AUTOMATED MODELING OF SURFACE DETAIL FROM POINT CLOUDS OF HISTORICAL OBJECTS

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ABSTRACT:

Terrestrial Laser Scanners are well suited for the acquisition of data for subsequent geometric modeling. Modern phase shift laser scanners allow the measuring of point clouds with very high point densities. The redundancy in the data can be used to reduce measurement error, leading to a point cloud with high precision and optimized point spacing. In combination with image data, very detailed models can be generated representing the main characteristics of a cultural heritage site. We developed a method which allows the determination of highly accurate geometric models from laser scanner point cloud in an economically feasible fashion. The method used for the point cloud processing is presented and analyzed and it is shown, how it can be applied fully automatically. To achieve this it is necessary to estimate a parameter for the size of the local neighborhood. A method for estimating this parameter is presented. Results of the method's application at the *UNESCO World Heritage Site Schönbrunn Palace* are presented and discussed.

1 INTRODUCTION

For documentation, management, and reconstruction of cultural heritage, high quality geometric modeling based on adequate data capturing methods is essential. In recent years terrestrial laser scanners (TLS) have successfully been used to perform these tasks. TLS can be divided into two groups, long range scanners having a measurement range from below one meter to several hundreds of meters and close range scanners with measurement ranges up to several meters. The best accuracy can be achieved with close range scanners. However, the high cost of the data acquisition with such scanners prohibits their use on a larger scale or for routine monitoring.

Alternative data capturing methods like interactive photogrammetric processing or tachymetry aim at the direct determination of characteristic structures (i.e. edges). This implies a high degree of generalization during data acquisition and like the data acquisition with close range scanners require a great amount of manual work. Furthermore, interactive methods are insufficient when the object being modeled consists of freeform surfaces. By contrast, autonomous data acquisition techniques as, for example, digital image matching or laser scanning determine numerous more or less randomly distributed points on the object's surface. While laser scanning is almost independent of the surface texture, matching requires uniquely identifiable structural or textural features.

Due to further-development of phase shift scanners, the point-sampling rates increased making high sampling density of surfaces economically feasible. The measurement error, however, largely stays the same due to physical restrictions of the sensors. This means that the ratio of measurement noise to point density worsens considerably and measurement errors can no longer be ignored or reduced to simply removing outliers. In order to produce geometric models that are both geometrically accurate and visually appealing this measurement noise must be reduced. This problem has traditionally been addressed by smoothing and thinning of the point cloud. In this process, however, detail is usually lost. Sharp edges and corners, for example, are very often rounded.

In this paper, the generation and application of models with highly detailed surface structures (i.e. a sculpture and an ornate room) from terrestrial laser scanning data will be presented. Alternative approaches have successfully been used for geometric modeling of cultural heritage (e.g., (Böhm and Pateraki, 2006), (Alshawabkeh and Haala, 2004), (Beraldin et al., 2002)). But the methods presented there either lack in economical feasibility (i.e. a lot of interactive post-processing is necessary or the data acquisition is time-intensive) or they do not achieve the best possible quality (both: precision and resolution) attainable by modern sensors. The method presented in this paper uses an innovative filtering method, that is capable of reducing the measurement noise considerably while striving to preserve detail. As a byproduct of the surface normal estimation outliers can be identified and removed. Other byproducts include an estimation of the surface roughness and the likelihood of the presence of high frequency features.

Although this method was developed for the processing of data acquired with long range laser scanners, it is independent of the scale of the measurements and the method of data acquisition and could equally well be applied to data from close range scanners or image matching. All parameters needed in the processing can either be estimated from the data or depend only on the scanner used. Thus no parameters need to be determined interactively making the presented method highly suitable for automatic data processing. The main two parameters are the size of the neighborhood which is to be considered when estimating the surface normal vectors - this can be estimated from the data - and the target point spacing which depends primarily on the maximum spatial frequency the scanner can resolve and it is known in advance.

