Experiences with low and high cost 3D surface scanner

Erfahrungen mit niedrig- und hochpreisigen 3D Oberflächenscannern

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Abstract - The increasing importance of virtual techniques in archaeology and anthropology puts the question of adequate hardware and software applications for a digitalization of collections for museums and institutions into the focus. Especially the market for mobile 3D scanning developed rapidly during the last years and provides a range of different models suitable for scientific purposes today. As the requirements for archaeological and anthropological applications are very high and differentiated - due to the, in some cases very complex surface morphologies of the objects and the different textures from shiny obsidian to porous bone - the decision for a scanner model is often complicated. The Neanderthal Museum and the Royal Belgian Institute of Sciences have been testing six different surface scanner from four companies during the last months concerning their suitability for archaeological and anthropological objects. Quality of the 3D models was rated by the visibility and exactness of standard attributes used for classification of the object type in archaeology or anthropology. Results are presented here. Generally, all types of archaeological and anthropological objects can be digitalized with surface scanner. If a high end or a low budget model should be used depends on the texture of the object and the intended purpose.

Zusammenfassung - *Mit der steigenden Bedeutung virtueller Methoden in Archäologie und Anthropologie gewinnt auch die Frage nach den geeigneten Geräten und Software Anwendungen für die digitale Erfassung von Sammlungen für viele Museen und Institute an Bedeutung. Vor allem im Bereich der mobilen 3D Oberflächen-Scanner hat sich der Markt in den letzten Jahren enorm entwickelt und bietet heute zahlreiche Modelle, die auch für wissenschaftliche Zwecke geeignet sind. Da die Anforderungen der Archäologie und Anthropologie aufgrund der, zum Teil sehr komplexen Oberflächenstrukturen und der unterschiedlichen Texturen, von glänzendem Obsidian bis hin zu porösem Knochen, an Oberflächenscanner jedoch sehr hoch und differenziert sind, ist die Entscheidung für ein Oberflächen-Scanner Modell oftmals schwierig. Das Royal Belgian Institute of Sciences und das Neanderthal Museum haben in den vergangenen Monaten sechs Oberflächen-Scanner von vier verschiedenen Herstellern auf ihre Eignung für archäologische und anthropologische Objekte hin getestet. Die Qualität der 3D Modelle wurde anhand der Sichtbarkeit und Genauigkeit der Merkmale bewertet, die in der Archäologie oder Anthropologie standardmäßig zur Klassifikation der jeweiligen Objektgruppe verwendet werden. Die Ergebnisse werden hier vorgestellt. Grundsätzlich lassen sich alle Arten von archäologischen und anthropologischen Objekten mit Oberflächen-Scannern digitalisieren. Ob ein hochpreisiges oder ein günstiges Modell verwendet werden kann, ist abhängig von der Objektbeschaffenheit und dem Verwendungszweck.*

Keywords - 3D scanner; paleoanthropology; archaeology; stereolithographic model; digitalization; virtual anthropology
3D Scanner; Paläoanthropogie; Archäologie; Stereolithographisches Modell; Digitalizierung; virtuelle Anthropologie

Introduction

Virtual techniques and three-dimensional modeling have become increasingly important for archaeology and anthropology over the last few years. The possibilities of accomplishing research digitally on screen have made enormous progress within short time and open a wide range of new analysis options (see e.g. Guipert et al. 2003; Mafart & Delignette 2002; Zollikofer et al. 1998).

Especially in the nowadays widely established discipline of virtual anthropology theoretical foundations were laid (see e.g. Bookstein et al. 2004; Gibbons 2002; Gunz et al. 2004; Mafart et al. 2004; Recheis et al. 1999; Weber et al. 1998) and a number of important studies working with digitalized specimen have been published (see e.g. Falk et al. 2000; Neubauer et al. 2004; Pfisterer et al. 2007; Seidler et al. 1997; Weber et al. 2004; Zollikofer et al. 1995). Less frequently, digital techniques have also

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been applied in Palaeolithic archaeology (see e.g. Borderie et al. 2004; Sumner & Riddle 2008). The advantages of 3D models are obvious as they do not only reduce traveling costs and preserve the originals but also assist the developing of new interdisciplinary approaches.

Digitalization of artefacts and human bones is often done by generating stereolithographic models (STLs) from computed tomography (CT) slices. CT scanning gives insights into the inner structures of scanned objects - an advantage no other system can offer. Recent developments of µ-CT in anthropology also study microstructures of human fossils with a resolution of 5 to 50 µm/pixel. Nevertheless where only the surface morphology is needed, 3D scanner offer a competitive and mobile alternative that could open the door for an extensive digitalization of archaeological and anthropological material.

