A COARSE-TO-FINE CURVED APPROACH TO 3D SURVEYING OF ORNAMENTAL ASPECTS AND SCULPTURES IN FAÇADES

J.Martínez, J.Finat, L.M.Fuentes, M.Gonzalo, A.Viloria
DAVAP Group, Lab. 2.2, R+D Building, M.Delibes Campus,
University of Valladolid, 47011 Valladolid, Spain
jmr@ega.uva.es, jfinat@agt.uva.es, lfuentes@opt.uva.es, marga@infor.uva.es, aviloria@infor.uva.es.

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ABSTRACT

Laser-based surveying of 3D curved objects is based on discrete clouds of points. Ordering such clouds of points simplifies the computer data management, but can increase troubles when misleading surfaces are superimposed to 3D objects. An evaluation of adaptive goodness-of-fit is need to bound errors and to maintain the model fidelity to the object to be surveyed. Unordered or ordered clouds of points pose different grouping strategies for the computer information management. In this work, we address an ordering scheme induced by curvature variation. The main contribution of this paper concerns the management of volumetric information of curved objects in terms of several *curvature maps*. A coarse-to-fine approach is developed with a concavity-convexity map, an automatic grouping around “typical” values of Gauss curvature, allowing bounded variations, and finally, the design of intelligent meshing algorithms adapted to the curvature. An additional contribution of this work concerns to the identification of error sources for geometric propagation models, and how to avoid them by using data fusion. An interface is developed for superimposing local results arising from different 3D laser scanning devices on local aspects arising from a global coarse model of several richly ornamented Spanish buildings of the late gothic and the early renaissance style. Maps of curvature provide a coarse-to-fine management of sculptures contained in a small pilot zone of the façade, which is compatible with three resolution levels. Occluded zones for 3D scanning laser is balanced with the insertion of high-resolution views on the 3D model tied by 3D control points. Our approach is flexible enough to be compatible with the analysis of another complex façades.

1. INTRODUCTION

Surveying of ornamental aspects in façades involves the evaluation of complex shapes. The high shape variability and complexity makes very difficult and perhaps impractical the development of software tools for automatic recognition, as it can be found in related problems of Computer Vision. Traditional image-based approaches are insufficient to obtain an accurate representation of a very complex geometry presented by different elements such as sculptures, high- or bas-reliefs, capitals or richly decorated entablatures. This difficulty is increased in façades with very rich ornamentation of the late gothic origin in European or the very rich decoration of Asian temples (Kajuraho in India or Angkor in Thailand, e.g.), most of them constructed along 14th and 15th centuries A.D. Nevertheless their strong stylistic differences, the identification of dominant planes in façades is relatively easy on large scale, and it allows the superposition of marching cubes for a coarse segmentation which simplifies the management of the geometric dataset.

Reconstruction techniques in Computer Vision have achieved a high degree of maturity, incorporating techniques from several related fields [Hartley and Zisserman, 2000]. Dense 3D reconstruction requires a very large number of views. Matching of views is less sensitive to errors in presence of a small baseline. Hand-held high-resolution video cameras satisfy usual requirements for visualization purposes. The earlier and spectacular results using the Computer Vision were obtained by Pollefeys et al. [Pollefeys, Koch, R., and VanGool, 1998]. Their work shows an accurate reconstruction of a sculptural group of the richly ornamented façade of an Indian temple, from a textured mapped 3D model using propagation along epipolar lines. This approach gives very nice results for rendering, but there is a lack of proper volumetric information.

The profusion of anthropomorphic representations in façades and other decorative elements poses serious problems for 3D surveying, which require the fusion of image-based and range-scanning approaches. In this work, we have concentrated our attention on laser-based approaches. We have used an ILRIS 3D from Optech for large-scale scans, and a Minolta 910 for closer range (60-250 cm). We have restricted ourselves to surveying low and high-relief ornamental details, from decorative elements in entablatures to almost natural size sculptures. An important trouble concerns the modelling of ornamental aspects for an efficient computer management. Usually, ornamental details cannot be reduced to simple geometric primitives, and one must work with different levels of detail and with different kinds of sensors.