The method presented in this paper has been tested on datasets acquired at the *UNESCO World Heritage Site Schönbrunn Palace*. Results from the application of the method on data from a sculpture from the park of the palace and on data from an ornate room within the palace are presented. Both datasets have been acquired using a phase shift scanner. The sculpture was scanned from several positions around it with a point-spacing of 2mm. The combined point clouds were preprocessed using the method presented in this paper. From the resulting point cloud a triangle mesh was derived. The suitability of this mesh for the purposes of monitoring, visualization, and reconstruction is discussed. The room was scanned with a point spacing of 1.5mm and 0.7mm in selected areas and this dataset was also processed using the same method. The results are compared with those from alternative methods.

2 METHODOLOGY AND RELATED WORK

The typical workflow from data (point cloud) acquisition to the final, geometrical surface model (e.g. triangulation (Amenta et al., 2001) or manual construction of primitives (Autodesk, 2007)) comprises the following steps:

- *Data acquisition:* Measurement of point cloud
- *Registration:* Definition of a reference coordinate system and transformation of all datasets into this system (in photogrammetric context often referred to as orientation)
- *Calibration:* Elimination of systematic effects (i.e. improving accuracy)
- *Minimization of the influence of measurement noise:* Often referred to as filtering or smoothing (i.e. improving precision)
- *Surface modeling:* Triangulation or freeform surface estimation

TLS for capturing point clouds was introduced in Section 1. Registration is not considered in this paper (e.g., (Ullrich et al., 2003), (Rusinkiewicz and Levoy, 2001)). The calibration is described in the following Section 2.1. Due to the redundant data acquisition (i.e. very low sampling distance versus relatively high measurement noise - confer Section 1), an adequate method for the elimination of the measurement noise is necessary. The currently applied steps are described in the sections 2.2 to 2.3. Finally, the determination of surface models from the smoothed point cloud is discussed.

2.1 Elimination of Systematic Errors

The data acquired with TLS contain systematic errors. These systematic errors must be modeled and the resulting correction function must be applied to the data. This process is known as calibration. The instruments are usually calibrated by the manufacturer on a regular basis, e.g. once a year. There are, however, calibration parameters which may change at a higher rate, making additional calibration before each survey campaign desirable. An example of how such a calibration can be performed under laboratory conditions is presented in (Lichti, 2007). Some of the calibration parameters even change from one scan to the next. These can no longer be determined under laboratory conditions, but must be determined in situ.

An example of such a fast changing phenomenon are cyclic errors of the phase shift rangefinder. Figure 1 shows the differences between measured ranges and a mean plane. (Lichti, 2007) described such a cyclic ranging error with a wavelength of 0.6 m, which is half the length of the shortest measuring unit used by the investigated scanner. Our findings using the same scanner model show that there is a harmonic spectrum of at least 4 significant harmonic waves with wavelengths of 0.6 m, 0.3 m, 0.2 m and 0.15 m respectively. If a plane patch - large enough to encompass more than the largest wavelength - can be found in a scan then it is possible to estimate the parameters of the calibration function.

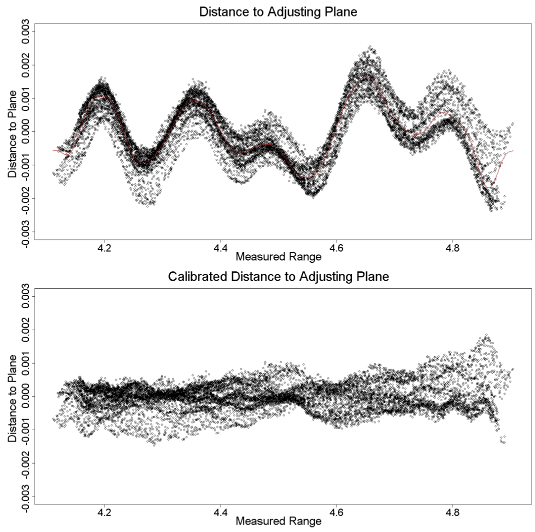

Figure 1: Distances to an adjusting plane by range for uncalibrated (top) and calibrated (bottom) data