During the last months, the Neanderthal Museum and the Royal Belgian Institute of Sciences (RBINS) subjected several surface scanner to test applications with the goal to ascertain which scanner suites best for which material and intended purpose. Tested were scanner by the companies Breuckmann, DEIOS, DesCam and NextEngine (Fig. 1). Materials were stone artefacts, ceramic and human fossils. Criteria for rating the quality of STLs were for stone artefacts the sharpness of retouches and Wallner lines. STLs of anthropological objects were evaluated after the visibility of sutures and the correct visualization of cancellous bone. The third important criterion for anthropological objects was how complete complex

	Structured Light		Structured Light Laser	Laser		Multi Laser	
Company	Breuckmann	Breuckmann	DEIOS	Descam	Descam	Nextengine HD	Nextengine HD
Model	OptoTop-HE	smartSCAN 3D	Prototype	Model Maker Z35	Microscribe / RSI	Scanstudio HD	Scanstudio HD PRO
Self-calibration	no	no	yes	yes	yes	yes	yes
automatic scan	yes	yes	no	no	no	yes	yes
Texture					yes		
Gray	yes	yes	yes	yes	yes	yes	yes
RGB	yes	yes	yes (recomposed)	yes	yes	yes	yes
Filtered	yes (optional)	yes (optional)	yes (each 10 nm)	no	no	yes	Yes (7 values)
Resolution							
Camera	5 Mp colour	1.4 Mp colour	1 Mp mono-chrome	CCD		CMOS 3.0 Mp colour	CMOS 3.0 Mp colour
Accuracy (µm)	+/- 5 µm bis 100 µm	+/- 10 bis 50 µm		+/- 18 µm bis 148 µm	+/- 200 µm	+/- 120 µm bis 360 µm	+/- 120 µm bis 360 µm
Min. depth resolution	2 µm	2 µm					
Acquisition Time	1 sec	1 sec	10 sec	23000 points/sec	28000 points/sec	35 - 150 sec	15 - 105 sec
Mode Small							
Field of View	60 mm diag.	90 mm diag.	50 mm diag.	35 mm stripe		180 mm diag.	180 mm diag.
Max. resolution	15 µm	50 µm	50 µm	25 µm	100 µm	120 µm (0,05 inch)	60 µm (0,0025 inch)
Speed at max. resolution	1 sec	1 sec	10 sec	23000 points/sec	28000 points/sec	150 sec	105 sec
Mode Medium							
Field of View	600 mm	300 mm	225 mm	70 mm stripe	100 µm	200 mm diag.	200 mm diag.
Resolution	200 µm	180 µm	225 µm	50 µm	28000 points/sec	130 µm (0.005 inch)	130 µm (0.005 inch)
Speed	1 sec	1 sec	10 sec	23000 points/sec		150 sec	105 sec
Mode Large					100 µm		
Field of View	1500 mm diag	600 mm diag.	600 mm diag.	140 mm stripe	28000 points/sec	350 mm diag.	800 mm diag.
Resolution	500 µm	360 µm	600 µm	100 µm		190 µm	380 µm
Speed	1 sec	1 sec	10 sec	23000 points/sec		150 sec	105 sec
Accessories							
Rotating Plate	yes, but not included	yes, but not included	no	no	no	yes	yes
Measurement arm	robot (optional)	robot (optional)	--	7 axes arm	7 axes arm	--	--
Software included	OPTOCAT	OPTOCAT	--	Kube	Muse	ScanStudio HD	ScanStudio HD Pro
3D alignment	yes	yes	yes	yes	yes	yes	yes
3D post processing	yes	yes	no	yes	yes	yes	yes
export	STL, PLY, VRML	STL, PLY, VRML	OBJ	STL, ASCII, IGES	STL, ASCII, IGES	STL, PLY, OBJ, VRLM	STL, PLY, OBJ, VRLM
import	STL, PLY, VRML	STL, PLY, VRML	OBJ	STL, ASCII, IGES	STL, ASCII, IGES	STL, PLY, OBJ, VRLM	STL, PLY, OBJ, VRLM
max triangles	100 Mio	100 Mio	unknown	unknown	unknown	4 Mio	4 Mio
Price	about 80000 €	about 50000 €	100000 € (not yet available)	about 93000 €	about 26000 €	about 2300 €	about 3100 €

Fig. 1. Table of tested scanner models.

Abb. 1. *Übersichtstabelle der getesteten Scanner-Modelle.*

structures like vertebrae or the area around the Arcus zygomaticus were recognized by the scanner and if the inner surface of eye sockets or foramen openings could be captured. For ceramic we considered most important that all details of the decoration are recognizable. Further tests in cooperation with the IIIPC de Cantabria, the MUPAC and the company Breuckmann also concerned rock art, portable art and statues (Breuckmann et al. in preparation).

