Terrestrial Laser Scanning for the Documentation of Archaeological Objects and Sites on Easter Island

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1. Introduction

One of the most unique - and remote - areas on Earth, is Easter Island, which is well known for its huge volcanic rock statues - called Moai by the islanders. Since 1995, the Moai have been protected as UNESCO (United Nations Educational, Scientific and Cultural Organization) World Cultural Heritage monuments. But so far, although the Moai are increasingly at risk of damage by animals, by exposure to weather (erosion) or by human vandalism, they have not been digitally documented and copied using an appropriate technique. Today, most of the more than 900 statues are in poor condition.

The statues, which have been carved out of volcanic tuff by the island inhabitants mostly between 1400-1600 AD, were almost all erected singly or in a few groups along the coast on stone platforms known as Ahu. Their ritual and cultural meaning has fallen into oblivion; however archaeological finds suggest that they were a component of an ancestor cult. Therefore, most archaeologists believe the Moai are standardized representations of powerful leaders on early Easter Island, or Rapa Nui, the name given to their land by islanders. Presumably during conflicts between the individual tribes of the island most ritual platforms were toppled and destroyed in the 18th Century.

The Photogrammetry & Laser Scanning Lab of the HafenCity University Hamburg (HCU) started documentation of the Moai in 2007 (KERSTEN et al. 2009) and of archaeological sites in 2008 by terrestrial laser scanning in cooperation with the German Archaeological Institute (DAI), Bonn. The long term goal of the archaeological project is (a) to document and to catalogue the remaining Moai as well as to collect all relevant data into an Archaeological Information System (AIS), (b) to analyse possible deformations on the statues, (c) to monitor planned conservation activities for selected Moai and, (d) to further research the island's history, its inhabitants and the still largely unknown Moai. The major focus of this paper is the recording, 3D modelling and visualisation of some statues and two archaeological sites by terrestrial laser scanning. Furthermore, first tests for deformation analysis by 3D comparison of selected Moai using temporal laser scanning data from 2007-2009 were carried out, although significant changes have not been expected for this short time interval of two years.

As known from the literature a terrestrial laser scanning system was used for the first time on Easter Island, when amongst others the Moai at the Museo Antropologico P. Sebastian Englert and the petroglyphs at Orongo were scanned by a CYRAX 2500 in 2003 for the University of Hawaii, Department of Anthropology (WELLMAN 2003).

2. Terrestrial Laser Scanning Systems used

The scanning of the archaeological objects and sites was performed with the following terrestrial laser scanning systems (Figure 1): Trimble GX (2007), Trimble GS101 (2008) and the IMAGER 5006 from Zoller + Fröhlich (2008 and 2009).

The laser scanning system Trimble GX consists of the scanner (weight 13.5 kg), a notebook for scanner guidance and software for data acquisition and processing. In addition a power supply is needed to run the system. The scanner has a range of 200m and a field of view of 360° in horizontal and 60° in vertical direction. The laser used is a green laser with 532nm wavelength. The Trimble GS101 is a predecessor of the GX with similar specifications, however the optimal range is limited to 100m and this instrument has no inclination compensator.

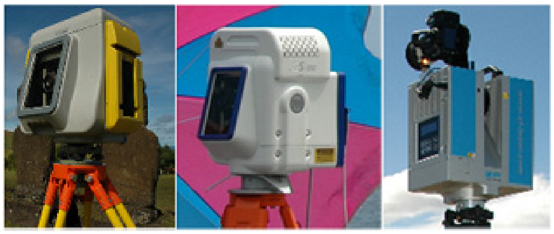

Figure 1: *Terrestrial laser scanning systems used: Trimble GX (left), Trimble GS101 (centre) and the IMAGER 5006 from Zoller + Fröhlich (right)*

In field campaigns in 2008 and 2009 the IMAGER 5006 from Zoller + Fröhlich has been used for scanning. The scanner is just as heavy as the Trimble scanner; however it can be used with batteries and without an external computer, so that the system is much handier and does not need as many accessories as is necessary for the GX and/or GS101. The field of view of 360° x 310° is larger than with the two Trimble scanners, while the wavelength of the laser is 658 nm (red light). While in each Trimble scanner a video camera is integrated, offering not very high resolution imagery (576 x of 768 pixels), a digital SLR camera, e.g. Nikon D40 (sensor 3008 x of 2000 pixels), can be installed onto the IMAGER using a special mounting plate.

