RECONSTRUCTION OF THE PEGASUS STATUE ON TOP OF THE STATE OPERA HOUSE IN VIENNA USING PHOTOGRAMMETRY AND TERRESTRIAL AND CLOSE-RANGE LASER SCANNING

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Abstract: This article describes the surveying work and the creation of a 3D model of a Pegasus statue, which builds the basis for a static analysis. The supporting legs of the statue were surveyed with the close-range laser scanner Minolta VIVID 900. Approx. 45 individual scans were required to cover each leg. The rest of the statue was surveyed with the terrestrial laser scanner Riegl LMS-Z420i with 8 individual scans. The surveying of the statue using these two laser scanners is particularly interesting because the statue represents a rather 'small' object for a terrestrial laser scanner, whereas for a close-range laser scanner it represents a rather 'huge' object. With the aid of photos of the statue, the relative orientation between the different laser data was determined in the course of a hybrid bundle block adjustment. Finally from the oriented data a 'waterproof' 3D model of this complex statue was derived.

1. Introduction

In the 19th century on top of the State Opera House in Vienna two Pegasus statues of size 4x3x4m were built. Because of this old age and the disadvantageous stabilisation (each horse stands on three legs, which are also almost arranged on one line, see figure 1), some concern about the stability arose and so a static expertise was commissioned for one of the two statues.

Prerequisite for such a static investigation is a 3D model of the entire statue. Because of the static nature of this expertise the accuracy for modelling the supporting legs is most important. The rest of the statue's body can be modelled with lower accuracy. The Institute of Photogrammetry and Remote Sensing (I.P.F.) of the Vienna University of Technology was commissioned to provide such a 3D model.

The Vienna University of Technology purchased two laser scanners in the course of so-called innovative projects: the terrestrial laser scanner Riegl LMS-Z420i (range: 2-800m with an accuracy of approx. 1cm), [6], in the course of the innovative project "The Introduction of ILScan technology into University Research and Education" and the close-range laser scanner Minolta VIVID 900 (range: 0.6-2.5m with an accuracy of approx. 1mm), [2], in the course of the innovative project "3D Technology". These two laser scanners were used for reconstructing the selected Pegasus-statue. The Minolta scanner was used for surveying the supporting legs, whereas the Riegl scanner was used for the rest of the statue. For transferring both data sets into the same system of coordinates, further photos with the digital camera Kodak DCS 460c were acquired around the statue. This paper describes all steps necessary to reconstruct the statue – from the survey work and the registration of all data to the creation of the final 3D model.

Figure 1: Left: The selected Pegasus statue on top of the State Opera House in Vienna. **Right:** The laser scanner Riegl LMS-Z420i on site (Photo: Riegl LMS).

2. The Surveying Work

The following table 1 gives a short overview of the properties of the laser scanners used to survey the Pegasus-statue.

	Minolta VIVID 900	Riegl LMS-Z420i
Type	close-range laser scanner	terrestrial laser scanner
Distance measurement	triangulation light block method	time of delay
Range	with a wide-angle lens: field of view (hz × v): 33° × 25° range: 0.6-2m (depending on focus)	horizontal: 0-360° vertical: 50-130° range: 2-800m
Accuracy	< ±1mm (at 1m)	< ±1cm (at 3m)
Points per scan	680 x 480	up to 280,000,000 (depending on selected angular range and angular increment)
Recorded intensity	RGB: immanent	intensity of backscattered laser pulse: immanent RGB: optional
Measurement time	2.5 sec	ca. 24000 Punkte/sec

Table 1: Overview of the two laser scanners used within the project.

2.1. The Close-Range Laser Scanner MINOLTA VIVID-900

The Minolta scanner, [2], is primarily conceived for indoor-surveying of objects with size of a few dm. Because of the triangulation light block method applied, the usage of the Minolta-scanner requires certain lightning conditions (i.e. constancy and not too bright). Scanning of an object is usually done in the following way: The object is placed on a rotary stage and is scanned for different rotations with a certain overlap by the Minolta-scanner, which is mounted on a fix tripod. From the viewpoint of the object, each of these scans represents a point cloud in a different system of coordinates. Consequently for representing the entire object, all the scans in their different systems have to be transformed into a common system of coordinates. This transformation is often termed 'registration'. Usually, in the individual scans no corresponding points can be identified because the scanning method delivers different (and unpredictable) points on the object every time. Therefore the shifts and rotations of the registration can not be computed in a simple way using some corresponding points. Instead, some form of the so-called ICP algorithm ('iterative closest point' [1]) is applied.