Methods of 3D scanning

3D scanner analyze the surface information (shape and sometimes also colour) of real world objects by projecting laser beams or structured light on the object. From these data, digital three-dimensional models can be constructed. As the information is based on the light that is reflected, shiny, mirroring or transparent objects encounter some difficulties. There is a wide range of different technologies.

Topometric 3D scanner work with a pattern of structured light projected on the object and a digital camera. A point cloud is then calculated based on the geometry of the sensor system and the phase images acquired by the camera.

Multi-laser scanner use an array of lasers to scan in parallel.

Handheld laser scanner project a dot or line onto the object from a handheld device and a sensor measures the distance to the surface.

To create a three-dimensional model, the scanner have to take a series of shots from different angles. Those shots can be aligned automatically by the software or might have to be aligned manually.

The market offers a wide range of different 3D scanner models from € 3 000 far beyond € 60 000. Our task was to explore the possibilities and limits of models from different price segments to find out which expenditures should be made to obtain suitable results. All scanner used in our tests do provide colour information.

Test results

Breuckmann

Breuckmann scanner work with structured light that is projected on the object via the patented MPT-technology, and digital cameras.

For the scanning of a skull we worked with the topometric 3D scanner smart*SCAN*^{3D}. The smart*SCAN*^{3D} works with the OPTOCAT software and offers a resolution of up to 50 µm depending on the used measuring field. The smart*SCAN*^{3D} has already been applied successfully in palaeoanthropology by the Senckenberg Museum (Hemm-Herkner 2007).

With a fully automated turntable we were able to scan a complete skull within under five minutes in good quality. The skull is placed on the turntable, which turns operated by the software. The different shots are aligned automatically. But separate scanning of the base of the skull and of complex details like the Arcus zygomaticus is necessary and has to be aligned manually. A disadvantage is that the scanner cannot capture the inner surface of a skull. The opening of the Foramen magnum does only provide space to reach very small areas of the endocranium. The eye sockets are also very time intensive to scan as a large series of shots is necessary to record the complete area and align it. If those details are not necessary, a quick and high-value scanning of skulls is possible with the smart*SCAN*^{3D}. Producing an exact digital copy of a skull is still a time consuming task.

For scanning of a small flint backed bladelet the opto*TOP*-HE was used. The opto*TOP*-HE is available with a standard objective with a measuring field of 50 mm to 775 mm diagonal. With supplementary telephoto- and wide-angle-lenses 30 mm to 1050 mm diagonal can be reached. The digital camera works with 1.4 MegaPixel and can be upgraded to 6.6 MegaPixel. opto*TOP*-HE works also with OPTOCAT.

The opto*TOP*-HE was used in several palaeoanthropological studies before (Henke & Tattersall 2007; Kullmer 2004; Ulhaast et al. 2007) but was first tested on a stone artefact by us.

It took several runnings before we found settings that produced results suitable for scientific purposes. A scanner with a measuring field of 60 mm diagonal, a lateral resolution of ca. 40 µm and a camera resolution of 1.4 MP finally produced the best scanning result for a stone artefact generally (Fig. 2). The retouches are very clearly and accurately visible and even the waves of percussion are in evidence. No other scanner recorded waves of percussion. We were able to examine all technological aspects of the backed bladelet on the STL, which means with such a high quality scan the complete stone artefact analysis could be done digitally while the original could be indeed very far away. The only remaining weakness of this method is

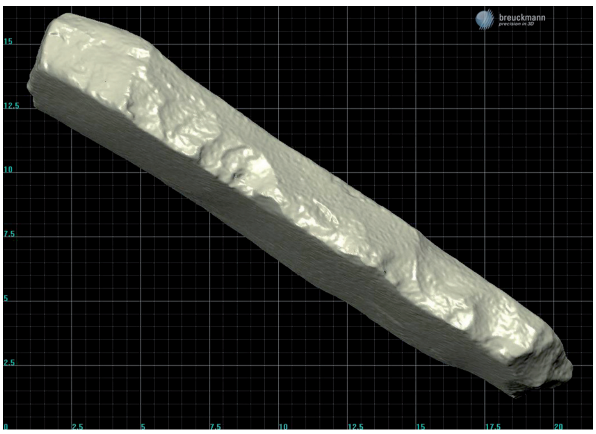

Fig. 2. STL of a backed bladelet scanned with a Breuckmann optoTOP-HE.

Abb. 2. *STL einer rückenretuschierter Lamelle gescannt mit einem Breuckmann optoTOP-HE Scanner.*

the raw material. Even though surface colour and texture is recorded by most 3D scanner, colours are still not realistic enough in most cases and aspects like the level of transparency or occlusions in the material are not detailed enough in the scans.

