IMAGE-BASED SURFACE MEASUREMENT FOR CLOSE-RANGE HERITAGE DOCUMENTATION

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ABSTRACT: Recent new developments in the electronics have leaded to the manufacturing of new high-resolution digital sensors (up to 39 mega pixel) for terrestrial cameras. These technological innovations, together with new processing algorithms of image matching, allow to obtain image-based surface models in an almost automatic way with an accuracy and a detail level that can be surely compared with the one achievable with active sensors. With this in mind, we present new developments in terrestrial 3D surface reconstruction and object modeling using digital images, reporting some tests conducted using low cost digital cameras and commercial or in-house software. The tests were conducted selecting different kinds of objects (low relief, statue, buildings, small heritage find, etc.), with different camera configurations and different image resolutions. Different image matching procedures are analyzed, comparing area-based, feature-based or an integration of both. A critical examination of the results is presented, with particular attention to the daily archaeological or heritage documentation purpose.

1. INTRODUCTION

Nowadays surface measurement and 3D modeling of objects are generally performed by means of images or active sensors (like laser scanner or structured light projectors), depending on the surface characteristics, required accuracy, object dimensions and location, budget, etc. Active sensors [Blais, 2004] have received in the last years a great attention, also from non-experts, for 3D documentation and modeling applications. Active sensors are easy to use and provide quickly and directly the required 3D data despite their high costs and the usual lack of texture. On the other hand images require a mathematical formulation to transform two-dimensional image measurements into three-dimensional coordinates. Image-based modeling techniques (mainly photogrammetry and computer vision) [Remondino and El-Hakim, 2006] are generally preferred in cases of lost objects, monuments or architectures with regular geometric shapes, low budgets, good experience of the working team, time or location constraints for the data acquisition and processing. Currently digital cameras equipped with 10-12 mega pixel sensors are quite common, very cheap if compared to range sensors and furthermore they can image objects of any size and at different distances simply using a different focal lengths. Image-based 3D modeling generally requires some user's interaction in the different steps of the modeling pipeline, reducing its use only to experts. Therefore fully automated methods based on a '*structure from motion*' approach [Vergauwen and Van Gool, 2006] are getting quite common in the modeling community, in particular for visualization and VR applications.

Many discussions are opened on which approach and methodology is better in which situation. Indeed image-based modeling needs some experience in the acquisition and data processing and still some manual interaction while range-based modeling requires large budgets and editing time and is unpractical in some field campaigns. Furthermore an actual deficit of most of the active sensors is the lack of texture information, which are generally acquired with a separate digital camera and afterwards registered onto the range data for texture mapping purposes. Remondino et al. [2008] showed that, in many terrestrial applications, image-based modeling and active sensors can reach very similar results in terms of accuracy, but in a fraction of time and costs using images. Indeed photogrammetric image matching is nowadays able to retrieve dense surface model with all the small details without neglecting precision and reliability of the results. Using advanced algorithms, dense point clouds of complex and free-form objects can be almost automatically retrieved. This is possible combining feature-based and area-based matching algorithms in order to obtain a detailed 3D reconstruction. Therefore we can safely say that with the appropriate surface modeler algorithm there are no differences between image- or range-based approaches and that the aspect that is no more decisive in the choice of the modeling technique is the accuracy and details of the final 3D model, at least in most of the terrestrial applications. Typical factors still involved in the choice of the technology are the costs, ease of use, portability and usability, experience of the operator, location constraints, object dimensions and final goal of the 3D modeling.

Nevertheless, to achieve a good 3D model of complex structures or sites, that respects the required level of detail, the better way is still the combination of different techniques. In fact as a single technique is not able to give satisfactory results in all situations, concerning high geometric accuracy, portability, automation, photo-realism and low costs as well as flexibility and efficiency, image and range data are generally combined [El-Hakim et al. 2004; El-Hakim et al., 2007].

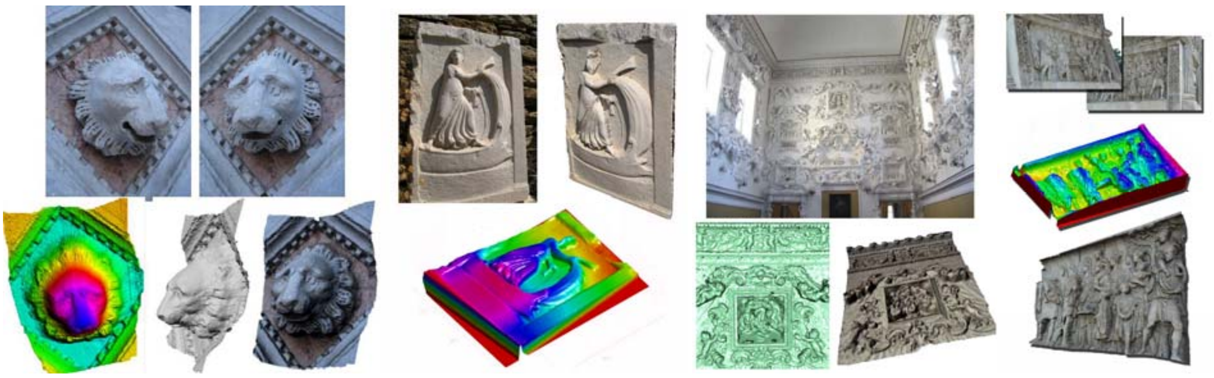

Figure 1: Typical terrestrial heritages modeled using dense surface measurements from sets of close-range images.