Figure 1 shows the described effect. A plane patch was taken from a real dataset and the distances to an adjusting plane are plotted versus the polar range. The upper diagram shows the uncalibrated data, where the cyclic error is clearly visible. The lower diagram shows the calibrated data where the pattern of waves is mostly eliminated. The median absolute deviation is reduced from 1 mm to 0.4 mm. Notice that there are a number of points not fitting very well to the majority of points, especially in the right part of the diagrams. The reason is that the patch - taken from a scan of a historic room - is not really a plane. This illustrates a general difficulty in performing in situ calibration. For an exact determination of the calibration an exact plane over the full spectrum of measured ranges would be necessary. However, this ideal situation will rarely occur in realistic data.

Another source of systematic errors are the points at the silhouette of an object. Since for phase shift scanners the measured range is integral over the entire instantaneously illuminated area (often referred to as footprint), points on or near the silhouette are invariably shifted. These points are gross errors and must be eliminated. The software provided by the scanner manufacturers usually provides such a functionality, however, there always remain some silhouette points. Silhouette points can also be dealt with by eliminating all points whose angle of incidence, i.e. the angle between the incoming laser beam and the surface normal vector, approaches 90°. Measurements with an angle of incidence close to 90° and not lying near the silhouette of an object are unreliable because the instantaneously illuminated area becomes very large. To avoid having uncovered areas additional scan positions are necessary.

2.2 Estimation of Surface Normal Vectors

Our approach uses a filtering method that is capable of reducing the measurement noise considerably while striving to preserve detail. This filtering is based on the Fast Minimum Covariance Determinant (FMCD) estimator (Rousseeuw and van Driessen,

1999) for the highly robust estimation of surface normal vectors. As a byproduct of the surface normal estimation outliers (i.e. points lying too far from the object's surface) can be identified and removed. The FMCD estimator robustly determines a covariance matrix C from the local neighborhood n. As the local neighborhood of a point p we use the n points which are closest to p. These n points can be found efficiently by using the kd-tree data structure (Berg et al., 2000). The surface normal is the eigenvector corresponding to the least eigenvalue λ_3 of the eigen-decomposition of C. The eigenvalues can also be used to estimate surface roughness. (Pauly et al., 2002) show that the surface variation σ_n^2 - which can be computed from the eigenvalues - can be used instead of the local surface curvature for determining surface roughness. Based on the surface roughness parameter the surface can be classified into smooth and rough areas. Note that σ_n^2 is dependent on the magnitude of n. It is thus essential to use an appropriate n.

2.3 Estimation of the Local Neighborhood

The most critical parameter that must be determined is the size of the local neighborhood. If the neighborhood is too small then the neighborhood is a more or less spherical region within the band of points and the estimated surface normal will be more or less arbitrary. The surface roughness will be high and mostly meaningless. If it is too large, the surface normals can be estimated correctly, however, high frequency (i.e. small) features will be increasingly smoothed. For the automation of the processing it is essential that the optimal neighborhood can be estimated locally. For a planar region this is possible.

If the neighborhood of a point is enlarged step by step and the smallest eigenvalue λ_3 of the covariance matrix is plotted for each neighborhood size n, you obtain a diagram like the one shown in Figure 2. λ_3 will increase until it reaches a level where it will remain more or less constant. From that point on the increase in variance caused by the enlargement of the neighborhood will be reflected only in λ_1 and λ_2. The n corresponding to the point where this level is reached is the optimal neighborhood size n_o. In practice the obtained samples are quite noisy. This makes it necessary to estimate n_o. Fortunately, this problem is very similar to the problem of fitting a variogram model to a spatial variogram, and existing methods for solving this problem (e.g. (Genton, 1998)) can be used.