Descam

The DesCam ModelMaker Z is another high-end scanner. Unlike the other scanner used in our test, the ModelMaker Z is a handheld laser scanner. It works with a 7-axes-tactile-index-arm that is passed around the object by the person who accomplishes the scan. So in this case, the scanner turns around the object while usually the object that is scanned has to be turned. Important to know is that the movement by a human hand does not produce irregularities in the scan. The ModelMaker Z is available with a band size of 50, 100 and 200 mm and works with the software KUBE.

We scanned a point with fine retouches and a polished white patina. Even with finest band range and point density, the ModelMaker couldn't produce scans that would have fitted for scientific purposes. Most surprising, the glossy surface of the point was no problem for the scanner, but it couldn't capture the small retouches precisely enough.

We also tried to scan the point with the MicroScribe digitizer with a laser scanner head. The MicroScribe is a model especially designed for scanning of small objects and has an operating range of 1.27 m to 1.67 m. It works with the utility-software MUSE. Results produced with the MicroScribe were somewhat

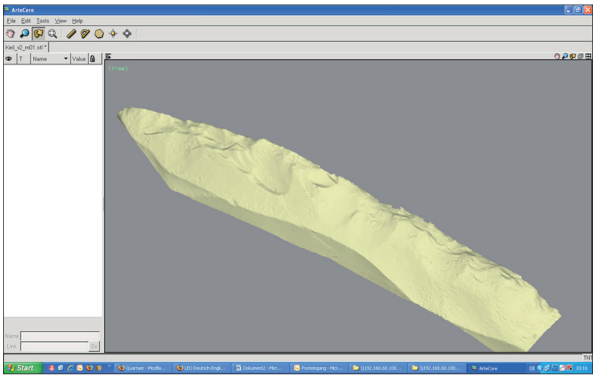

Fig. 3. STL of a point scanned with a DesCam ModelMaker Z.

Abb. 3. *STL einer Spitze, gescannt mit einem DesCam ModelMaker Z Scanner.*

better but unfortunately still not precisely enough for stone artefact analysis (Fig. 3).

Much more appropriate results are produced by the ModelMaker Z in scanning of complex bony structures like skulls or vertebrae. The 7-axes-tactile-index-arm allows scanning of complete skulls within a single measuring procedure and the flexible sensor can be used to scan the inner surface of a skull or eye sockets relatively uncomplicated (Fig. 4). It is possible to stop the scan during the measuring procedure to turn the object and then continue without having to start a new scan. This makes complicated and time consuming fusion of different scans to one STL model unnecessary. Scanning of a complete human skull with all details would take ten to fifteen minutes. The

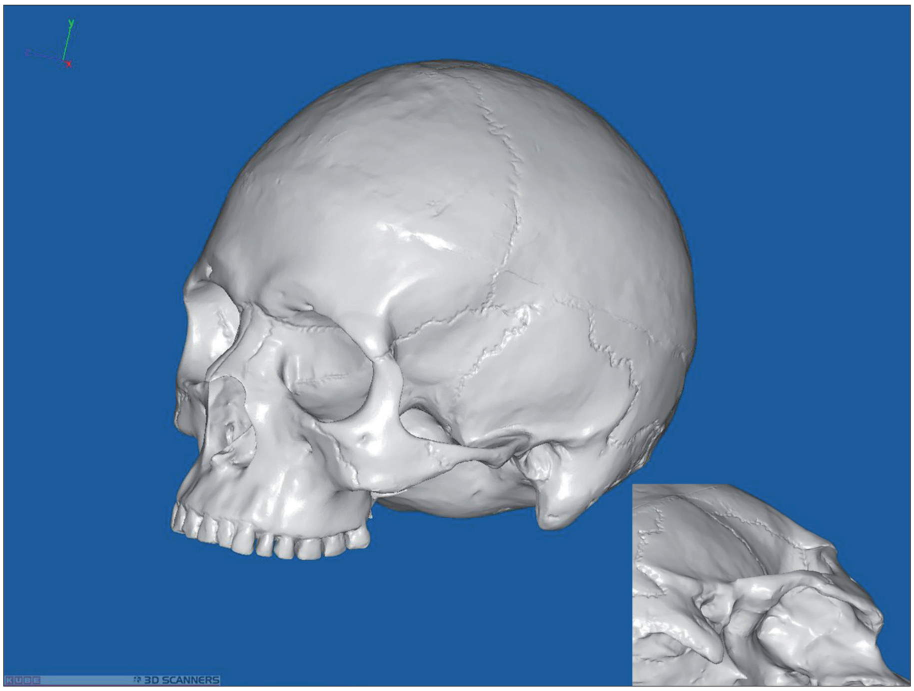

Fig. 4. Fronto-lateral view of a skull scanned with a DesCam ModelMaker Z and detail of the region around the Arcus zygomaticus.

