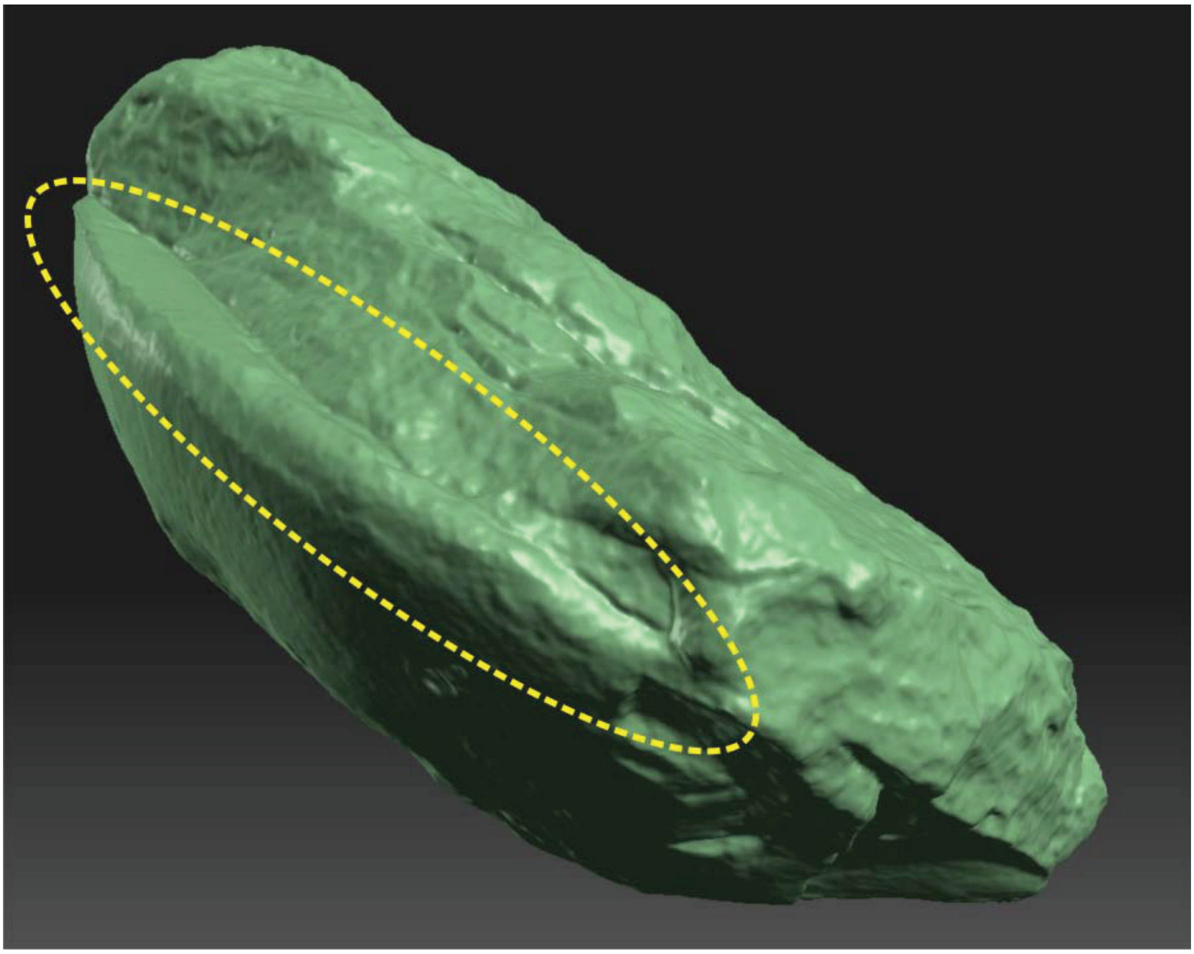

Figure 7: Rostral view (upside down) of *Limulus decheni*. The yellow line shows the acute angle of the carapace.

lections have been scanned in 3D (HAUSCHKE et al. 2011; SCHIMPF et al. 2012). In a pilot project, we applied the established methods to Eocene xiphosurans.

Depending on the size of the fossil xiphosurans (up to ca. 40 cm), the scanning system described earlier needed to be scaled up to fit these conditions. This was done by using two wooden tabletops equipped with a calibration pattern, which was created with a standard plotter, as the calibration background. The camera and the laser were affixed on suitable mountings. Because of the weight of the objects it was not possible to use the stepper-motor as is done with smaller objects. However, the objects needed to be moved into position manually for the partial scans. To avoid disturbing the lighting conditions, the setup was placed in a dark room. The scanned objects consist of a light grey to light brown coloured sandstone, which eliminates the need to use any coatings (needed for dark and heavy reflective materials). Only some small quartz grains led to some noise and/or holes during the scanning process. These unconformities had a maximum size of less than 1 mm, so they could easily be eliminated without influencing the recognized level of detail of the scanned object. Depending on the size of the scanned area a single partial scanning process took between five and ten minutes. Looking forward to the alignment (registration) of the single meshes, the object has to be placed so that the partial scans cover at least 20% of the neighbouring ones. But in consideration of the shape of the xiphosurans, especially the rostral part of the carapace, a few additional scans were needed because of the acute angle (Fig. 7) between the upper and lower sides. These angles lead to the polygon deforma-

Table 1: Properties of the three "*Limulus*" *decheni* specimens and the resulting 3D meshes.