The largest difference between the two scanning systems is the scanning speed for the distance measurements. While with the Trimble scanners point rates of less than 1000 points per second are obtained in reality, the IMAGER achieves over 100,000 points per second. This fact will influence the later data processing significantly; the pure scan data of the IMAGER can result in several GBytes for each object, while with Trimble scanners 50 - 100 MBytes are usually available for the same object. The technical specifications of the terrestrial laser scanning systems used are summarised in KERSTEN et al. 2009a.

Additionally, the objects were documented by photographic image acquisition using commercial digital SLR cameras Nikon D40 and D70 (28mm lens).

3. Archaeological Objects and Sites

3.1 Archaeological Objects – Moai & Ahu

The Moai are monolithic statues carved from rock on Rapa Nui. Pater Sebastian Englert numbered and listed 638 statues for the first time in the middle of the last century (ENGLERT 1948). Prior to this current project, the only available documentation of the Moai had been created in the form of pictures and drawings, combined with sketches of a few selected figures, wherein 887 Moai of approx. 1000 still existing figures had been catalogued by the Easter Island Statue Project (VAN TILBURG 1994, VAN TILBURG & VARGAS 1998). Nearly half (397) of these 887 Moai are still around the main Moai quarry (Rano Raraku), but 288 were transported from there and set on Ahu (platforms), which were mostly close to the sea at the island's perimeter. 92 Moai are on a route to an Ahu. Almost all have overly large heads three fifths the size of their body. The Moai are the 'living faces' and representations of chiefly, deified ancestors, sitting on their Ahu with their backs to the sea. Nowadays, most are toppled due to earlier tsunamis, earthquakes and conflicts between different clans on the island. Since 1956 only some of the figures have been restored and erected at their original places.

Many of the statues lying on the ground have been partially decomposed to powder by weathering. With others the top layer of the statues is deeply weathered to approximately 20-30cm, while the still existing stone, which is directly influenced by decomposition, is damaged at the back side (ROTH 1989). The reason for these destructions is the high water absorption ability of the stones on one hand, while on the other hand the climate of the island is responsible for changes from high amounts of precipitation, which come down frequently as short rainstorms, and fast drainage of the stone surface by very active wind. Nevertheless, the Moai are also increasingly at risk of damage by animals (e.g. horses) and by human vandalism (BUSH 2004). In the last two centuries sheep farming on the entire island formed a factor of risk for the damage of the Ahu, while today approx. 15000 wild horses leave their traces at many cultural monuments of the island.

3.2 Archaeological Sites

Ava Ranga Uka A Toroke Hau (ARUTH)

Since 2008 the DAI has carried out archaeological soundings in different places at the archaeological site Ava Ranga Uka A Toroke Hau (ARUTH). Here, the excavations are supported by geophysical prospection, geodetic surveying work and the use of terrestrial 3D laser scanners. The archaeological excavation site ARUTH is located in the centre of Easter Island at the southern slope of the volcano Maunga Terevaka approx. 200m above sea level. The site is in an erosion gutter, which drains the crater of the volcano. It contains the following archaeologically investigated objects (Figure 2): two remainders of dam plants, a stone basin, a cave, as well as an Ahu with one overturned Moai.

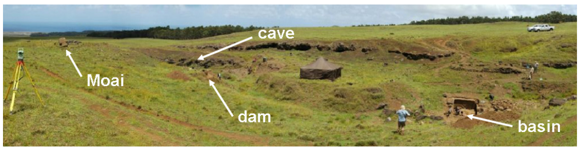

Figure 2: *Archaeological excavation site Ava Ranga Uka A Toroke Hau (ARUTH)*

Miro O One

The archaeological excavation site Miro O One (Fig. 3) is located approx. 1.5km from the southern coast of Easter Island at a height of approx. 55m above sea level. In general, it represents a stone ring resembling the contours of a European boat with a length of approx. 40m and a width of approx. 15m. This excavation site has been investigated by the team of the American anthropologist Charles M. Love of the Western Wyoming Community College since the beginning of 2009. Due to the specific shape of this site one can assume that the object was developed in the late phase of the Rapa Nui culture, thus after the first contact to Europeans in the year 1722. Whether the object had a ritual-religious or other meaning (e.g. theatre) has not yet been clarified.