Abb. 4. *Fronto-laterale Ansicht eines Schädels, gescannt mit einem DesCam ModelMaker Z Scanner und Detailansicht der Region um den Arcus zygomaticus.*

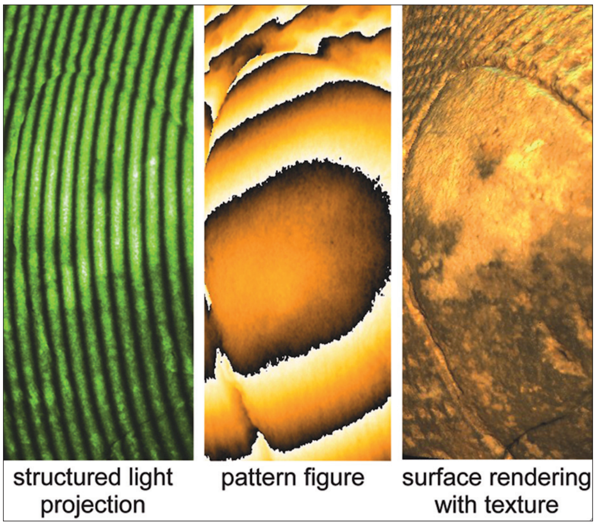

Fig. 5. Examples for the functionality of the DEIOS prototype.

Abb. 5. *Beispiele für die Funktionsweise des DEIOS Prototyps.*

software does alignment automatically during the scanning process without any problems. The scanner was also used successfully in palaeontology for digitalizing a dinosaur skull (Hone 2005).

Deios

During two years RBINS and DEIOS collaborated in developing a 3D scanner prototype specially dedicated to archaeological and anthropological objects and using a patented technology of structured light with laser source (Fig. 5). The prototype used a B/W camera with a set of coloured LCD filters in order to obtain the complete colorimetric profile of each pixel. The DEIOS prototype has to be considered as the state of the art of 3D surface scanning, but in the second part of 2008 a bankruptcy of the DEIOS Company unfortunately abandoned the progress abruptly. The prototype was sold by the trustee and is not open to archaeological and anthropological investigations any more.

NextEngine

The multi-laser scanner NextEngine is a low budget model also affordable for smaller museums and institutions. We tested the 2020i Desktop 3D NextEngine HD. This is the newest version of the scanner with major technical improvements. The NextEngine is delivered with a fully automated turntable for 360° acquisition. The previous version of Nextengine scanner was already used for recording rock art (Cavers et al. 2008) and metallic decoration (Guidi et al. 2007).

We did a first set of scanning with the Studioscan 1.7.3 application, which cannot use the HD functionalities. Different settings of resolution (macro or wide) and speed can be defined for the scan. The fastest operates in 35 seconds while the best resolution necessitates 120 seconds. Complete

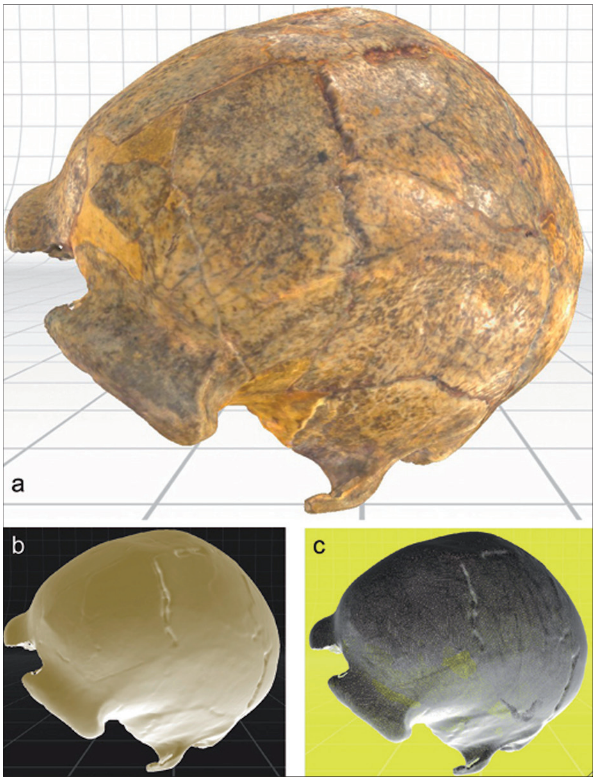

Fig. 6. STL of the Neanderthal skull Spy II, scanned with the NextEngine. a. with colour texture b. without texture c. pointcloud model.

Abb. 6. *STL des Neanderthaler Schädels Spy II, gescannt mit dem NextEngine. a. mit Farbtextur b. ohne Farbinformation c. Punktwolken Model.*

acquisition of a hand axe needs a 360° acquisition composed of 8-12 shots and at least two series in order to scan the top and the bottom parts of the artefact. The number of shots is about 20 in order to digitize the whole artefact with texture and mesh.