In this contribution we firstly review the methods for surface measurement from (terrestrial) images based on matching techniques. We assume the camera fully calibrated and the images oriented with sub-pixel accuracy. We do not consider reconstruction methods based on the visual hull, factorization methods, shape from shading or contours or texture. Then we report some tests performed with different commercial and research packages to generate 3D models of close-range heritages. The tests try to investigate all the actual problems in correlation and surface measurement from convergent terrestrial images. We report advantages and disadvantages of the existing approaches and describe an ideal procedure for surface modeling in terrestrial photogrammetry.

1.1 Towards standards in digital documentation and 3D modeling

“It is essential that the principles guiding the preservation and restoration of ancient buildings should be agreed and be laid down on an international basis, with each country being responsible for applying the plan within the framework of its own culture and traditions” [The Venice Charter, 1964 i.e. The International Charter for the Conservation and Restoration of Monuments and Sites]. Even if this was stated more than 40 years ago, the need for a clear, rationale, standardized terminology and methodology, as well as an accepted professional principles and technique for interpretation, presentation, digital documentation and presentation is still evident. Furthermore “Preservation of the digital heritage requires sustained efforts on the part of governments, creators, publishers, relevant industries and heritage institutions. In the face of the current digital divide, it is necessary to reinforce international cooperation and solidarity to enable all countries to ensure creation, dissemination, preservation and continued accessibility of their digital heritage” [UNESCO Charter on the Preservation of the Digital Heritage, 2003]. Therefore, although digitally recorded and modeled, our heritages require more international collaborations and information sharing to digitally preserve them and make them accessible in all the possible forms and to all the possible users and clients.

From a more technical side, we have seen in the last decades many image-based modeling packages and range-based systems coming out on the market to allow the digital documentation and 3D modeling of objects or scenes. Many new users are approaching these methodologies and those who are not really familiar with them need clear statements and information to know if a package or system satisfies certain requirements before investing. Therefore technical standards for the 3D imaging field must be created, like those available for the traditional surveying or CMM. A part from standards, comparative data and best practices are also needed, to show not only advantages but also limitations of systems and software. In these respects, the German VDI/VDE 2634 contains acceptance testing and monitoring procedures for evaluating the accuracy of close-range optical 3D vision systems (particularly for full-frame range cameras and single scan). The American Society for Testing and Materials (ASTM) with its E57 standards committee is trying to develop standards for 3D imaging systems for applications like surveying, preservation, construction, etc. The International Association for Pattern Recognition (IAPR) created the Technical Committee 19 - Computer Vision for Cultural Heritage Applications - with the goal of promoting Computer Vision Applications in Cultural Heritage and their integration in all aspects of IAPR activities. TC19 aims at stimulating the development of components (both hardware and software) that can be used by researchers in Cultural Heritage like archaeologists, art historians, curators and institutions like universities, museums and research organizations. NRC Canada [Beraldin et al., 2007] and the American NIST [Cheok et al., 2006] are evaluating the performances of 3D imaging systems within their facilities built to develop test protocols, performance metrics and hopefully derived standards.

As far as the presentation and visualization of the achieved 3D models concerns, the London Charter [2008; http://www.londoncharter.org/] is seeking to define the basic objectives and principles for the use of 3D visualisation methods in relation to intellectual integrity, reliability, transparency, documentation, standards, sustainability and access of Cultural Heritage.

2. SURFACE MEASUREMENT AND RECONSTRUCTION

The image-based measurement of an object’s surface is generally performed establishing correspondences between primitives extracted from two or more images (i.e. image matching). Those primitives correspondences are then converted into 3D information through a mathematical model (e.g. collinearity model or camera projection matrix). The problem of image correlation has been studied since more than 30 years but still many problems exist: complete automation, occlusions, poor or un-textured areas, repetitive structures, moving objects (including shadows), radiometric artifacts, capability of retrieving all the details, transparent objects, applicability to diverse camera configuration, etc. In the aerial and satellite photogrammetry the problems are limited and almost solved (a prove is the large amount of commercial software for automated image triangulation and DSM generation), whereas in terrestrial applications the major problems are related to the three-dimensional characteristics of the surveyed object and the often convergent or wide-baseline images. These configurations are generally hardly accepted by modules developed for DSM generation from aerial or satellites images.

Overviews on terrestrial stereo matching can be found in Scharstein and Szeliski [2002] and Brown et al. [2003], while Seitz et al. [2006] compared multi-view techniques (i.e. 3D reconstruction from multiple images and not only stereo-pairs). Image databases with ground truth results were also used, although they were not really examples similar to the daily heritage documentation, the objects were few cm big and the image resolution was very small (640x480 pixel).