Fusion of information has already a long history and has been recently applied for reconstructing destroyed monuments from quite different old sources, with metric accuracy even in absence of 3d laser information. A paradigmatic case corresponds to the great Buddha statue in Bamiyan (Afghanistan), where a 3d virtual reconstruction has been performed with a very high degree of accuracy [Gruen, Remondino and Zhang, 2002 and 2003]. Dense information contained in 2d views can be reprojected on the dense cloud of 3d points with their metric information. Unfortunately, 3d propagation models with 2d boundary conditions are not elementary, and computer management of propagation models is very difficult. If local data are accurate enough, robust and precise global models can be given by increasing the number of scans or high-resolution views. Complete geometric and radiometric information of 3D objects is difficult to achieve. Obviously, there are objects for which a complete surveying is virtually impossible due to the intricate structure of engraved braids, even when some appropriate mirrors are used.

Discrete clouds of 3d points provide an accurate and robust geometric support for matching scans. Accuracy of dense information depends on the laser device used for capturing data; in our case, Minolta 910 for the small range and Ilris 3d (Optech) for larger ranges. Robustness is characterized by the stability of the 3d geometric model with respect to small perturbations linked to radiometric properties or the aggregation of information arising from other sensors and data. Robustness is due to the rigid nature of metric information for scanned object. Stability is linked to optimization algorithms for merging clouds of points. Grids and isosurfaces provide ordering criteria for unordered clouds of points. Richly ornamented façades provide a test bed for integrating local and global approaches for surveying.

Figure 1: A challenge for sculptural range-scanning surveying

The superposition of regular grids simplifies the global management of very large and complex façades. Isosurface extraction based on marching cubes approximates 3d shapes [Lorensen and Cline, 1987], which can be adapted for decomposing original clouds in subsets of clouds corresponding to different objects in the foreground. Refinement and grouping are the following steps to be done for recognition systems of complex shapes. The solution must be enough robust to make compatible geometric data linked to geometric and radiometric properties contained in superimposed structures. Some elements of the pipeline for volumetric recognition include: a) 3d volumetric segmentation, b) rupture curves for visibility hulls defined as the boundaries of critical regions, c) control points for rupture curves, d) the insertion of additional elements based on 2D information linked to high resolution models, e) their propagation from rupture curves following a combination of automatic restoration models for 2D views applied to the boundary of almost critical surfaces, and a manual intervention similar 3D warping, f) the design and implementation of propagation models for coarse and fine curvature maps, and g) the interplay between representations with different levels of detail.

This program is far from being reached, and we shall limit ourselves to sketch some related partial results. The paper is organized as follows: In section 2, some related aspects in high resolution views and range scanning are displayed. Next, we introduce elements for geometric modelling which simplify static grouping and quasi-static propagation models. The section 4 is devoted to adapting algorithms for simplifying the management of partially occluded volumetric objects. In the fifth section we introduce a hybrid functional and discuss some partial results and their integration in a global representation. We finish with some conclusions and future work relative to the construction of support for propagation models for complex objects in façades.

2. RELATED WORK

2.1 Digital Photogrammetric and Computer Vision approaches

Coarse-to-fine strategies for the shape estimation of complex 3d objects are based in the extraction-grouping of contours, and in advanced shape recognition, including eventually the identification of geometric invariants. Metric information on views is crucial for advanced shape estimation, but its lifting for a 3d object modelling is far from being elementary, and requires an estimation of the camera calibration. Coarse approach based in 2d silhouettes extracted in views presents similar difficulties: An ideal geometric model for a pinhole camera from a fixed pose F is given by a projecting cone with vertex F and directrix curves given by identified visible 2d silhouettes. Given two views with known homologue silhouettes, each 3d contour is analytically defined as the intersection of at least two projecting cones with homologue directrix curves in corresponding views.

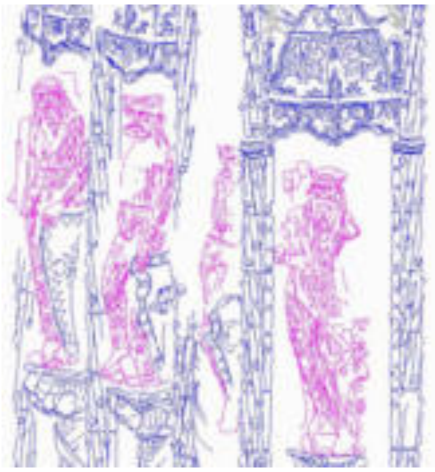

Figure 2: Detail of manual restitution of the Façade of the National Museum of Sculpture (Valladolid)

Classical restitution based in stereo pairs uses the principles mentioned above for displaying a planar representation of 3D contours on a dominant plane linked to frontal rectified view, but requires hard and expert human work. Another important task is the automation of contours extraction for professional conservation and restoration, by avoiding the hard manual work of traditional restitution. Even if geometric information about silhouettes and internal boundaries is available, the intersection of projecting cones is not easy to solve. Furthermore, under unrealistic hypothesis of complete information for objects to be surveyed in Cultural Heritage, contours are bad conditioned due to shape irregularities and deterioration (erosion, fissures and fractures).