Figure 3: *Panorama view of the excavation site Miro O One*

4. Scanning of Objects

The spatial distribution of 45 Moai and the two archaeological sites on Easter Island, which were scanned during three German field campaigns to the island from 2007 to 2009, is illustrated in Figure 4. The Moai at the three Ahu Hanua Nua Mea, Hanga Mea and Akahanga are overturned, while the other Moai of twelve scanned Ahu have already been re-erected. An overall summary of all scanned Moai in 2007/2008 is given in KERSTEN et al. 2009a and in 2009 in KERSTEN et al. 2009b.

Before laser scanning an object a geodetic network with permanent point marking was established and determined in a local net (3D point precision of approx. 4mm) with a total station Leica TCR 407. Additionally GPS measurements on the marked points were acquired with AshTech Pro Mark II L1-GPS receivers, while the permanent international GPS station present at Easter Island was used as a reference station. The scanning with the two Trimble scanners GX and GS101 has already been described in KERSTEN et al. 2009a. For the scanning with the IMAGER 5006 at least four black-and-white targets were used for the registration and georeferencing of the scans for each scanner station. The UTM coordinates of the scanner targets were determined by the total station in the geodetic network before scanning. Depending upon distance to the object the scan resolution was set on High or on Superhigh (6.3mm or 3.1mm@10m, respectively). The data acquisition took between six and ten minutes for each scanner position including changing the position.

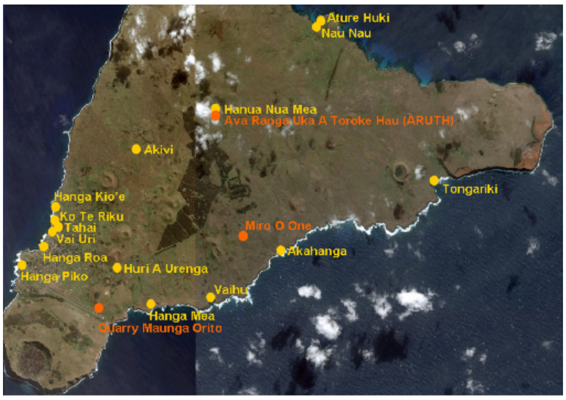

Figure 4: *Spatial distribution of the scanned Moai (yellow) and archaeological sites (orange) on Easter Island, represented in a satellite image of Google Earth*

The front and back side of Ahu Tongariki (Fig. 5) with its 15 Moai, which have been re-erected from 1992-1996, were scanned in 2008 with the IMAGER 5006 from 21 scan stations during one working day with two persons. In total 25 GB of scan data has been acquired. The point clouds were registered using 84 targets with a precision of 1.6mm, while the entire point cloud could be georeferenced with an accuracy of 2.5mm.

Figure 5: *Photo of the Ahu Tongariki with its 15 Moai*

The Ahu Akivi has been scanned in the years 2007 and 2008 with the Trimble scanners and in 2009 with the IMAGER 5006. In comparison, in 2008 six scan stations were used over almost four hours with two persons for the scanning of the platform and the seven Moai, while in 2009 the Ahu could be scanned in 2.5 hours using the IMAGER 5006 on 12 scan stations. The registration and georeferencing of the point clouds were in the range of better than 6mm for both scanners.

The stone basin (Fig. 6) of the archaeological excavation site ARUTH, which has the dimensions of ca. 5.9 x 3.9 x 1.9 m^3, has been scanned from four scan stations outside and two inside within two hours using eight targets for registration and geo-referencing of the point clouds.

Figure 6: *The excavated basin as a photo (top) and as a RGB-coloured point cloud (bottom)*

For the excavation site Miro O One the data acquisition consisting of geodetic network, GPS point measurement and laser scanning has been carried out within six hours with a team of two persons. Before scanning the ground surface of the object had been cleaned of vegetation (Fig. 3). Within 2.5 hours scanning had been conducted from 16 scan stations, which corresponds to 9 minutes scanning per station. The scans were geo-referenced with an accuracy of better than 5mm. Each scan consists of 20 million points, which corresponds to 190 MBytes data volume per scan.