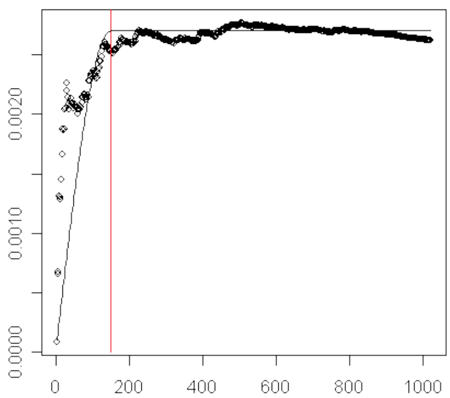

Figure 2: Estimation of the optimal neighborhood size: A spherical variogram function is fitted to the variance-neighborhood plot to estimate the range

2.4 Thinning of the Point Cloud

The normal vectors (c.f. Section 2.2) are then used to determine points having the highest probability of being closest to the real surface. We take all points lying within a cylinder with a radius r around a randomly selected point, whose axis is defined by the average normal vector. The points are considered to be redundant measurements of more or less the same area - this can be assumed if the point spacing is smaller than the laser footprint. The points within the cylinder are projected onto the cylinder axis. Along the cylinder's axis a univariate density is estimated and the point being closest to the mode of this distribution is chosen as the representative point. The other points are removed from the dataset. This is repeated until the desired point density is reached. The result is a resampled point cloud in which random measurement noise is largely suppressed and which has a more homogeneous spacing of points while preserving detail. This is because in areas with higher point densities - either because of being closer to the scanner, because of the incidence angle, or because of overlapping scans - more points are deleted than in areas of low point densities. The radius r can be chosen adaptively depending on the roughness classification and thus allowing for curvature based thinning, i.e. more points are retained in rough areas than in smooth areas.

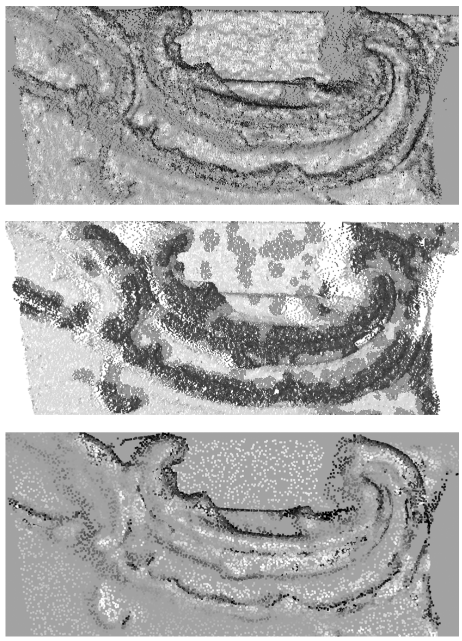

Figure 3: The thinning process: Shaded original points (top), roughness classification (middle) and resampled point cloud (bottom)

Figure 3 illustrates this processing step. The shown dataset represents a 20 by 35 cm part of a stove. The top part shows the fairly noisy original data as shaded points. The roughness classification is shown in the middle part where points are classified into smooth (light grey) and feature-rich (medium and dark grey) areas. The bottom part shows the resampled point cloud after the thinning step. More points are aggregated in smooth areas (e.g. lower, left part) compared to feature-rich areas, where more points are left.

2.5 Triangulation

The triangulation of unstructured point clouds has been actively studied in computer graphics for some time. Numerous algorithms exist that can be used to reconstruct surfaces from noise-free point samples, e.g. (Hoppe et al., 1992), (Edelsbrunner and Mücke, 1994), (Amenta and Bern, 1999) or (Dey and Goswami, 2003). Some of these algorithms have been extended such that they also work with noisy data, e.g. (Dey and Goswami, 2006), (Kolluri et al., 2004), or (Kazhdan et al., 2006). They only seem to work well when the noise level is low, which makes it necessary to reduce measurement noise as described above in situation where noise levels are high. Another problem with the latter two algorithms is that they optimize globally, which makes them unsuitable for large datasets. Currently efforts are being made to derive localized algorithms, e.g. (Schall et al., 2007).