2.2 Range-scanning approaches

Nowadays 3d surveying of sculptures is linked to the identification of piecewise smooth (PS-) surfaces in 3d, which can be approximated by piecewise linear (PL-) surfaces which are optimally fitted to the cloud of points. PL-models contain information for relative orientations maps, which allow identify zones with maximal risk for meteorological (rain, water ice) or animal aggressions (birds). Even when volumetric segmentation can not be performed (bas-reliefs, e.g.), it is possible to construct a high-risk map (see below).

Some additional problems arise from incomplete information, i.e., situations where local data are not enough accurate and making a fusion of information arising from different sources is needed. In this case, the errors estimation becomes a formidable problem due to the disparity of files, the absence of calibration and the inexistence of a model for contrast. However, the distribution of errors in data structures arising from a 3D laser scanning is not homogeneous. Two typical sources of error are linked to the lack of stability of apparent contours (tangency locus for some projection) or the lack of enough information (scarce overlapping). Both questions involve to the connections between local and global aspects.

Fig 3: Map of orientations maximizing components with vertical normal vector in a low-relief

3. DENSE MODELS FOR GROUPING

In absence of previous models, dense information contained in high resolution views or scans provides the nearest approach for surveying ornamental elements in façades. Dense information can be obtained from a total station in traditional Photogrammetry, high resolution views in Computer Vision or from 3d laser scans devices. As pointed before, in this work, two laser scanners have been used for capturing information: Minolta 910 for close range scanning and Ilris 3D from Optech, for large range scanning.

3.1 An experiment for fusion of 3d information.

Range-scanning approaches allow superimposing high resolution meshes for small details on large mid-resolution files and a joint information management of the whole model which can be also applied to indoor scenes. An example corresponding to the low-resolution scanned interior of a Romanesque chapel with high-resolution scanned tombs appears below.

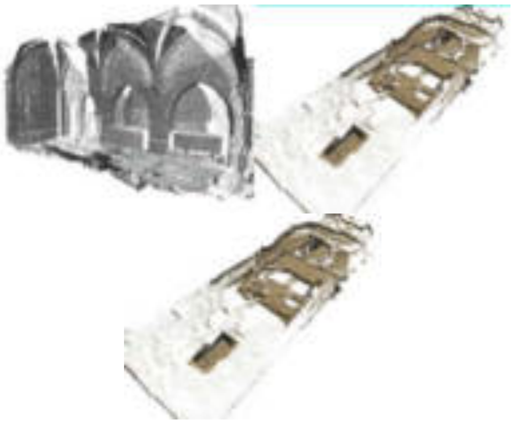

Figure 4: Fusion of high-and mid-resolution scanning in an indoor scene

3.2 A coarse to-fine approach

A well-known result in Differential Geometry says that any smooth surface is uniquely determined up to rigid motions by total and mean curvatures, i.e., the eigenvalues of the curvature matrix (Gauss).

The object to be surveyed is geometrically modelled as a piecewise smooth (PS-) volume with a boundary given by a PS-surface; the scanned portion is the visible hull of a dense discrete cloud on the surface. For a pinhole camera, the tangency locus for the projection of a surface on the computer screen is ideally a collection of curves on the object. A 3D laser scan has a scanning window which captures a large truncated cone. Thus, the geometric model is not exactly a conical projection. In particular, the visible hull of the discrete tangency locus is supported on 2D regions, which are "near" to the intersection of the scene with the boundary of projecting cone, and make part of the quasi-critical values; let us remark that quasi-critical values don't belong to the image of the critical locus, but to a "collar" of the critical locus.

In discrete terms, proximity is defined in terms of the nearest neighbours with respect to a prefixed threshold. By analogy with the ideal pinhole camera, we shall call it the discriminant locus of the conical projection. In particular, if the normal to the surface to be scanned is "almost perpendicular" to the scan direction, then there appear errors around the discriminant locus. Errors can be locally detected as non-optimal mesh triangles (the minimal angle is not maximized) with large holes between them, i.e., sampling displays strong irregularities for the cloud of points. In both cases, high resolution views provide accurate information that must be inserted inside the robust components of the 3D model

To prevent propagation of errors linked to relatively small field of view or almost critical regions, it is convenient to perform a coarse-to-fine approach starting from general views of large zones of the object and superimpose finer local elements. In our case, we have used an ILRIS 3D and a Minolta 910 for global and local aspects, and a metric camera.