5. 3D Modelling

After registering and geo-referencing of the scans the entire point cloud of each object has been segmented, i.e. all points, which do not belong to the object or which are not necessary, were deleted. Thus, the point cloud could be slightly reduced for further data processing with the modelling software Geomagic (V10 and 11). Here, the point clouds were additionally resampled by decreasing the grid spacing, e.g. 20mm, which offers faster visualisation performance on a standard notebook. The quality of the point cloud could be improved by filtering and subsequent elimination of blunders, which caused a further reduction of 10% for the point cloud. Finally, a triangulation (meshing) of the point cloud resulted in 3D models of the objects (e.g. Moai), as depicted in Figures 7-10. Especially, Fig. 7 (top left) demonstrates clearly the problem of obtaining data from the top of the figures, which was not possible in most scanning cases. These meshed 3D models can now be used for further investigations such as volume calculations, cutting slices, etc. and also for visualisation tasks (e.g. in the tourism) using photo-realistic texture mapping as shown in Figure 8. Additionally, such virtual 3D models can be used as a basis for documentation in an archaeological information system and for restoration and preservation tasks.

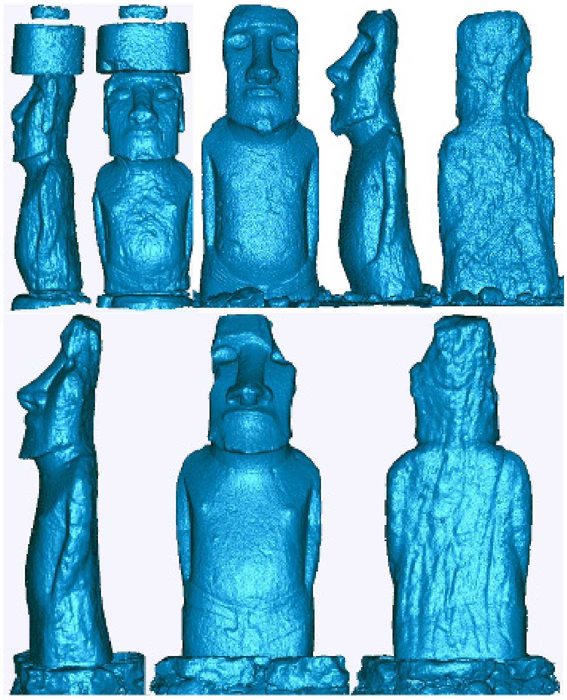

Figure 7: *Meshed 3D model of Moai Ko Te Riku (top left), "travelling" Moai from Tongariki (top right), and the Moai Huri A Urenga (bottom)*

Figure 8: *Visualisation of the Moai from Ahu Akivi with photo-realistic texture*

Dense meshed 3D models of the Moai also tell the story about the production process and the weathering processes of the stone during the last centuries. Fig. 9 illustrates the single Moai Vaihu from four different views, which demonstrate the carving tracks in the stone and the erosion effects by weathering, indicated by the harder material sticking out of some stones.

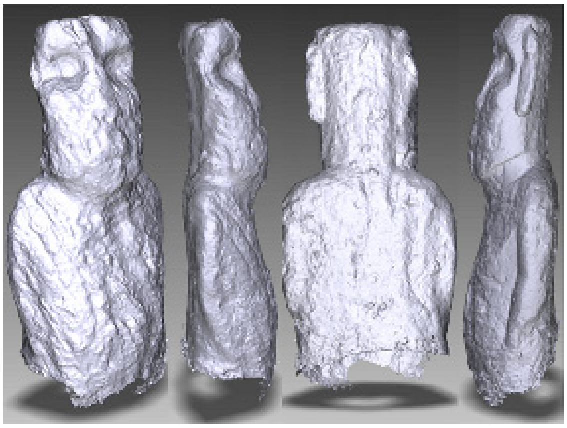

Figure 9: *Four different views of Moai Vaihu illustrating carving tracks and erosion effects by weathering*

The enormous data volumes, which can be acquired with the IMAGER 5006 in a short time interval represent a substantial problem for computer performance during data processing. In a project using the IMAGER 5006 data volumes of over 50 million points can easily be achieved, therefore suitable processing strategies for the reduction of the number of points is essential for an efficient workflow. Although the triangles of the 15 Moai of Ahu Tongariki have been limited to 1,000,000 for modelling of each sculpture, a file size of approximately 800 MB of (Fig. 8) has been obtained. Using the generated 3D models a mass of 59.6 tons has been derived from the determined volume of 32.7m^3 (using a specific weight of 1.82 g/ccm) for the 11th figure (from left in Fig. 8), which has a height of 8.40m.