The integration of a suitable triangulation algorithm into our workflow is currently being researched. For the presented examples we used the commercially available software *Geomagic Studio 9* to do the triangulation.

3 RESULTS AND DISCUSSION

So far, we discussed the individual steps to determine a triangulation model from a laser scanner point cloud. To demonstrate the capabilities of our method, we are now presenting results from point clouds, acquired in *Schönbrunn Palace*. The first example shows an ornate room with sophisticated stuccoes and a highly detailed stove. The second example shows a marble sculpture situated in the Baroque garden of the palace. Finally, we are discussing the achievable results and their quality with respect to alternative model determination approaches as provided by commercial modeling software packages.

3.1 Modeling an Ornate Room

The four Rococo rooms on the ground floor of *Schönbrunn Palace* are not accessible for tourists. They were redecorated in 1770 and were used as dining-rooms and additionally as ceremonial rooms. The decoration is typical of the Rococo décor with white wooden paneling outlined with guilt bordering and Rocaille work. Isolated flower garlands in part cover the paneling. On the one hand, geometrical patterns have increasingly been used in the guilt ornamentation in these rooms, an indication of the transition to classicism, but, in one of the four rooms, on the other hand, the undulating lines and sculptured décors are still completely Baroque. Results from modeling this room are considered in the following. In order to document the status after the recent restoration of these rooms, high detailed geometry models including textural information need to be determined.

Figure 4: Rendered image of a Rococo room of *Schönbrunn Palace*

Figure 4 shows a textured rendering of one of the Rococo rooms. The extension is about 7.5 by 7m (confer Figure 5, second room from the right). The data has been acquired by a *Faro* phase-shift scanner from the centre of this room. The entire room was sampled with a mean point spacing of 1.5mm at the object. Additionally, the stove was scanned with a higher resolution (0.7mm). The final model, combining both scans, consists of 4 million triangles for the entire room. Due to the lack of adequate photographic images of the walls, the material properties of the triangles were classified according to the reflected infrared light intensity measured by the scanner. The texture of the floor was generated from a photograph. From this photograph, the image of a single floor tile was undistorted and used to texture the triangles. As texture coordinates the affinely transformed x-y coordinates were used.

Based on these results, the survey of all four Rococo rooms together with five other rooms of similar size was recently done. For that, 63 scan positions were necessary. Figure 5 shows the scanner positions (numbered dots) for the four Rococo rooms. Stoves are represented by circles.

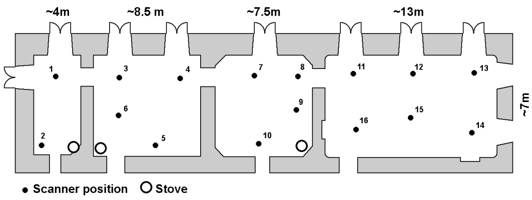

Figure 5: Scan positions (black dots) for scanning four rooms of *Schönbrunn Palace*

The data acquisition took four working-days including the definition of a local reference system (by tachymetric measurements) and the registration of all point clouds. The resulting point cloud has close to 4 billion points. The model generation process by means of the described approach (confer Section 2) is performed automatically. Thus, almost no additional manpower (except quality control) is necessary. The expected computation time is three weeks using a workstation with four 3GHz Xeon CPUs.

3.2 Sculpture Monitoring

In the so-called Grand-Parterre which is part of the designed Baroque garden of *Schönbrunn Palace*, forty-three sculptures of 2.5 meters height are situated. The total height including the pedestal is 3.5 meters. The sculptures are made of Sterzinger marble and represent famous scenes from the Roman and Greek mythology. In order to monitor the status of the surface structure and the current condition of the surface material of these sculptures (e.g. biogenous destruction, frost damage, ...) the implementation of an adequate information system is currently investigated. This information system shall be based on appropriate highly detailed geometry models.