4. A HIERARCHY FOR SUPERSIMPOSED STRUCTURES TO THE CLOUD OF POINTS.

Volumetric segmentation concerns to modelling and implementing algorithms for decomposition criteria that can be superimposed to 3d sub-clouds with an arbitrary geometric support. For architectural or urban scenes, volumetric segmentation is easier: it suffices 1) to identify large dominant planes from neighbour points making part of triangles with near normal vectors; 2) to impose elementary geometric conditions to normal vectors to adjacent triangles; see [Fernandez-Martin et al, 2005] for details. Reference or dominant planes in very ornamented façades play a very secondary role for sculptural surveying, and it is necessary to adopt a finer approach linked to a volumetric segmentation which is superimposed to the intrinsic geometry of the object. After substracting the background, our finer approach to the volumetric foreground (bas-reliefs and high-reliefs) has two levels corresponding to the determination of concave-convex regions, and the identification of curvature maps for individual objects. A very complex example corresponds to the façade of San Pablo (Valladolid) where late gothic and early renaissance elements can be easily identified [Fernandez-Martin et al, 2005].

The methodology for insertion of accurate scans is illustrated with sculptures lying in a rectangle of the low right side. In view of large variations of curvature, eight scans were recorded with a variable accuracy (spot between 3mm and 20mm depending on the distance). Low reflectivity of sculptures allows concentrate the attention on their geometry for high resolution scans. A coarse-to-fine strategy provides a discrete cloud of 3d points for managing 3D data structures and navigating around sculptures. The lack of laser scan information for some occluded regions is partially corrected by means of the insertion of high resolution 2d views, which are warped on the 3d model in an interactive way. The management of this additional information requires a superficial support for propagation that is constructed following a triple coarse-to-fine strategy:

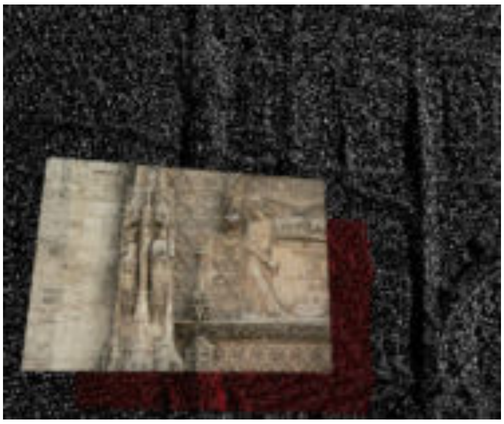

Figure 5: Global scan and a detail of the façade of San Pablo (Valladolid, Spain)

1) Piecewise Linear (PL-) model M_L given by the original mesh associated to the discrete cloud of 3d points (see Figure 6)
2) Concave-convex (CC-) model M_C, resulting from evaluating the sign of the total curvature in each point based in the triangular original mesh (Figure 7).
3) Piecewise Smooth (PS-) model M_S given by the map of total and mean curvatures which determine locally the surface up to rigid transformations (Figure 8)

Meshing can be performed in different ways [Heckbert and Garland, 1997], and their applications to surveying sculptures are well documented in the literature. A crucial aspect concerns to the memory management; important details with applications to surveying complex sculptures can be found in [Cignoni et al, 2004] The updating of local information for high resolution curved models is also performed following a coarse-to-fine approach, similarly to bounding boxes strategy [Livnat, 2005], but adapted to the whole object geometry.

4.1 Maps of concave and convex regions

Concave and convex regions are identified from the sign (positive or negative) of Gauss or total curvature of visible hulls. In 2D case, bitangent lines in pairs of contact points are the responsible for 2D occlusions; the locus between two tangency points of the same line does not belong to the visual hull, and there is an uncertainty about the depth. In 3D case, bitangent cones along pairs of contact curves do present similar troubles for alignment, but increased by the uncertainty about concavity and convexity of zones away from the intersection of visual hulls. Luckily, the information provided by RapidForm for scan files of Minolta 910 solves the problem. As a practical application, it is possible to construct a map of sunned or shadowed zones, e.g., a map of regions characterized by the proximity with respect to a predominant normal vector to a plane which is fixed by the user.