The registration of two point clouds A and B with a sufficient overlap by means of the ICP algorithm is done in the following way. Point cloud A is kept fix and the other is shifted and rotated iteratively so that the distance between the points of A to the closest points of B (in the overlap) is minimised. The final registration of the two point clouds will not be optimal in general, because the iteratively assigned point pairs never really correspond.

A refinement of the original ICP algorithm is the so-called SDM algorithm ('squared distance minimization'; e.g. [4]). With this algorithm not the distance between the points of cloud A and the closest points of cloud B is minimized but the distance to the closest tangent plane in B. In this way not only a better registration can be achieved also the SDM algorithm converges much faster than the ICP algorithm (quadratic vs. linear).

The data acquired with the Minolta scanner can directly be processed with the software Raindrop Geomagic Studio 5 [5], which computes the registration of two or more scans using the SDM algorithm.

2.2. The Terrestrial Laser Scanner RIEGL LMS-Z420i

The LMS-Z420i, [6], is equally suited for in- and outdoor projects. It has an active laser source and therefore does not require certain lighting conditions. Opposed to the Minolta scanner, the LMS-Z420i is used for objects with extents of a few meters up to some hundred meters. Independent on the size of the object more than one scan will usually be required to cover the entire object.

In principle the registration of several Riegl scans can also be done with the ICP or SDM algorithm. Usually in practise, however, before using the laser scanner retro-reflecting targets are sticked onto the object or in its vicinity. After scanning the entire object together with the targets, the latter can be identified in different scans and therefore allow for a registration of the different scans by means of really corresponding points. Furthermore, by using such targets the different scans can be made with a lesser overlap than if the registration would be done by ICP or SDM.

Controlling the scanner and processing the data is done with the software RiSCAN-Pro [6].

2.3. Surveying The Selected Pegasus Statue

Because the supporting legs had to be modelled with much more detail than the rest of the statue, these legs were scanned with the Minolta scanner. Due to the small field of view of the Minolta scanner each supporting leg (height approx. 1.5m) had to be composed of a lot of scans. Each single Minolta scan covers approx. 30x30cm^2 with a typical point sampling distance of 1mm on the object; see figure 2 (middle). In order to register all the scans of one leg in Geomagic with the SDM algorithm, the different scans were acquired with an overlap of 30-40%. Some parts of the legs were very difficult to access, e.g. the hoof parts, the bended heel, or the inner sides of the legs, which were only accessible from under the statue. Because of these circumstances about 200 different Minolta scans were needed to completely survey all three supporting legs (duration: approx. 10 hours separated over 3 days).

Surveying the entire statue with the Riegl scanner turned out to be much easier. In 6 hours the entire statue was covered with 8 scans (including the stomach, omitting a few non visible higher regions and a total number of points of approx. 2.4 million). With the aid of 23 retro-reflecting targets all scans could be registered on site.

The stress analysts made radiographic and ultrasound measurements at certain spots of the statue. These spots were marked with white tape strips, see figure 2 (left), whose coordinates should be determined also. For this purpose 8 images were acquired with a digital camera Kodak DCS 460c and a 15mm objective. As most of the Riegl targets are visible in these images, the images provide the frame for transforming Riegl and Minolta data into a common system of coordinates. The connection between the different data sets is made by the white tape strips and the Riegl targets: The targets and many tape strips are visible in the intensity images of the Riegl scans, and also some tape strips can be identified in the RGB image of a few Minolta scans.

In order to model the Pegasus statue correctly with respect to the gravity, the Riegl targets were surveyed with a level. All surveying was accomplished from begin to mid of November 2003. The usage of the Riegl and Minolta scanner at the Pegasus statue is depicted in figure 1 and 2 respectively.