There are mainly two main classes of matching primitives: (1) image intensity patterns (i.e. windows composed of grey values around a point of interest) and (2) features (i.e. edges or regions). According to these primitives, the resulting matching algorithms are generally respectively classified as area-based or feature-based matching. In its oldest form, area-based matching (ABM) involved 4 transformation parameters (cross-correlation) [Foerstner, 1982]. Further extensions considered a 6- and 8-parameters transformation, leading to the well known non-linear Least Squares Matching (LSM) estimation procedure [Gruen, 1985; Foerstner, 1986]. Gruen [1985], Gruen and Baltsavias [1986], Baltsavias [1991] introduced the Multi-Photo Geometrical Constraints (MPGC) into the image matching procedure, integrating also the surface reconstruction into the process. Goesele et al [2007] recently presented a reformulated version of the MPGC-based framework. ABM was also generalized from image to object space, introducing the concept of 'groundel' or 'surfel' [Helava, 1988]. ABM, especially the LSM method with its sub-pixel capability, has a very high accuracy potential (up to 1/50 pixel on well defined targets) if well textured image patches are used. Disadvantages of ABM are the need for small searching range for successful matching, the possible smooth results if too large image patches are used and, in case of LSM, the requirement of good initial values for the unknown parameters (although this is not the case for other techniques such as graph-cut [Scharstein and Szeliski, 2002]). Furthermore, matching problems (i.e. blunders) might occur in areas with occlusions, lack of or repetitive texture or if the surface does not correspond to the assumed model (e.g. planarity of the matched local surface patch).

On the other hand, feature-based matching (FBM) involves the extraction of features like points [Mikolajczyk and Schmid, 2005; Remondino, 2006], edges [Ziou and Tabbone, 1998; Schmid and Zisserman, 2000] or regions [Mikolajczyk et al., 2005]. Features are first extracted and afterwards associated with attributes ('descriptors') to characterize and match them [Vosselman, 1992; Gruen and Li, 1996; Schmid and Zisserman, 2000; Mikolajczyk and Schmid, 2005]. A typical strategy to match characterized features is the computation of similarity measures from the associated attributes. Larger (or global) features are called structures and are usually composed of different local features. Matching with global features is also referred to as *relational* or *structural matching* [Wang, 1998]. FBM is often used as alternative or combined with ABM. Compared to ABM, FBM techniques are more flexible with respect to surface discontinuities, less sensitive to image noise and require less approximate values. The accuracy of the feature-based matching is limited by the accuracy of the feature extraction process. Moreover, due to the sparse and irregularly distributed nature of the extracted features, the FBM results are in general sparse point clouds and post-processing procedures like interpolation need to be performed. Therefore the combination of ABM and FBM is the best choice.

Once the object's surface has been measured from two or more images and a 3D point cloud is produced, a polygonal model (mesh) is usually generated to produce the best digital representation of the surveyed object or scene. Afterwards texture-mapping is performed for a photo-realistic visualization of the 3D results.

For Cultural Heritage objects like those shown in Figure 1, we can safely said that, in order to capture information needed for a digital 3D documentation, conservation or physical replica and based on the current state of the available technologies, the resolution of the 3D reconstruction in most parts must be around 1-2 mm while the accuracy should be 0.5 mm or better.

	SOCET SET ATE / NGATE	**TOPCON PI3000**	**SAT-PP**	**ARC-3D**
Image pyramids	yes	no	yes	no
Automated tie point extraction in the orientation phase	yes[1]	no	no	yes
GCPs required for the orientation	yes	no	no	no
Image-correlation with Least Squares Matching	yes	yes	yes	no
Stereo matching	yes	yes	yes	yes
Multi-photo matching [2]	no	no	yes	no
Area-based matching	yes	yes	yes	yes
Feature-based (edge) matching	no / yes	no	yes	no
Adaptive matching parameters	yes	yes	yes	yes
Z axis [3]	yes	no	yes	no
Masking region of interest [4]	no	yes	yes	yes
Stereo view for measurements and results inspection	yes	no	yes	no

1) The function for automated tie point extraction works only with aerial images. In our tests did not work using convergent terrestrial images.
2) More than 2 images simultaneously matched with a geometrical constraint.
3) If the Z axis (depth) must be always almost parallel to the optical axis of the camera.
4) Segmentation of foreground / background

Table 1: Commercial and research packages for surface measurement tested with different sets of terrestrial images.

3. COMMERCIAL AND RESEARCH PACKAGES

Two commercial packages (BAE Systems *SOCET SET* and Topcon *PI-3000*) and two research software (*SAT-PP* and *ARC3D*) were tested and evaluated using terrestrial convergent images. The main features and characteristics of those packages are summarized in Table 1. Research works with the mentioned commercial software are reported respectively in [Zhang et al., 2006; Menna and Troisi, 2007] and [Kadobayashi et al., 2004; Chandler et al., 2007]. The Topcon software was available only in demo version, so no 3D model could be exported and no results will be shown. The software works using epipolar images, generated once the images have been manually oriented and it produces a TIN surfaces from stereo pairs. Other commercial packages, developed for the DTM generation from aerial images (frame and line sensors) and from various types of satellite imagery are ERDAS *LPS*, Z/I *ImageStation*, Inpho *MATCH-T* and SimActive *Correlator3D*. Recently PhotoModeler (generally used for terrestrial and architectural applications) released a new version, called PhotoModeler Scanner, which seems to be able to perform dense reconstruction from stereo-pairs. All these packages were not tested in our work.

The two mentioned research packages are briefly presented in the next sections.