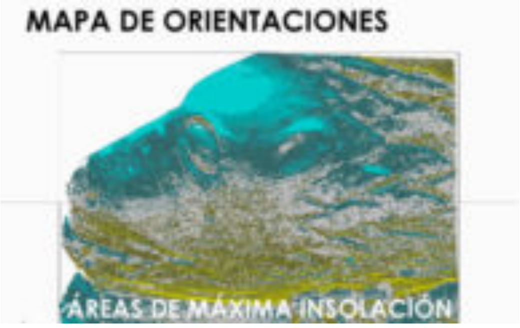

Figure 6: CC-model corresponding to the signed total or Gauss curvature extracted from the original mesh

4.2 Maps of total and mean curvatures

Fine volumetric segmentation linked to the allowed variations for total and mean curvature in a range fixed by the user. K.F. Gauss has proved that total k_t and mean k_m curvature determine uniquely the surface up to rigid transformations.

Figure 7: A PS-map linked to the estimation of the total curvature for small regions of a high-relief.

Figure 8: A piecewise smooth map linked to the estimation of the total and mean curvatures for small regions of a high-relief

4.3 Optimization of superimposed structures.

The displayed examples show how CC-map and PS-model can present very small irregularities. Often such irregularities are not meaningful for larger visualizations, or are caused by noise. For grouping them around typical characteristic values, a cooperative-competitive model can be implemented following a strategy similar to that of Voronoi diagram [Berg et al, 1999], but now linked to the variation of curvature instead an ordinary distance. The adaptation is very easy if we think at curvature as the square of distance in the tangent fibre bundle. The resulting map of curvature variations provides a mesh simplification that is better adapted to the geometry than other combinatorial sampling processes due to their nature as PS-models.

Additional troubles for the discrete dense approach arise from the 3d vector nature of large datasets to be managed. So, it is possible to obtain different representations which are sensitive to the choice of meaningful parameters. An example is given by two vector maps of the following sculpture:

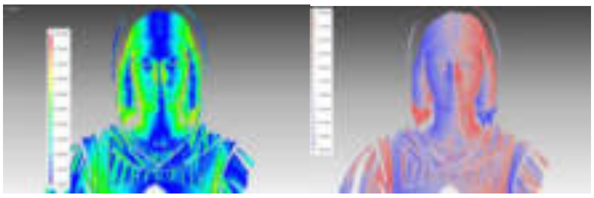

Fig 9: Two vector maps of a sculpture in wood

To minimize the dependence with respect to the choice of parameters, it is convenient to introduce hybrid multi-objective functional. Optimal criteria for the above models are relative to hybrid cost functions given by a total energy functional

$$E_{total} = E(K, M_L) + E(K, M_C) + E(K, M_S)$$

This functional is also constructed following a coarse-to-fine strategy with a hierarchy from PL- till PS-model. In this way, a sequential implementation is easier and avoids a simultaneous optimization with high computational cost. To facilitate an automatic information management by the computer, it is necessary to bound the cost function in each step, and to make compatible robustness, accuracy and flexibility for optimal geometric models: 1) *Robustness* involves the independence of topological PL-models with respect to small perturbations; hence, performs a resampling of the original cloud preserving the topology of the cloud K, (minimizes the difference of the sum of squared distances of resampled points with respect to the nearest facets of the original mesh). 2) *Accuracy* involves to the desired coincidence between estimated and true data; hence induces modifications on small concave and convex mini-regions but preserving the global distribution of large regions of the CC-map. 3) *Flexibility* involves to the adjustment of 2d and 3d data to a PS-model; hence it is linked to minimization of abrupt changes relative to curvatures. This problem is far from being elementary, as it can be seen from a direct examination of the following example:

Figure 10: Identification of plane dominants for re-projection and alternant bas- and high-reliefs in real façades

The on-going research is focused towards the selection of a strategy with different levels of accuracy involving 1) a volumetric segmentation for the coarsest level with dominant planes for façades and dominant cylinders for figures, 2) a precise evaluation of metric properties involving each segmented object, 3) a methodology for re-projection (on planes and cylinders) allowing to visualize the whole object, even under uncertainty.