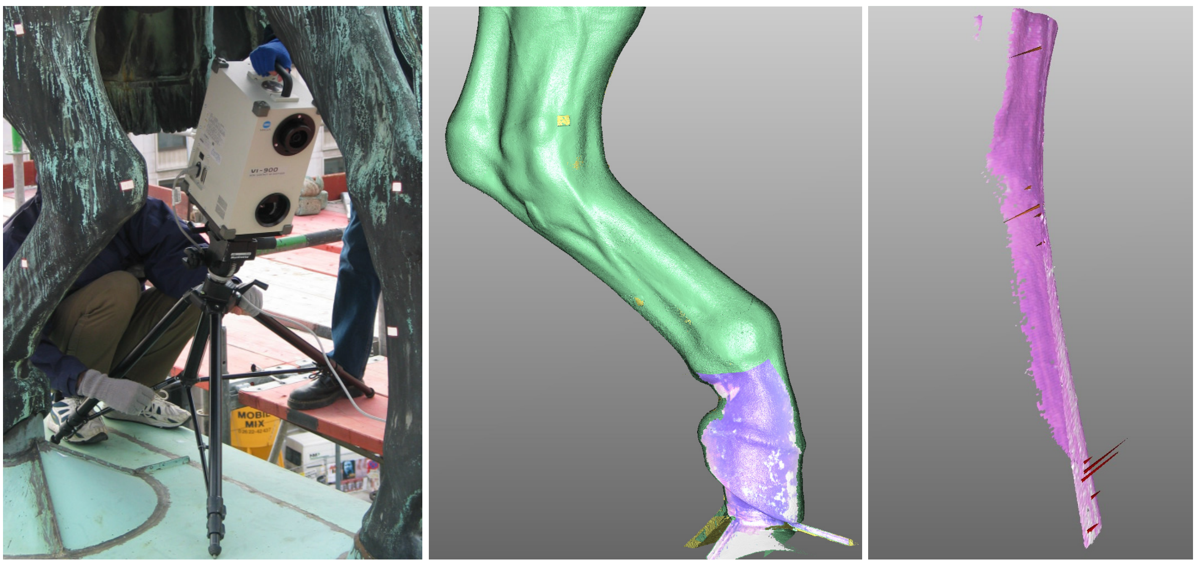

Figure 2: Left: The laser scanner Minolta VIVID 900 on site.
Middle: One selected Minolta (25x35x20cm³) scan on the bended leg (height ca. 1.3m). For modelling this particular leg 42 scans in total were used. This selected individual scan is depicted with the originally recorded RGB information and superimposed on all 42 registered scans, which are shown in green.
Right: Gross errors (highlighted in red, max. error 4.5cm) of one original Minolta scan (shown in the recorded RGB texture, size 30x15x8cm³).

3. Orientation Of All Data

First all Minolta scans taken from each supporting leg were registered separately. Then all data – 8 images, 8 Riegl scans, the combined Minolta scans for each of the 3 supporting legs and the level data – were simultaneously orientated in a hybrid bundle block adjustment.

3.1. Registration Of The Minolta Data

In total 200 Minolta scans were originally acquired, and finally 45 scans were used for each supporting leg (see figure 2 (middle) and figure 3 a)). The registration was done with the program Raindrop Geomagic Studio 5. At first gross errors were removed from all the scans (see figure 2 (right)) and the noise in the data was slightly reduced. The registration itself starts with two scans. One of them is kept fixed and the other is registered to the first. The SDM algorithm for the registration needs a rough initialisation, which is provided by manually identifying three corresponding regions in both scans.

Afterwards both now registered scans are kept fixed and a third scan in added etc. until all scans of one supporting leg are registered. Finally the registration of all scans can be further improved by running a so-called global registration. In the course of that all scans are shifted and rotated simultaneously. After the global registration each supporting leg was represented by approx. 4.5 million points. In order to ease the handling of the legs the points were thinned out – especially in the overlapping regions, where up to 4 different scans overlapped. Using the Geomagic tool 'Select Best Data' the data for each leg was reduced to approx. 2 million points; i.e. the original scans overlapped by 50% on average.

After running the global registration Geomagic Studio returns a standard deviation for the distance between the scans. For each supporting leg the standard deviation was about 0.2mm. Unfortunately such a small value does not guarantee a proper registration, as each leg showed a few gross registration errors; see figure 3. The reason why the overall standard deviation is practically not effected by these gross errors, is that for a very high percentage of the data the residual errors are small and accidental. So the effect of the few large and systematic errors is cancelled down by the huge denominator. It is rather difficult to spot such gross registration errors visually by looking at the registered set of points. This way only registration errors that produce errors outside of the hull of the leg can be seen, errors inside the hull remain unrecognised. A possible strategy to find such errors inside the object is to thin out the data coarsely (e.g. only one point per 4mm voxel) and then to look at the thinned out data from several directions and to search for point accumulations; see figure 3.