3.1.1 SAT-PP

The ETH image matching package was designed for the automated surface measurement from high-resolution linear array sensor images [Zhang and Gruen, 2004; Zhang, 2005] and afterwards adapted to process image data such as the traditional aerial photos or convergent close-range images [Remondino and Zhang, 2006; Lambers et al., 2007; Remondino et al., 2008]. *SAT-PP* features a multi-image approach, based on the Multi-Photo Geometrically Constrained (MPCG) Least Squares Matching (LSM) framework of Gruen [1985], Gruen and Baltsavias [1988] and Baltsavias [1991]. It uses a coarse-to-fine hierarchical solution with an effective combination of several image primitives (interest points, edges and grid points), image matching algorithms (Geometrically Constrained Cross-Correlation technique, MPCG LSM and Least Squares B-Spline Snakes) and automatic quality control. The method, taking advantage of both area- and feature-based matching techniques, uses local and global image information and, exploiting the multi-image concept, obtains highly redundant and reliable matching results.

3.1.2 ARC 3D WebService

ARC 3D (homes.esat.kuleuven.be/~visit3d/webservice/v2/) [Vergauwen and Van Gool, 2006] is a group of free tools which allow users to upload digital images to a server where a 3D reconstruction is performed and the output reported back to the user in few hours. *ARC 3D* also provides a tool for producing and visualising the 3D scene using the data computed on the servers. The uploaded images can be sub-sampled before uploading for a faster service. *ARC 3D* computes the reconstruction over a distributed network of PCs and depending on size, number and quality of the images that have been uploaded, a typical job may take from 15 minutes to 2 or 3 hours. If the reconstruction has been successful, the system notifies the user by email and the data can be downloaded and used with the model viewer tool. The system is fully automated therefore its success is strongly related to the input images. A minimum of 5-6 images is required and the angle between them should be quite small. The scene should not be planar otherwise the system will not work. The focal length should be constant and no rotations between the images should be present.

MeshLab (http://meshlab.sourceforge.net/), an open source tool developed by the CNR-ISTI in Pisa (Italy) for the processing and editing of unstructured 3D triangular meshes, is also recommended for the visualization of the 3D results of *ARC 3D*.

4. EXAMPLES AND PERFORMANCE ANALYSIS

We acquired different sets of images, at different resolution and scale (Table 2), using previously calibrated digital cameras.

	Numb of images	Image resolution	Scale Number	GSD [mm]
Venice	3	5 MP	550	14
Edzna	9	3 MP	850	3.3
Dresden	6	6 MP	300	0.6
Stone	3	6 MP	215	0.4
Bern	7	7 MP	125	0.3
Eye	4	7 MP	6	0.015

Table 2: Used data sets and relative characteristics.

The DSMs generated with the different packages (*Socet-Set NGATE* and *ATE*, *SAT-PP* and *ARC 3D*) are shown in Figure 2-7. All the data sets were oriented with sub-pixel accuracy using a relative orientation approach and scaling the results with a known distance. As in *SOCET SET* is not possible to orient a set of images without control, the exterior orientation parameters obtained in other software were manually imported. As *ARC 3D* performs automatically the entire modeling pipeline, we could not control the calibration and orientation phases and we often obtained results which were not correctly scaled and easily comparable with other models. Furthermore, no accuracy output is provided by *ARC 3D*.

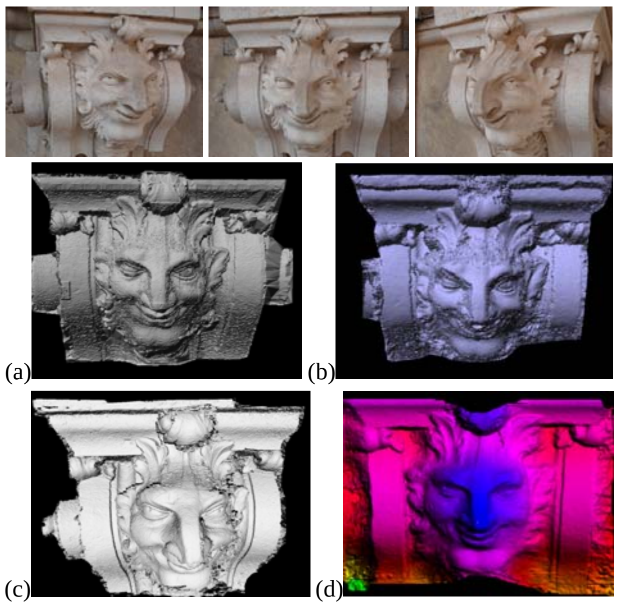

Figure 2: The Dresden face and 3D models coming from NGATE (a), ATE (b), ARC 3D (c) and SAT-PP (d). Some noise in the final smooth-shaded models is not visible in the reported snapshots.

Socet Set NGATE matcher, although very slow, improved a lot its results compared to the *ATE* version, in particular in getting less smooth surfaces, less blunders (see the 'Venice' results) and using also a features-based matching. It still works on a stereo-pair approach but provides a final 2.5D surface model automatically derived by joining all the pairs point clouds.

ARC 3D seems to be quite powerful, despite many problems encountered in converting its v3d output format in a complete high-resolution 3D model, in particular with *MeshLab*. Much experience with these free modeling tools is really required to fully exploit their potentialities and understand their limitations. In *ARC 3D* each image provides a separate depth map which has then to be joined with the others. Therefore in the overlapping areas many blunders and useless triangles are present, which should be removed with heavy and long post-processing operations. Furthermore very short baseline images seem to be really necessary to avoid gaps in the final model and help the stereo-pair approach. Due to its fully automated approach, the images should be acquired with some rules that do not give much freedom in particular in heritage areas with difficulties in moving around. The system showed also problems in modeling planar objects, due to the auto-calibration function. In some of our tests, the *ARC 3D* models were not correctly scaled compared to the 3D results generated using images oriented with a photogrammetric bundle adjustment. This fact raised many problems in the comparisons of the 3D models coming from the different packages.