With the NextEngine we scanned the same flint point as with the ModelMaker. Scanning of ten shots took 21 minutes in standard resolution, without post-processing and alignment. The retouches were badly captured and sometimes even wrong reproduced. The surface had a lot of holes. This is due to the difficult, glossy texture of the object.

Scanning of a flint core with patina produced usable results with the same settings. Negatives were clearly visible and the scan had only very small holes. The scanning procedure took around 45 minutes, postprocessing another 40 minutes.

The third lithic object we scanned was a flint dirk with retouched surface. Scanning took 33 - 43 minutes, depending on the settings. Even with highest resolution, retouches were only visible with colour texture. The stereolithographic model showed no retouches at all, so the scanner did not record the 3D information of the retouches.

The skull of the Neanderthal Spy II was also scanned with wide view and yielded a good result (Fig. 6). Scanning took more than a day and it could be shown that there is no qualitative difference between scans in highest and normal resolution.

Since 2009, the NexEngine is delivered with a new version of the software Studioscan HD that in theory allows obtaining more accurate models. We compared the old software package and the new one with a neolithic hache (Fig. 7). The resolution is higher and the retouches are now visible in most of cases. Some defects remain and are due to high contrast in the texture which is interpreted as relief.

The HD scanning is also faster. It takes 105 sec by shot and it is possible to buy additional software (ScanStudio HD Pro) that scans twice as fast with a higher resolution.

We also evaluated the NextEngine for scanning of pottery with ornamentation. It is sometime difficult to see the ornamentation techniques with a heterogeneous texture. Removing texture on the scanned view allows seeing the details of the décor (Fig. 8).

Scans done with the NextEngine can be in a good quality depending on the texture of the scanned object. The NextEngine is a good tool for 3D representation in museums, lectures or movies. It is also very useful for simple surface scanning as for the reconstitution of ornamentation techniques of pottery.

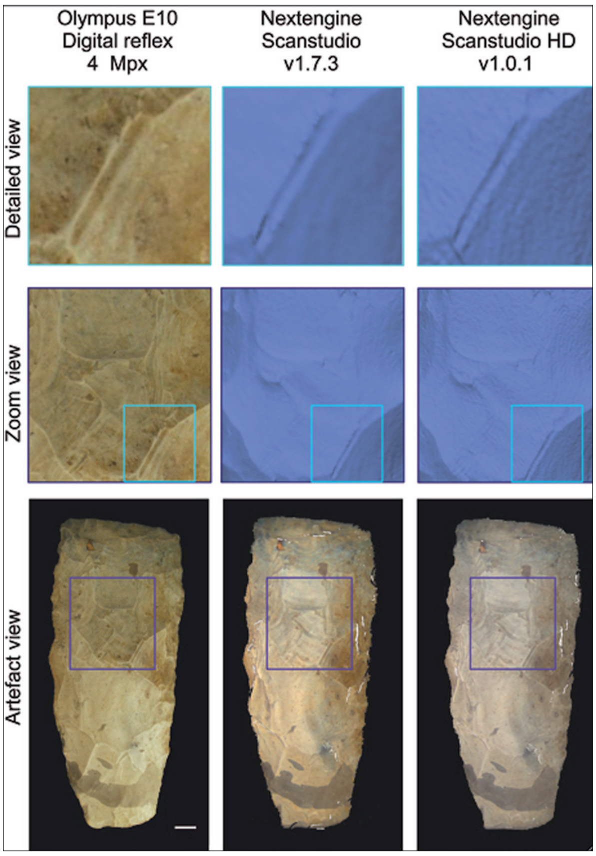

Fig. 7. Comparison of different scans of the same neolithic hache with the old and the new version of the NextEngine.

Abb. 7. *Vergleich verschiedener Scans derselben neolithischen Axt mit der neuen und der alten Version des NextEngine.*

Scanning of complexes surface is possible but necessitates many shots and a long post-processing and alignment time. The software aligns automatically in many cases but manual alignment is still necessary for objects with low contrast or with too many points. Problems also occurred during fusing of the different shots. The software is limited to fuse ~2 million points with textures and ~4 million points with out textures (NextEngine support). This is mainly due to the 32 bit windows application and could not be enough for highly detailed model of large object.

This could be solved by the use of an external 3D application for the post-processing of the data like Rapidform or other 3D softwares with 64 bit OS. NextEngine is also developing a 64 bit version os Scanstudio for Windows XP64/Vista 64.