5. DISCUSSION

In the above paragraph, we have considered three maps which are linked to the original cloud K of points, linked to PL, CC- and PS-models which are labelled as M_L, M_C, and M_S respectively. Optimality criteria for meshes follow the same hierarchy:

The compatibility between cost functions for involved multi-optimization requires to identify the sources of errors, and to design models to avoid them. Common geometric facts provide a support for the information fusion relative to radiometric properties. However, even under the same relative localization and illumination for a small region, discrete clouds of points are not exactly the same. In some triangulation laser scan devices (Minolta 910, e.g.), this problem is solved by performing three spots for each scan with controlled illumination variations and by taking a mean of the resulting information.

In addition, under laboratory conditions, it is possible to control the radiometric information in the short range. Unfortunately, away from Laboratory conditions, fieldwork does not allow to maintain illumination constraints. Sometimes, additional perturbations linked to the interference of artificial or natural light with laser rays are clearly visible in final models. In this case, it is convenient follow a coarse geometric approach and grey-level intensity function as the only internal radiometric information.

The approach developed in this work suggests that the estimation of geometric information (relative to contours, surfaces and volumes) must be performed a post-processing stage, after the fusion of 2d and 3d information.

6. CONCLUSIONS.

Volumetric segmentation is a mid term research goal which requires the design and implementation of propagation models on 3d support. Intrinsic data are linked to mean and total curvature, which can be obtained from adapted meshes to a dense cloud of 3d points. Irregularities in the distribution of true curvature values illustrate the necessity of grouping criteria following a coarse-to-fine approach. Two additional maps linked to the PL-models, given by the sign and the estimated value for principal curvatures, provide a 3d support for propagation models which are relevant for assisting conservation tasks and deterioration tracking of stone in bas- and high-reliefs.

Next steps to be taken are linked to the design and implementation of software tools for constrained optimization linked to volumetric subdivisions. An interactive quick management will require the design of simple interfaces for contracting and expanding subjacent geometric models depending on resolution and interaction capability. The implementation of an interactive software tool will require a dynamic version of curvature maps linked to variational approaches for hybrid energy functional which is a more far-reaching research goal.

REFERENCES:

References from Journals:

Cignoni, P.; De Floriani, L.; Magillo, P.; Puppo, E.; Scopigno, R..: *Selective refinement queries for volume visualization of unstructured tetrahedral meshes,* IEEE Trans con Computer Graphics and Visualization, 10 (1), 29 – 45, 2004

Gruen, A. Remondino, F., and Zhang, L.: *Reconstruction of the Great Budha of Bamiyan (Afghanistan)*, The Intl Archives of Photogrammetry and Remote Sensing, 34 (5), 363-368, 2002.

Gruen, A. Remondino, F., and Zhang, L.: *Image-based reconstruction and modelling of the Great Budha of Bamiyan (Afghanistan),* The Intl Archives of Photogrammetry and Remote Sensing, 34 (5), 173-175, 2003.

Lorensen, W.E. and Cline, H.E.: *Marching cubes: A high resolution 3d surface construction algorithm*, Computer Graphics 21 (4), 163-169, 1987.

R**eferences from Books**:

Berg, M.; Kreveld, M.; Overmars, M.; Schwarzkopf, O.: "*Computational Geometry Algorithms and Applications 2nd Edition*", Springer-Verlag, 2000.

Hartley, R. and Zisserman, A.: *Multiple View Geometry in Computer Vision,* Cambridge University Press, 2000.

References from Other Literature:

CIPA 2003: *New Perspectives to Save Cultural Heritage*, XIXth International Symposium (Antalya, 2003).

Fernández-Martin, J.J.; J.I.SanJosé, J. Martínez and J.Finat:

Multirresolution Surveying of complex façades: a comparative analysis between digital photogrammetry and 3d laser scanning, CIPA Symposium, Torino, 2005.

Heckbert, P.S.; Garland, M.: "*Survey of polygonal surface simplification algorithms*", Multiresolution Surface Modeling Course SIGGRAH 1997.

Livnat, Y.: *Accelerated Isosurface Extraction Approaches*, in C.D. Hansen and C.R. Johnson, eds: "*The Visualization Handbook*", Elsevier, 2005.

Pollefeys, M., Koch, R., and VanGool, L.: "*Self-calibration and metric reconstruction in spite of varying and unknown internal camera parameters*", in Proc. 6th Intl Conf on Computer Vision, Bombay, India, 90-96, 1998.

Schroeder, W., Zarge, J., Lorensen, W: *Decimation of triangle meshes*, Proc. Siggraph 1992

Vision Techniques for Digital Architectural and Archaeological Archives, The Intl Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XXXIV, Part 5, W12. Comm.5, 2003.

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