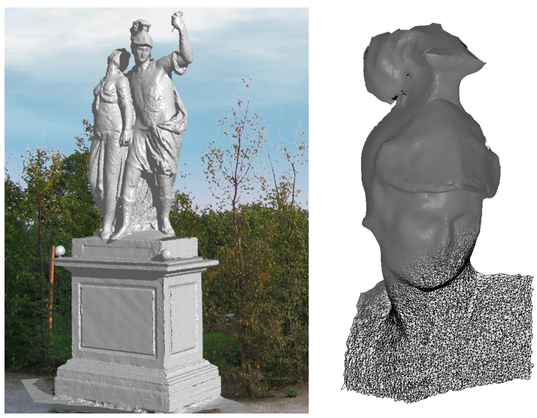

Figure 6: Rendered model (left), and rendering of the head and the corresponding triangulation (right)

To test the capabilities of our modeling approach, three scans from different positions with a mean point spacing of 2mm were acquired from such a sculpture. These scans were used to generate a model of the sculpture including its pedestal. Figure 6 (left) shows a rendering of the sculpture. The geometric model consists of some 1.5 million triangles with a mean edge length of 5mm 6 (right).

3.3 Quality Analysis

To assess the quality of our algorithm we compared it with the preprocessing tools available in the software packages *Geomagic Studio 9* and *Rapidform 2006*. If possible, the following processing steps were applied: Removal of outliers and disconnected components, adaptive thinning, and finally smoothing of the resulting point cloud. For visualisation a triangulation was performed using *Geomagic Studio 9* with identical settings, therefore the triangulation should have no influence on the result. The parameters were determined such that the final cloud was about 10% of the original and that the visual appearance of the flat areas appeared almost similar.

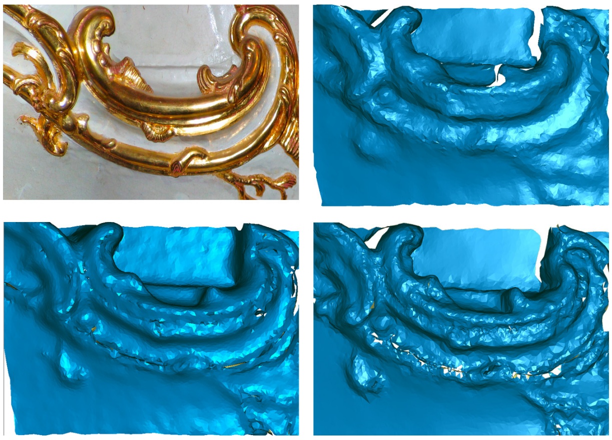

Figure 7: Comparison of different thinning/smoothing methods. Photograph of the area (top left), *Geomagic Studio 9* (top right), *Rapidform 2006* (bottom left), our method (bottom right)

Figure 7 shows the result of the comparison. It can be seen that our method does indeed preserve detail better than any of the alternative methods, with the overall smoothness and the reduction rate being fixed. On the other hand it also contains the most holes. With an integrated triangulation algorithm it should be possible to overcome this problem. The result achieved with *Geomagic Studio 9* is the smoothest with most detail being lost, but it is also the surface with the least holes. *Rapidform 2006* is somewhere in between, but it was not possible to achieve the same amount of smoothness as with either our method or *Geomagic Studio 9*.