Discussion

In general, stone artefacts were the most difficult objects to scan with the models we used. This is due to their smooth texture, which is in most cases semi-transparent and glassy as well. Such a kind of surface absorbs most of the projected laser light and causes imprecise results, especially for fine details like retouches. A dark colour further complicates the scanning. High-resolution scanner with tight laser raster and high-quality software like the Breuckmann models still produce good results suitable for scientific purposes. A solution for scanning stone artefacts with budget-priced scanner is the use of a white developer spray on menstruum basis. Such sprays can be removed with water after scanning (Hemm-Herkner 2007) but spraying of artefacts is often impossible due to conservation restraints. Therefore, we did not use spray in our tests.

The enamel of teeth also absorbs part of the laser beam. But as the absorption is much lower than for flint or obsidian, spraying usually is not necessary if the time for repeated scanning and intensive post-processing is taken, even with lower priced models.

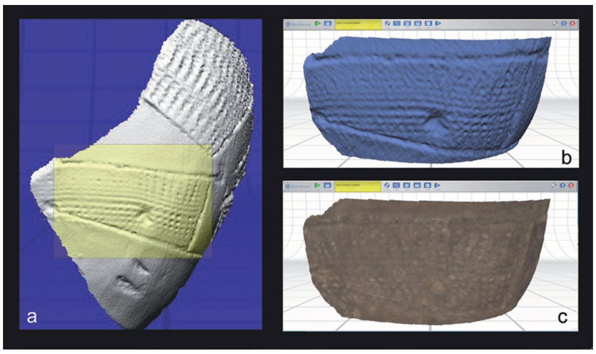

Fig. 8. Details of ornamentation on pottery scanned with the NextEngine and the new Studioscan HD software.

Abb. 8. *Details der Ornamentierung auf einer Keramikscherbe, gescannt mit dem NextEngine und der neuen Studioscan HD Software.*

The texture of bones is in principle uncomplicated for scanning but their complex geometry can cause difficulties. Scanner with a tactile index arm like the DesCam Model Maker are the best solution for anthropological applications. They do not only significantly reduce the time for scanning but also allow capturing of elements like the inner surface of the skull or the eye sockets, which are not - or only fragmentarily - attainable by other scanner.

Challenging is the scanning of cancellous bone. As a lot of fossils dealt with in palaeoanthropology are broken, this is a problem that appears quite often and unfortunately cannot be resolved completely. A greater number of shots in highest resolution produce better results but perfect quality can't be reached for cancellous bone with surface scanning. Even stereolithographic models generated after CT data sometimes struggle with the graphical representation of cancellous bone.

Our point is that the decision for a scanner should be taken on base of the intended purpose. A high priced scanner is not necessarily the best choice for every task.

Despite the difficulties and the money and time that have to be invested, surface scanning should become a standard application in archaeology and palaeoanthropology. 3D scanner are mobile alternatives to CT scanning and make digital copies of the precious originals available for research. Over the online database NESPOS (www.nespos.org) the data can be shared with colleagues worldwide, which reduces traveling costs and preserves the cultural heritage (Berens & Slizewski 2008; Weniger et al. 2007).

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Literature cited

Berens, D. & Slizewski, A. (2008). Neandertaler digital - Fundkatalogisierung mit der Online-Plattform NESPOS. *Der Präparator* 54: 84-88.

Bookstein, F. L., Schaefer, K., Mitteroecker, P., Gunz, P. & Seidler, H. (2004). The geometry of anthropometrics: a new typology of landmarks. *American Journal of Physical Anthropology, Supplement* 38: 66.

Borderie, Q., Torguet, P., Subsol, G., de Lumley, H., Mafart, B. & Jessel, J. P. (2004). 3D modeling of palaeolithic tools. Workshop on Archaeology and Computers. Vienna, 3-4 November 2004.

Breuckmann, B., Arias Cabal, P., Mélard, N., Ontañón Peredo, R., Pastoors, A., Teira Mayolini, L. C., Fernandez Vega, P. A. & Weniger, G.-C. (in press). Surface scanning – new perspectives for archaeological data management and methodology? Computer Applications and Quantitative Methods in Archaeology, Conference Williamsburg 2009.

Cavers, G., Hepher, J. & Hale, A. (2008). Recording rock art: a comparison of techniques for digital recording and monitoring of rock art used at Ormaig, Argyll and Bute. Paper presented at the World Archaeology Congress 2008, Dublin.

Falk, D., Redmond, J. C. & Guyer, J. (2000). Early hominid brain evolution: a new look at old endocasts. *Journal of Human Evolution* 38 (5): 695-717.

Gibbons, A. (2002). Glasnost for hominids: seeking access to fossils. *Science* 297: 1468.

Guidi, G., Remondino, F., Morlando, G., Del Mastio, A., Uccheddu, F. & Pelagotti, A. (2007). Performances evaluation of low cost active sensor for cultural heritage documentation. 8th Optical 3D. Zurich, 9-12th July 2007.