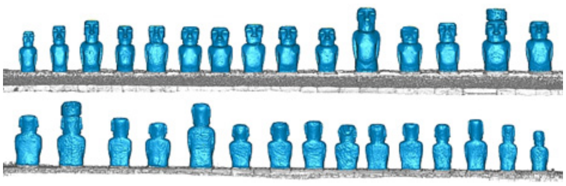

Figure 10: *The 15 Moai of Ahu Tongariki as a 3D model of the front (top) and back side (bottom)*

One option to reduce data is polygon decimation, which is implemented in Geomagic. But this option is always a compromise between geometric data quality and data volume. The more the user reduces the data by polygon decimation, the better the computer performance is for further data processing, but the worse the geometric correctness and visual quality is affected. Investigations demonstrated that the polygons can be reduced down to 10% for smooth surfaces (KERSTEN et al. 2010), but for rough surfaces such as those of the Moai, it is only possible to decimate the polygons to just 50% or in some cases to 25% without loosing significant geometric and visual quality. Fig. 11 illustrates the polygon decimation of a Moai head as an example, where it is obvious that polygon decimation down to 10% or even less affects the geometric and visual quality significantly.

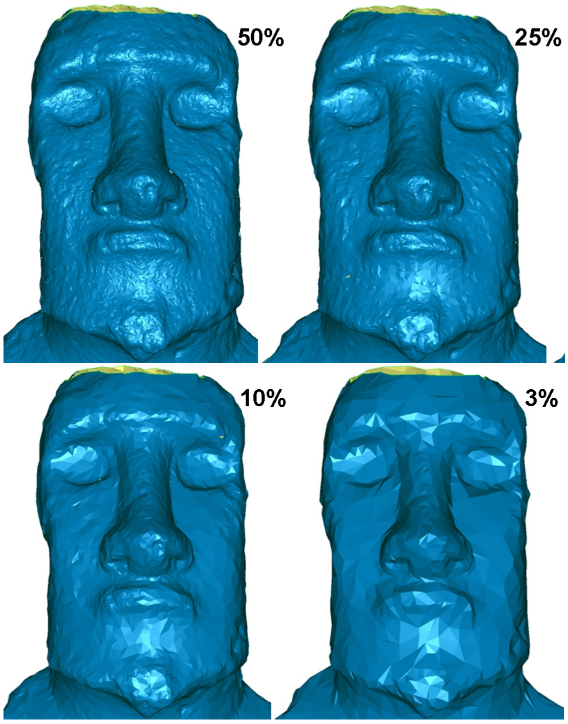

Figure 11: *Data reduction from 50% to 3% by polygon decimation using Geomagic sets illustrating the achieved quality of the 3D model*

If the Moai were scanned at regular temporal intervals, changes, which have been caused by erosion (weathering by long term monitoring) or animals or human beings (even by short term monitoring), can be detected and analysed. Therefore, a 3D comparison of the two triangulated meshes of both epochs is required using Geomagic. A simple method is the 3D model-to-model registration, which has been computed based on the ICP algorithm (iterative closest point) using only the 3D models of each epoch and without any GPS data for geo-referencing. A better solution would be a 3D comparison of the models, which have been georeferenced within the same static geodetic network, so that even a tilt, rotation and a settling of the figures can be proven. This method has not yet been established. Figure 12 shows the result of a 3D comparison of the head of a Moai at Ahu Nau Nau, a part of the ear of which was destroyed by vandalism by a Finnish tourist in March 2008.

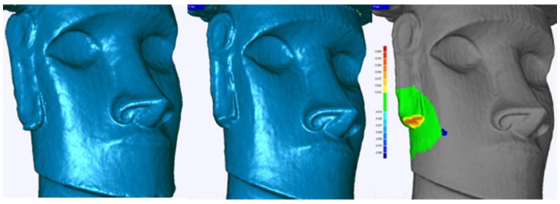

Figure 12: *The ear of the Moai at Ahu Nau Nau, which was damaged by a Finnish tourist in March 2008: 3D model of the head in 2008 (left) and 2009 (centre) with visualisation of the damage (right)*

Figure 13 indicates only slight changes, which are in the range of the scanning noise, on the Moai between the years 2007 and 2008.