SAT-PP, although not yet fully automated, has different advantages, also visible in the obtained 3D models. The multi-photo method gives more precise and reliable results and allows the use of convergent images while the grid method helps in low-texture areas.

Except SAT-PP, the packages showed problems in un-textured areas. Therefore advanced image pre-processing techniques are really necessary (Sat-PP uses Wallis filter) to enhance the image data and reduce the noise. In modern cameras, often sharpening functions are applied to make the image visually more appealing. However this can increase the image noise and introduces edge artefacts, both negative for automated image-based measurements.

For the data set "Eye", range data acquired with a Breuckmann Opto-Top SE stripe projection system (50 μm feature accuracy) were at our disposal. The different DSMs were compared with the reference one using Polyworks IMAlign (Figure 4). A first rough alignment between the DSMs was carried out by using the N-Point Pairs procedure which uses a similarity transformation without scale factor. Supposing this alignment as a good approximation of the best one, a successive "Best Fit Alignment" procedure based on ICP (Iterative Closest Point) was used. In this step, the software minimizes the differences between the two meshes within a "maximum distance" and provides a standard deviation as result of the minimization. For all the employed packages, a standard deviation of 0.03 mm was achieved. This is a promising result, although many more tests must be done and a standard procedure is really required. Indeed there is no standard procedure to compare 3D results in form of dense point clouds or meshes. For 2.5D models the measurement of the deviations is generally based on the orthogonal or shortest distance. For complete 3D models it is much more complicated. We have no defined rules yet to do the comparisons, so most of the judgements still come from visual inspections of the results or 'best fit' functions which do not give a clear statement about the "winner". Moreover a true reference dataset is generally required and it is not always available in the heritage field. Commercial reverse engineering and modeling packages (e.g. Polyworks, Geomagic, RapidForm, etc) have functions for comparing meshes or point clouds. They are mainly based on the ICP algorithm for the data registration and alignment. If differences in the scale of the model are present, they might not be correctly compensated. This would be reflected in wrong comparison results. For these reasons and due to the missing of standard methodologies, only one comparison has been reported (Figure 4). Different problems were indeed encountered in comparing the meshes. Furthermore, the different packages used for the 3D comparison, gave different results.

Research works and free packages related to mesh comparison have been presented in [Cignoni et al., 1998; Roy et al., 2004; Silva et al., 2005].

5. CONCLUSIONS

The surface measurement and reconstruction problem using terrestrial images as input data source has been discussed and reported in this contribution. Due to the paper's limitation in space, the graphical results are reported probably with too small pictures, limiting the reader's interpretation and judgment of the models. Indeed noise and gaps in the surface models are not clearly visible although present in some models.

Nowadays different packages are available on the market and many more are probably lying inside research institutes. The obtained results are promising, even if the reliable and precise processing of convergent terrestrial images is still behind its potentialities. But even if many 3D modeling technologies are nowadays available, we lack a reliable and standard procedure to perform the 3D comparison and provide clearer results of the inspection. Furthermore, comparative data and best practices are also needed. In our comparisons, the differences between the models were mainly located close to large depth discontinuities and due to smoothing effects of the automated matching procedures. Indeed too large matching patches can smooth out small features, resulting in smoothed surface models. *Socet Set ATE* and *ARC 3D* seem to provide 3D results more noisy compared to *NGATE* and *SAT-PP*. In any case more tests and comparisons are necessary to draw a clearer statement about the state of the art of automated surface measurement in terrestrial applications.

From the experience gained, we can say that a successful image matcher and surface measurement approach should (1) use accurately calibrated cameras and images with strong geometric configuration, (2) use local and global image information, to extract all the possible matching candidates and get global consistency among the matching candidates, (3) use constraints to restrict the search space, (4) consider an estimated shape of the object as a priori information and (5) employ strategies to monitor the matching results.

REFERENCES

Baltsavias, E.P., 1991: Multi-Photo geometrically constrained matching. PhD Thesis, Institute of Geodesy and Photogrammetry, ETH Zurich, Switzerland, 221 pages

Beraldin, J.-A., Rioux, M., Cournoyer, L., Blais, F., Picard, M., Pekelsky, J., 2007: Traceable 3D Imaging Metrology. Videometrics IX, SPIE Electronic Imaging, Vol. 6491, pp. B.1-11

Blais, F., 2004: A review of 20 years of Range Sensors Development. Journal of Electronic Imaging, 13(1): 231-240

Brown, M. Z., Burschka, D., Hager, G. D., 2003: Advance in computational stereo. IEEE Trans. PAMI, 25(8), pp. 993-1008

Chandler, J., Bryan, P., Fryer, J., 2007: The development and application of a simple methodology for recording rock art using consumer-grade digital cameras. Photogrammetric Record, 22(117), pp. 10-21

Cheok, G., Lytle, A., Saidi, K. 2006: Status of the NIST 3D imaging system performance evaluation facility. Proc. of SPIE Defence and Security Symposium, Orlando, FL