Guipert, G., Subsol, G., Jessel, J. P., Delingette, H. & Mafart, B. (2003). The FOVEA project: a new look at human past. 9th International Conference on Virtual Systems and Multimedia, Montreal (Canada), October 2003.

Gunz, P., Mitteroecker, P., Bookstein, F. L. & Weber, G. W. (2004). Computer aided reconstruction of incomplete human crania using statistical and geometrical estimation methods. *In: Enter the Past: Computer Applications and Quantitative Methods in Archaeology.* BAR International Series 1227. Archaeopress, Oxford, 92-94.

Hemm-Herkner, C. (2007). Einsatzmöglichkeiten von 3D - Scannern in der Paläontologie und deren Anwendungen. Das dreidimensionale Erfassen von Objekten. *Der Präparator* 53: 24-28.

Henke, W. & Tattersall, I. (2007). *Handbook of Paleoanthropology: Vol I: Principles, Methods and Approaches.* Springer, Heidelberg.

Hone, D. (2005). *The phylogenetics and macroevolution of the Archosauromorpha.* PhD thesis, University of Bristol.

Kullmer, O. (2004). Präzisionswerkzeuge der Evolution - Okklusionsflächen im Wandel. *Dental Dialogue* 5 (3): 96 – 104.

Mafart, B. & Delingette, H. (2002). *Three-dimensional imaging in paleoanthropology and prehistoric archeology.* Archaeopress. British Archaeological Series 1049. Actes du XIVème Congrès UISPP.

Mafart, B., Guipert G., de Lumley, M. A. & Subsol, G. (2004). Three-dimensional computer imaging of hominid fossils: a new step in human evolution studies. *Canadian Association of Radiologists Journal* 55 (4): 264-270.

Neubauer, S., Gunz, P., Mitteroecker, P. & Weber, G. W. (2004). Three-dimensional digital imaging of the partial *Australopithecus africanus* endocranium MLD 37/38. *Canadian Association of Radiologists Journal* 55 (4): 271-278.

Pfisterer, T., Bookstein, F. L., Breuckmann, B., Schaefer, K., Viola, T. B., Woerner, H. & Seidler, H. (2007). The variability of the proximal femur in catarrhines - a new 3D method for describing anatomical structures. *American Journal of Physical Anthropology* 132: 188-189.

Recheis, W., Macchiarelli, R., Seidler, H., Weaver, D. S., Schaefer, K., Bondoli, L., Weber, G. W. & zur Nedden, D. (1999). New methods and techniques in anthropology. *Collegium Antropologicum* 23: 495-509.

Seidler, H., Falk, D., Stringer, C., Wilfing, H., Mueller, G., zur Nedden, D., Weber, G. W., Recheis, W. & Arsuaga, J. L. (1997). A comparative study of stereolithographically modelled skulls of Petralona and Broken Hill: implications for future studies of middle Pleistocene hominid evolution. *Journal of Human Evolution* 33: 691-703.

Sumner, T. A. & Riddle, A. (2008). A virtual paleolithic: assays in photogrammetric three-dimensional modeling. *PaleoAnthropology* 2008: 158-169.

Ulhaast, L., Kullmer, O. & Schrenk, F. (2007). Tooth wear and diversity in early huminid molars: a case study. *In:* S. E. Bailey &

J. J. Hublin (Eds.) *Dental Perspectives on Human Evolution.* Springer, Heidelberg, 369 – 390.

Weber, G. W., Recheis, W., Scholze, T. & Seidler, H. (1998). Virtual Anthropology (VA): methodological aspects of linear and volume measurements - first results. *Collegium Antropologicum* 22: 575-584.

Weber, G. W., Mitteroecker, P., Gunz, P., Neubauer, S. & Bookstein, F. L. (2004). The Upper Paleolithic Mladec assemblage: cranial geometry compared with anatomically modern humans and Neanderthals. *American Journal of Physical Anthropology, Supplement* 38: 204-205.

Weniger, G.-C., Döllner, J., Macchiarelli, R., Mandel, M., Mayer, P., Radovcic, J. & Semal, P. (2007). The Neanderthal TOOLS and NESPOS. In: *The world is in your eyes - Proceedings of the XXXIII Computer Applications in Archaeology Conference*: Tomar, March 2005, 267-269.

Zollikofer, C. P. E., Ponce de León, M. S., Martin, R. D. & Stucki, P. (1995). Neanderthal computer skulls. *Nature* 375: 283-285.

Zollikofer, C. P. E., Ponce de León, M. S. & Martin, R. D. (1998). Computer-assisted paleoanthropology. *Evolutionary Anthropology* 6: 41-54.