Specimen	Partial-scans	Dimensions (length × width × height [mm])	Merged result		Polygon reduced result		PDF size [MB]
			No. Polygons	File size [MB]	Number of Polygons	File size [MB]	
1	22	338.1 × 205.7 × 145.6	2,298,550	245	150,000	9.8	4.24
2	28	382.4 × 332.7 × 111.7	3,101,691	324	150,000	16.8	6.29
3	24	176.2 × 183.5 × 71.4	3,504,938	384	150,000	16.7	5.51

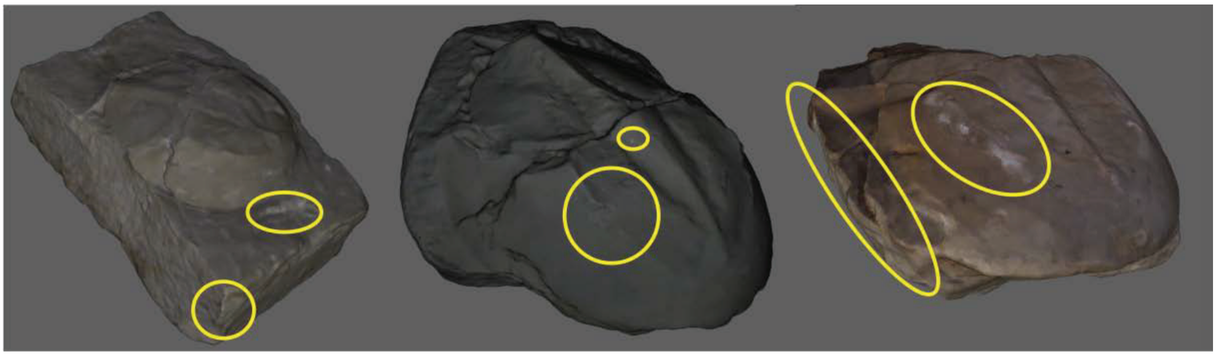

Figure 8: Images of specimens 1, 2, and 3 (left to right) taken from the 3D PDFs. The objects are not true to scale. The texture mistakes occurring due to the polygon reduction process are marked in yellow.

Figure 9: Images of specimens 1, 2, and 3 (left to right) rendered with 3D Studio Max in HD (1920 × 1080 px). The objects are not true to scale.

tions shown in Fig. 2 and will make the alignment process difficult.

Within this project, three specimens of "*Limulus" decheni* (including the holotype) have been digitized and archived in wavefront object format (*.obj), which are now available for further usage. The intermediate and final results are listed in Table 1. The resulting file size and the huge number of polygons are unsuitable for either the usage of the 3D PDF format or any other interactive application. Reducing the number of polygons to 150,000 provides a good compromise between file size and the quality of the mesh. Using these reduced models for PDF creation results in a PDF size suitable for fast and easy data exchange. Although it is a good compromise, especially the texture (shown in Fig. 8) and even the geometry can lose quality. For this reason and because of the internal format (embedded geometry) of a 3D PDF, these files are only used for a data exchange without the need for any special viewing software. To allow further usage like high-end renderings and animations, the original merged result is also attached to the Specify 6 database.

4. CONCLUSIONS AND PERSPECTIVES

Digital duplicates of macro fossils can never replace the existing ones but they can ease and extend the scientific exchange and in this case stimulate discussions on the phylogenetic relationships among extant and fossil limulids from the Mesozoic and Cenozoic. Although there are many commercial scanning systems, their cost–performance ratio is not very satisfying and they are often not affordable. We present a solution which is accurate and also affordable by private persons. Scaling the setup provides an application for nearly every special need depending on the used hardware components. The resulting textured 3D mesh can be used in many different ways not only to create 3D PDFs and animations but also for printing 3D replicas.

At the moment a self-written controlling software named AutoScan allows full automated 360° scans of objects with a maximal diameter of about 15 cm. Bigger objects need an adaptation of the hardware setup. However depending on the size and complexity of the specimen the whole process (scanning, alignment, post-processing) can be time consuming. Also the quality of the texture images still needs some improvement.

As described before, we decided to use the 3D PDF format for a fast and easy data exchange. Our results show the capability to extend the possibilities of palaeontological methods and working. The ability to conduct fast and accurate measurements without the negative influence of the perspective when using 2D data, like photographs or drawings, is one of the most convincing arguments. Although the aim of this project was to enrich the palaeontological workflow, it is obvious that the generated data can also be used for non-scientific applications. These applications may include educational purposes like eLearning but also linear (high quality renderings; see Fig. 9) and interactive contents for exhibitions and web sites.

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