The actual reason for these gross registration errors could not be found. Possible reason may be the following:

- The conditions on site were not optimal:
  - The statue was only accessible via a scaffold. Therefore swinging movements during the scanning can not be excluded. Very often the Minolta scanner had to be taken off the tripod in order to reach certain parts of the statue. Several times the scanner had to be brought into unusual orientations (extremely tilted or almost 'lying on its back'). At this occasions the scanner could only be stabilized per hand or with a lump of wood. Consequently certain dynamic errors could have been generated during the small but finite scanning time of approx. 2.5 seconds.
  - After the first day of scanning the legs, we saw that certain parts were missing. Therefore on another day additional scans had to be made. On both days (in

November) it was generally very cold (deviating a lot from the usual indoor conditions) and further the temperature was different for both days and also different during acquiring the individual scans, which were taken at different altitudes of the sun and different cloud arrangements. These changes in temperature could have effected the basis length between laser part and camera part of the scanner. So it is possible, that different groups of individual scans were acquired with different scales; i.e. the calibration of the whole scanner should have been checked several times (requiring a suitable mobile calibration device).

- The large number of 45 individual scans per supporting leg, together with their large overlap and the huge amount of 4.5 million points may have overstrained the registration algorithm of Geomagic. In particular the establishing of the correspondences between the points and tangent planes could have been effected.

After the first global registration of each leg the result was inspected for gross registration errors and the respective scans were removed entirely. Afterwards the global registration was repeated.

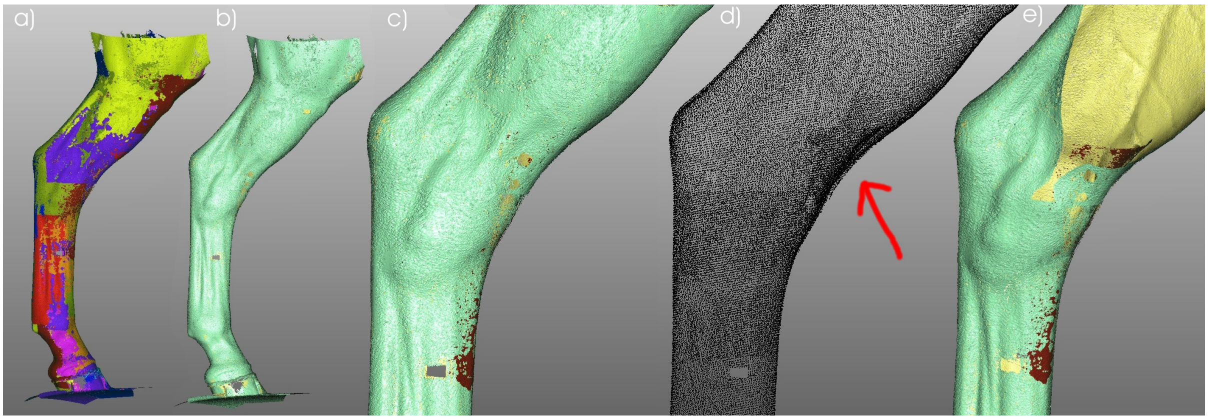

Figure 3: The stretched rear supporting leg.

a) Result of the first global registration. Each individual scan is shown in a different colour.
b) Same as a); all scans shown in the same colour (green = exterior, yellow = interior).
c) Detail of b); one wrong registered scan is shown in red, which, however, can not be detected as such just by looking from outside.
d) Same as c); tinned out point cloud (one point per 4mm voxel). Areas with dense point accumulations mark regions with registration errors.
e) Same as c); rotated representation with a planar section. In case of proper registration, the section line of the red scan should be aligned with the green scans.

3.2. Hybrid Bundle Block Adjustment Of All Data

First the white tape strips and the Riegl targets were measured in the DCS images, the Riegl scans and in the Minolta legs, and then these measurements together with the level measurements were introduced into a hybrid bundle block adjustment. For this we used the program ORIENT [3]. Table 2 gives a short overview on the statistic of the adjustment. The datum for the adjustment was defined in the following way: The origin was placed in one of the Riegl targets at the fundament of the statue, two rotations were fixed due to the level measurements and the scale was given by the data of both laser scanners. The missing horizontal rotation was defined so that the block got a proper northward orientation. The latter was necessary because measurements for wind direction and wind strength by the official weather station should be considered in the static expertise, particularly to assess their influence on the wings of the Pegasus statue.