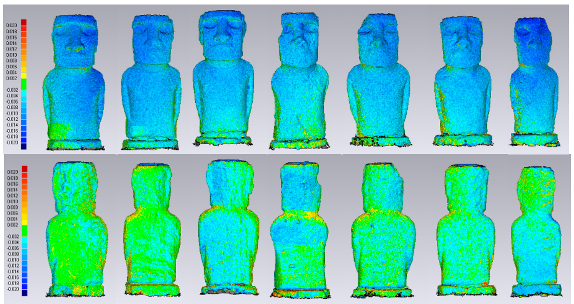

Figure 13: *3D comparison of two data sets of Ahu Akivi (2008 – 2009) indicating little differences in the range of the scanning noise*

The generated 3D models of the two archaeological sites are depicted in Figure 14 and 16. In Fig. 14 (top) the RGB representation of the 3D model of the stone basin is shown, while in Fig. 16 the RGB textured 3D model of the archaeological site Miro O One is presented. For the graphical documentation of the pavement in a part of the stone basin detailed and scaled hand drawings can be derived from the scanning data using maps of the point cloud in orthogonal projection with a scale 1:20 (Figure 14 bottom, Fig. 17). On the basis of such a draft detailed and small object structures can be emphasized by drawing after interpretation on-site. Thus, these objects can be represented scaled at the correct position without further measurements on-site.

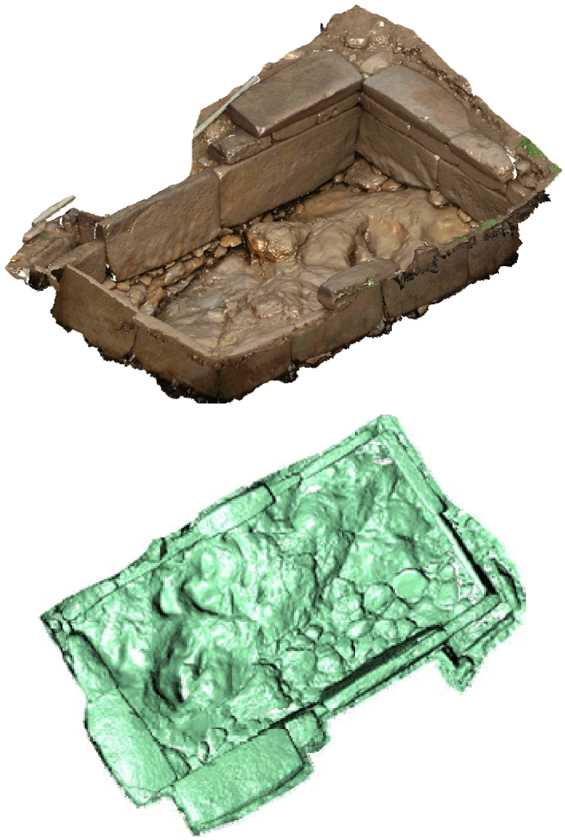

Figure 14: *The stone basin at ARUTH as photo-realistic textured triangle meshing (top, approx. 3 million triangles), and as an orthogonal projected map for drawing draft (bottom)*

Even small objects such as the petroglyph of a footprint can be seen in the presentation of a rendered point cloud (Fig. 15). Therefore, the petroglyph at the bottom of the underground rock has been scanned in detail, i.e. with a high resolution which corresponds to a point distance 0.3mm@1m at the object. In general, the recognisability of small structures (<3mm) is affected by the system-dependant scanning noise; however the total structure of the petroglyph is clearly recognisable.

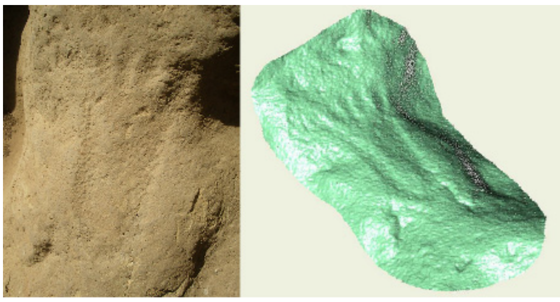

Figure 15: *Photo of footprint (petroglyph) in the bottom of the basin (left) and as a rendered point cloud (right)*