Cignoni, P., Rocchini, C., Scopigno, R., 1998: Metro: measuring error on simplified surfaces. Computer Graphics Forum, Blackwell Publishers, vol. 17(2), pp 167-174

El-Hakim, S.F., Beraldin, J.A., Picard, M. and Godin, G., 2004: Detailed 3D reconstruction of large-scale heritage sites with integrated techniques. IEEE Computer Graphics and Application, 24(3): 21-29

El-Hakim, S., Gonzo, L., Voltolini, F., Girardi, S., Rizzi, A., Remondino, F., Whiting, E., 2007: Detailed 3D modeling of castles. Int. Journal of Architectural Computing, 5(2), pp. 199-220

Foerstner, W., 1982: On the geometric precision of digital correlation. International Archives of Photogrammetry, 24(3), pp.176-189

Foerstner, W., 1986: A feature based correspondence algorithm for image matching. International Archives of Photogrammetry, 26(3), Rovaniemi

Goesele, M., Snavely, N., Curless, B., Hoppe, H., Seitz, S.M., 2007: Multi-view stereo for community photo collections. ICCV 2007, Rio de Janeiro, Brasil

Gruen, A., 1985: Adaptive least square correlation: a powerful image matching technique. South African Journal of PRS and Cartography, 14(3), pp. 175-187

Gruen, A., Baltsavias, E., 1986: Adaptive least squares correlations with geometrical constraints. Proc. of SPIE, Vol. 595, pp. 72-82

Gruen, A., Li, H., 1996: Linear feature extraction with LSB-Snakes from multiple images. IAPRS, 31(B3), pp. 266-272

Helava, U.V., 1988: Object-space least-squares correlation. PE&RS, 54(6), pp. 711-714

Kadobayashi, R., Kochi, N., Otani, H., Furukawa, R., 2004: Comparison and evaluation of laser scanning and photogrammetry and their combined use for digital recording of cultural heritage. IAPRS&SIS, 35(5), pp. 401-406

Lambers, K., Eisenbeiss, H., Sauerbier, M., Kupferschmidt, D. Gaisecker, T., Sotoodeh, S., Hanusch, T., 2007: Combining photogrammetry and laser scanning for the recording and modelling of the Late Intermediate Period site of Pinchango Alto, Palpa, Peru. Journal of Archaeological Science, 34

Menna, F., Troisi, S., 2007: Photogrammetric 3D modelling of a boat's hull. Proc. of Optical 3-D Measurement Techniques VIII, July 9-12, 2007, Zurich, Vol. II, pp. 347-354

Mikolajczyk, K., Schmid, C., 2005: A performance evaluation of local descriptors. IEEE Trans. PAMI, 27(10), pp.1615-1630

Mikolajczyk, K. Tuytelaars, T., Schmid, C., Zisserman, A., Matas, J., Schaffalitzky, F., Kadir, T. and Van Gool, L. 2005: A comparison of affine region detectors. International Journal of Computer Vision, 65(1/2), pp. 43-72

Remondino, F., 2006: Detectors and descriptors for photogrammetric applications. IAPRS&SIS, 36(3), pp. 49-54

Remondino, F., El-Hakim, S., 2006: Image-based 3D modelling: a review. Photogrammetric Record, 21(115), pp. 269-291

Remondino, F., Zhang, L., 2006: Surface reconstruction algorithms for detailed close-range object modeling. IAPRS&SIS, 36(3), pp. 117-121

Remondino, F., El-Hakim, S., Gruen, A., Zhang, L., 2008: Development and performance analysis of image matching for detailed surface reconstruction of heritage objects. IEEE Signal Processing Magazine, (in press)

Roy, M., Foufou, S., Truchetet, F., 2004: Mesh comparison using attribute deviation metric. International Journal of Image and Graphics (IJIG), 4 (1), pp. 127-140

Scharstein, D., Szeliski, R., 2002: A taxonomy and evaluation of dense two-frame stereo correspondence algorithms. IJCV, 47(1/2/3): 7-42

Schmid, C., Zisserman, A., 2000: The geometry and matching of lines and curves over multiple views. International Journal of Computer Vision, 40(3), pp. 199-233

Seitz, S.M., Curless, B., Diebel, J., Scharstein, D., Szeliski, R., 2006: A comparison and evaluation of multi-view stereo reconstruction algorithm. CVPR, pp.519-528

Silva, S., Madeira, J. Santos, B.S., 2005: PolyMeCo - A polygonal mesh comparison tool. Proc. 9th International Conference on Information Visualization (IV05), IEEE Computer Science Society, pp. 842-847, London

Vergauwen, M., Van Gool, L., 2006: Web-based 3D reconstruction service, Machine vision and applications, 17(6) p. 411-426

Vosselman, G., 1992: Relational matching. Lecture Notes in Computer Science, No. 628, Springer Berlin, 190 pages

Wang, Y., 1998: Principles and applications of structural image matching. Journal of Photogrammetry and Remote Sensing, 53(3), pp. 154-165

Zhang, B., Miller, S., De Venecia, K., Walker, S., 2006: Automatic terrain extraction using multiple image pair and back matching. Proc. ASPRS Annual Conference, Reno, USA

Zhang, L., Gruen, A., 2004: Automatic DSM generation from linear array imagery data. IAPRS&SIS, 35(3), pp. 128-133

Zhang, L., 2005: Automatic Digital Surface Model (DSM) generation from linear array images. PhD Thesis Nr. 90, Institute of Geodesy and Photogrammetry, ETH Zurich, Switzerland, 199 pages

Ziou, D., Tabbone, S., 1998: Edge detection techniques - an overview. Journal of Pattern Recognition and Image Analysis. Vol. 8, pp. 537-559

Figure 3: Stone example, modeled from 3 images: results respectively from NGATE, ATE, ARC 3D and SAT-PP.