Observation type	Standard deviation
Photos (DCS 460c)	0.5pixel
Riegl scans: **Hz-angle** **V-angle** **Distance**	 0.07^{gon} 0.05^{gon} 0.02m
Minolta scans: **x,y,z**	 0.003m
Level	0.005m

Table 2: Accuracies (as standard deviations) of each observation type used in the hybrid bundle block adjustment.

The main result of the bundle block adjustment are the improved positions and rotations of the 8 Riegl scans and of each Minolta leg with respect to the mentioned datum. Figure 4 depicts this adjustment result by superimposing the point clouds of the 8 Riegl scans with the Minolta legs.

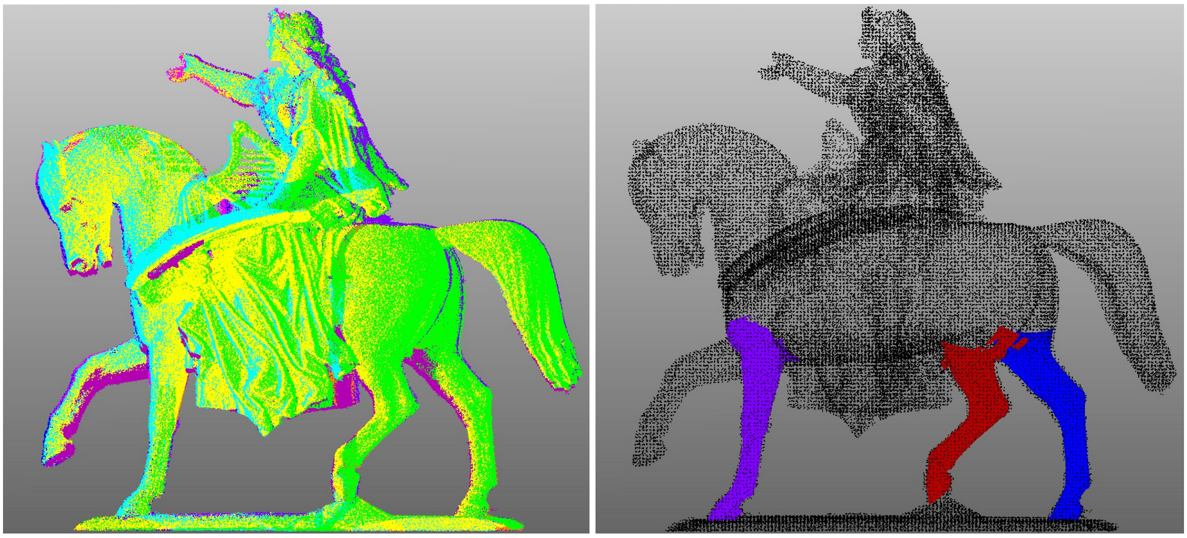

Figure 4: Visualisation of the orientation of the Riegl scans and Minolta legs resulting from the hybrid adjustment. **Left:** The 8 Riegl scans shown in different colours. **Right:** The orientation of the Minolta legs with respect to the Riegl scans, the latter being thinned out for visualisation purposes.

Before introducing the Minolta legs into the hybrid adjustment, we tried to register the Minolta data and the Riegl data using the SDM algorithm in Geomagic. The result, however, was not very satisfying, as after the registration the Minolta data did not lie symmetrical to the

Riegl data as one would expect. We suppose the reason for this to be the different noise level in both data types, which may lead to problems in the SDM algorithm: The Riegl data, with relatively large noise, are kept fixed during the registration and define the tangent planes, which are then the reference for the registration of the Minolta data, which have relatively smaller noise.

For that reason the Minolta legs were introduced also into the hybrid block adjustment with the white tape strips used as tie points. And indeed, the registration between the Riegl and Minolta data turned out to be slightly better. Because of the problems during registration of the Minolta data (mentioned in section 3.1) and the resulting insecurity concerning the correctness of the registered supporting legs, each leg was divided into two overlapping upper and lower parts. During the adjustment these divided Minolta legs could optimally adapt to the other data (Riegl scans and images) via the tie points. Consequently the registration between the Riegl and Minolta data was further improved.