Figure 8 shows a the color coded differences between the triangulated surface and the original point cloud. Within the smooth

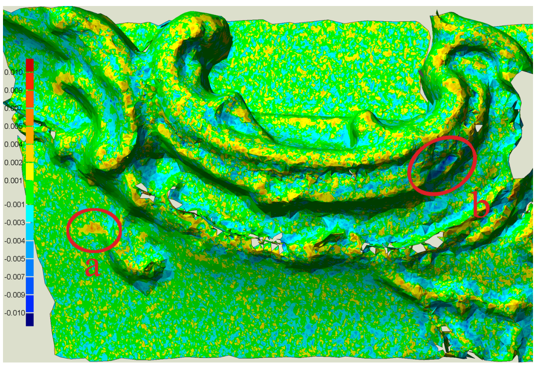

Figure 8: Color coded differences between the triangulated surface and the original point cloud

areas the differences stay within the bounds defined by the specified measurement noise of the scanner. One can also see, that there is still a slight tendency to smooth over highly curved surface areas. In two areas high deviations can be observed. In the area marked with (a) a part of the ornament is missing completely in the triangulation. The reason is that because of a disadvantageous scan angle comparably few points were measured on this part and those were thus classified as outliers and filtered out. In the area marked with (b) specular reflection caused grossly erroneous measurements, some of which were not detected and thus caused the deformation of the surface. We are currently researching if these issues can be overcome by combining scans from several scan positions. At this level of detail the requirements for the accuracy of the registration of multiple scans and the modeling of systematic errors are extremely high.

4 CONCLUSIONS AND FUTURE WORK

We stated that the generation of detailed models from characteristic features of cultural heritage sites is necessary for adequate management of the facility. We introduced terrestrial laser scanning as a suitable and efficient data acquisition technique for that purpose. The presented method is an effective tool to generate models in an economically feasible manner. Compared to other, commercially available surface modeling methods, our approach is superior as it is possible to be applied without the need for interactive determination of control parameter and thus runs automatically. Long computation times are not cost intensive if human supervision is not necessary. Besides, the implementation supports multi-core processors or even computer clusters allowing to decrease the computation time. As the only input parameter (i.e. the local neighborhood size) is determined from the data automatically (confer Section 2.3), the described smoothing and thinning processes are fitted automatically to the local data and the error distribution. By contrast, commercial available methods (e.g., *Geomagic Studio 9*, *Rapidform 2006*, *Polyworks 10*) appear as black boxes to the user demanding for numerous control parameter which have to be predefined by the user without detailed description. This fact makes an automatic processing of TLS difficult as these parameter have to be determined by trial and error for every scan and taking local variations of the surface characteristics into account is only possible with significant interactive work.

Results from modeling two different assets of *Schönbrunn Palace* have been presented. The models of the Rococo rooms are used for documentation of the final status of the preceding restoration. A future application will be the derivation of high quality renderings for virtual reality environments (e.g., (Gatiatzes et al., 2001), (Drap et al., 2006)). Two different applications of the sculpture models are discussed. On the one hand, it can be used for rapid reproduction by means of CNC-milling machines and on the other hand, the implementation of a sculpture monitoring system is planned which should be based on a high quality geometric model and will support the restoration process.

The data acquisition has so far been performed by a scanner of one manufacturer, *Faro*. We are currently investigating alternative products as well, because the diversity of the occurring surface structures and textures influences the quality of data acquisition. Due to the fact that the physical properties of TLS systems from different providers are not equal (e.g. they differ in wavelength, footprint-size, illumination power, ...) the appropriate field of application has to be determined for each individual scanner. So far, we used the commercial software product *Geomagic Studio 9* to generate the three-dimensional triangle-mesh from the preprocessed points. As, for our application, the software suffers from certain deficiencies (e.g. the resulting model is not waterproof thus containing holes; it cannot cope with very large datasets), we are currently implementing an adequate triangulation method.

Finally, it can be said that generally the adequate modeling of both surface structure and texture from cultural heritage sites has been a time and thus cost intensive procedure. Therefore, it has rarely been performed. The application of upcoming data acquisition methods like terrestrial laser scanning in combination with automated model generation methods as presented in this paper increases the cost efficiency to a great extent, thus making it suitable as a standard procedure for adequate cultural heritage site management as already realized by the management of *Schönbrunn Palace*.

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