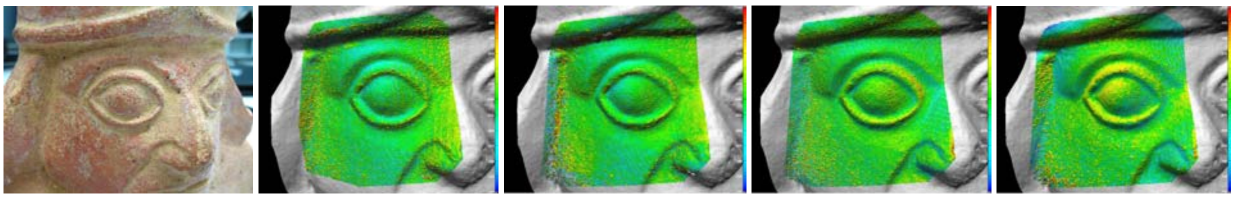

Figure 4: Eye example (area of ca 3x3 cm): results of the comparison between the range data and the image-based results (NGATE, ATE, ARC 3D, and SAT-PP respectively). The colour legends on the right of each picture show differences between + 0.15mm and – 0.15mm.

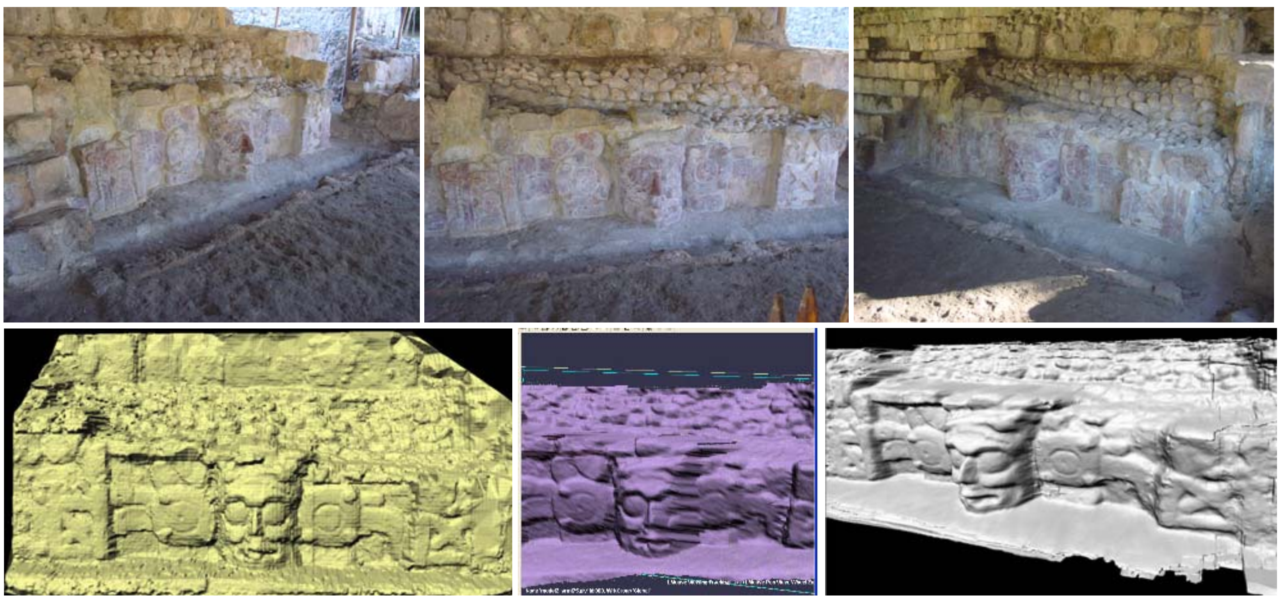

Figure 5: The Edzna bass-relief and the surface measurement and reconstruction results derived in NGATE, ARC 3D and SAT-PP respectively.