4. 3D Model Of The Statue

The aim of this survey was a 3D model of the entire statue. Because of the subsequent static modelling the 3D model had to be free of holes. It had to represent a 'waterproof' volume. Further the 3D model had to be represented as compact as possible, because for the static modelling the geometric volume model would by replaced by finite elements. For these reasons (holes and large data volumes) the registered and thinned out point clouds could not be simply triangulated. Instead a so-called NURBS model was created in Geomagic. NURBS is an abbreviation for ‚Non-Uniform Rational B-Splines'. A NURBS model is an analytical representation of the statue, which is derived from the original point cloud. Therefore the NURBS model combines the detail richness of a dense point cloud with the efficiency of an analytical representation.

Creating a NURBS model in Geomagic is done in several steps (the Minolta and Riegl data are dealt with separately and are combined only at the very end):

1. Transformation of the different data into the same system of coordinates:

   Using the Geomagic tool 'transform' the translations and rotations determined in the adjustment can be applied to the different data sets (8 Riegl scans, and the 3 Minolta legs).

2. Thin out of the original point clouds (Geomagic tool 'uniform sample'):

   The Minolta data of the supporting legs were thinned out with a point distance ranging from 3mm (hoof) to 15mm (upper end of leg). Finally each Minolta leg was represented by approx. 150000 points. The Riegl data were thinned out with point distances of 15 – 20mm and finally contained approx. 450000 points in total.

3. Triangulation of the data (Geomagic tool 'wrap') including triangulation-corrections (Geomagic tool 'clean') and one time minimal noise reduction (Geomagic tool 'noise reduction'):

   It turned out to be beneficial to apply 'wrap' and 'clean' several times on after the other: in doing this the triangulation has to be broken up (Geomagic tool 'modify current points') before each rerun to access the adapted point cloud. In this way the number of holes decreases a lot, whereas the number of points decreases only slightly; e.g. in the beginning the Riegl data contained 100000 holes and after running 'wrap' and 'clean' four times just 200 holes remained. These remaining holes were centred at three regions (the upper side of the wings, the passage from the saddlecloth's inner side to the horse's stomach, the passage from the rider to the horse's back) and could be filled manually.

4. Combining all triangulated data (Geomagic tool 'merge') and automatic NURBS creation:

   The four data sets (3 Minolta legs and the Riegl body) must be combined as triangulations (and not as point clouds), because of their very different point densities. If the data sets were combined as point clouds many new holes would be created at the segues. The NURBS creation of the entire statue can then be derived rather simple from the combined triangulation and is controlled only by a few parameters (e.g. surface accuracy and detail richness); see figure 5.