Figure 16: *Photo-realistic textured 3D model of the archaeological site Miro O One indicating the shape of a European boat*

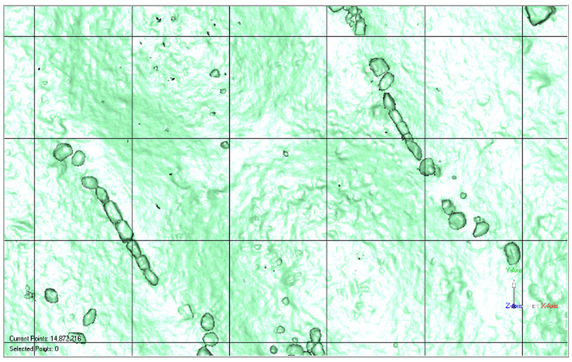

Figure 17: *Orthogonal projected map of the point cloud in a 2m x 2m grid for drawing draft of a part of the archaeological site Miro O One*

Table 1: *Comparison of object parameters (height, width and mass) of the seven Moai of Ahu Akivi from an old source (M=Mulloy) and derived from laser scanning data (L)*

Moai	47		48		49		50	
	M	L	M	L	M	L	M	L
H[m]	3.95	3.83	3.90	3.85	3.90	3.96	4.28	4.28
W[m]	1.30	1.33	1.50	1.55	1.50	1.46	1.70	1.65
M[T]	8	4.0	10	5.8	10	6.4	14	6.4
Moai	**51**		**52**		**53**			
	M	L	M	L	M	L		
H[m]	4.19	4.31	3.93	3.93	4.08	4.06		
W[m]	1.60	1.52	1.60	1.45	1.60	1.58		
M[T]	14	8.4	10	6.0	14	6.8		

From current laser scanning data or from 3D models different object parameters of the individual Moai can be precisely derived. For example a comparison of the parameters height, width and mass was performed for the Moai of Ahu Akivi using older information from MULLOY & FIGUEROA (1978) and measurements in the current 3D models, which have been derived from laser scanning data (ZABEL 2010). The results of these comparisons are summarised in Tab. 1. The metric information of the respective height and width of the seven Moai differ slightly, while the older mass data deviated clearly (heavier by a factor 1.7-2.2) from those derived from a volume model. For the computation of the mass of each Moai the same specific gravity (1,82g/cm^3) was used as in MULLOY & FIGUEROA (1978).

6. Conclusions & Outlook

In the three years from 2007 to 2009 twelve Ahu with 45 erected Moai were documented by terrestrial laser scanning using the scanners GX/GS101 from Trimble and Z+F IMAGER 5006, whereby three Ahu were already scanned three times in order to examine changes (deformations) by a simple 3D comparison. However, as expected no significant changes could be determined at these Moai for the short time period (KERSTEN et al. 2009a). In general, the scanning of the Moai top sides is still a problem due to the huge height of the statues, since suitable scanner stations from higher positions are rarely available. Nevertheless, stable mobile platforms for laser scanners or so-called UAVs (unmanned autonomous vehicles, e.g. wind-stable helicopters or mini drones) with cameras could support the data acquisition in the future.

The generation of 3D models of all already scanned Moai is not yet completely finished (June 2010). The workflow from 3D modelling to photo-realistic texturing and visualisation of the Moai must still be optimised. However, the data volume of each 3D model must be significantly reduced, if interactive visualisations of the data are requested. The data acquisition of the Moai and archaeological excavations by terrestrial laser scanning will be continued in future years. In particular, the documentation of excavation sites by orthogonal maps of the point clouds offers a very efficient method for archaeological interpretation and measurements on-site.

The great cultural heritage of Easter Island – the Ahu and Moai, and all other archaeological sites – is increasingly endangered. In the past the statues were mainly toppled by natural disasters like earthquakes and tsunamis and probably by human beings after a civil war. Today's danger, besides the effects of natural forces and freewheeling horses, is the influence of human beings with constantly increasing tourism and some extreme effects such as vandalism. This demonstrates clearly the necessity for efficient and detailed documentation of the UNESCO world cultural heritage monuments by terrestrial laser scanning. Hence, detailed 3D models, generated from laser scanning data, open new possibilities for the production of replicas and can also be used as a documentation basis for preservation and restoration.

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