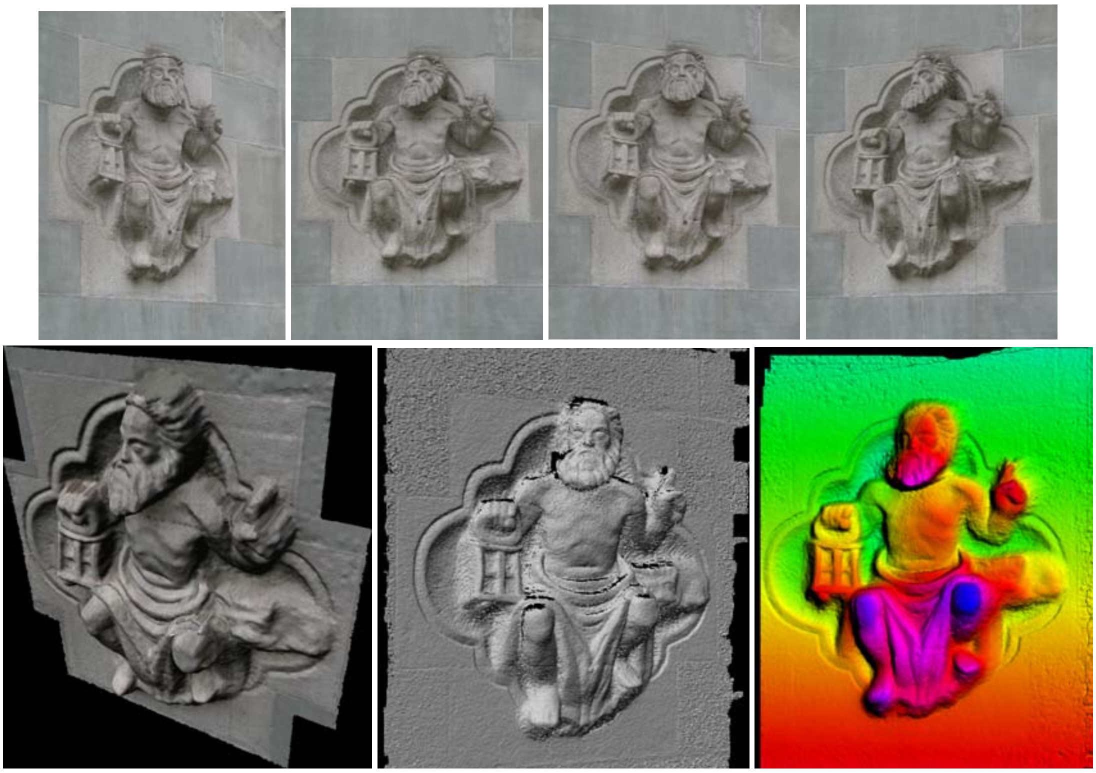

Figure 6: Bern relief (7 images) and relative surface models achieved in NGATE, ARC 3D and SAT-PP.

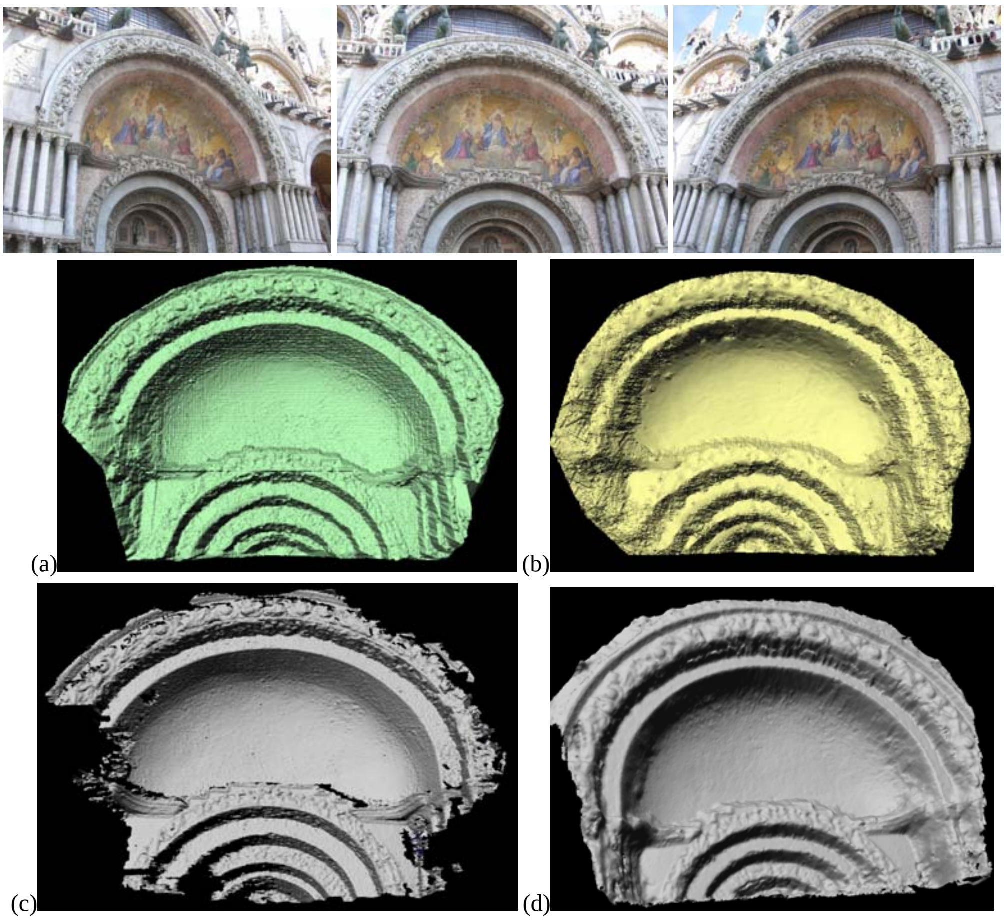

Figure 7: Venice portal, modeled with 3 very convergent images: results from NGATE (a), ATE (b), ARC 3D (c) and SAT-PP (d). ATE presents a quite smooth and noisy surface model compared to the other results. ARC 3D ended with some gaps in the final model. Great experience to correctly tune the different parameters of the tools is really required.