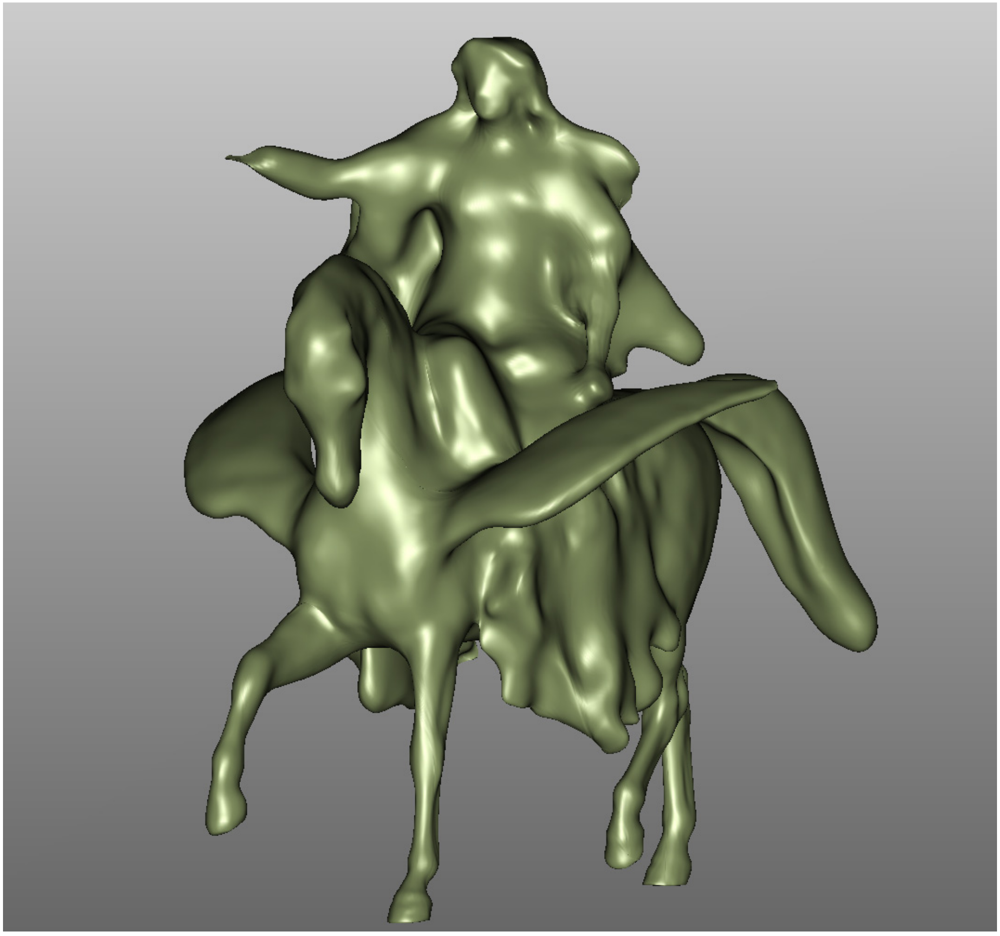

Figure 5: The 3D model of the entire Pegasus statue as NURBS representation. Finally only 165000 points were used for the NURBS creation – originally each of the three Minolta legs consisted of approx. 4.6 million points and the 8 Riegl scans consisted of 2.4 million points in total. Because of the smaller point density many details vanished at the upper part of the statue during the modelling (e.g. harp or right hand). For subsequent statistic analysis, however, these lost details were of no concern.

5. Summary

In this paper we described the reconstruction of a Pegasus statue using two different laser scanners (Minolta VIVD 900 and Riegl LMS-Z420i) for the purpose of generating a 3D model for static analysis. The registration of the Minolta data was done with the program Raindrop Geomagic Studio 5. There it showed that after the global registration still a few gross registration errors were present although the standard deviation between the individual scans was given to be 0.2mm. We assume these gross errors to be caused by the non optimal surveying conditions on site and an overstraining of the registration algorithm implemented in Geomagic by the high number of individual scans.

The registration between the Riegl data and the for each leg combined Minolta data was determined in a hybrid bundle block adjustment involving also images of the statue. The a-posterior accuracy of the combined Minolta data determined at individual points turned out to be approx. ±3mm. This example shows that the registration of point clouds without any real correspondences, at least in the way at it is implemented in Raindrop Geomagic Studio 5, can be a very difficult task. This holds true especially for scans, which are not acquired under indoor conditions, and for objects, which require a large number of individual scans to get a full coverage. In such cases a large part of the accuracy of the individual scan gets lost during the registration. The accuracy level reached, however, was far sufficient for the static problems to be dealt with on basis of this 3D model.

In the meantime a new version of Raindrop Geomagic Studio was released, which provides some new registration features. Therefore, we wish to repeat the registration of the Minolta data (at least for some parts) with the latest version of Geomagic. Perhaps this will deliver some new insights into the registration problems discussed in section 3.2.

References:

[1] Besl, P.J., McKay, N.D.: A method for registration of 3-D shapes. IEEE Trans. Pattern Analysis and Machine Intelligence. 14 (2), 239-256, 1992.

[2] Konica Minolta Photo Imaging: http://kmpi.konicaminolta.us/vivid/

[3] ORIENT – An Universal Photogrammetric Adjustment System, Product Information, Institute of Photogrammetry and Remote Sensing, TU Vienna, http://www.ipf.tuwien.ac.at/products/produktinfo/orient/html_hjk/orient_e.html

[4] Pottmann, H., Leopoldseder, S., Hofer, M.: Simultaneous registration of multiple views of a 3D object. Proceedings PCV ’02, Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XXXIV, Part 3A, Commission III, 2002

[5] Raindrop Geomagic, Inc.: http://www.geomagic.com/products/studio/

[6] Riegl Laser Measurement Systems: http://www.riegl.co.at/

All http-links were accessed in June 2005.