Improvement of Metric Accuracy of Digital 3D Models through Digital Photogrammetry. A Case Study: Donatello's Maddalena

Beraldin, Jean-Angelo; Guidi, G.; Ciofi, S.; Atzeni, C.

National Research Council Canada
Conseil national de recherches Canada

Institute for Information Technology
Institut de technologie de l'information

Improvement of metric accuracy of digital 3D models through digital photogrammetry. A case study: Donatello's Maddelena.

Beraldin, J.-A., Guidi, G., Ciofi, S., and Atzeni, C.
June 2002

* IEEE Proceedings of the International Symposium on 3D Data Processing Visualization and Transmission (3DPVT 2002), Padova, Italy. June 19-21, 2002. NRC 44911.

Improvement of Metric Accuracy of Digital 3D Models through Digital Photogrammetry. A Case Study: Donatello's Maddalena

J. -A. Beraldin[1], G. Guidi[2], S. Ciofi[2] and C. Atzeni[2]
[1]*National Research Council Canada, IIT, Ottawa, Ont., Canada*
[2]*Università degli Studi di Firenze, DET, Florence, Italy*
angelo.beraldin@nrc.ca

Abstract

In spite of an undoubted richness of information produced by 3D optical technologies, in some cases, the method for generating a digital model from single 3D acquisitions involves the propagation of errors. These errors limit the overall metric accuracy attainable with such procedure. This happens when small 3D images are assembled together in order to model a large object. The authors present a procedure by which the metric reliability of the 3D model, obtained through iterative alignments of single range maps, can be guaranteed to an acceptable level. For this purpose, non-impeding optical targets were specifically designed for placement around the object. These are measured using a close range digital photogrammetry technique and by the 3D range camera system. From these measurements, transformation matrices have been calculated. Each matrix allows for the roto-translation (pose) of the 3D images from the local coordinate system of the range camera to an accurate global coordinate system determined by the digital photogrammetric procedure.

1. Introduction

Non-contact 3D optical measurement techniques like those based on laser or on structured light projection have found wide spread use in industrial metrology and reverse engineering. Such technologies attempt to structure the environment through artificial light projection means. The results are dense range maps extracted from visible surfaces that are rather featureless to the naked eye [1]. In the field of cultural heritage preservation and diffusion, on-site and complete 3D documentation is necessary in situations where objects and/or environments can't be moved or their access is restricted [2]. The NRC of Canada, the University of Florence and the Opera del Duomo in Florence have agreed to carry out a cooperative program in the field of digital three-dimensional (3D) imaging applied to Cultural Heritage. The first work of art selected is an important wooden sculpture by Donatello, the Maddalena (circa 1446-1450) that is about 180 cm tall. This artwork is characterized by a highly complex surface with some portions of it not easily accessible, and, a surface texture that is composed of highlights and very dark areas. Centuries have left an indelible mark on this statue since it has lost its original golden layer. Furthermore, the 3D acquisitions had to be carried out in a relatively short time frame, i.e. in a matter of a few days [3]. Since a global methodology is critical for obtaining high-quality reconstruction of 3D models from range imagery, a sensor fusion approach is proposed, in order to solve accuracy problems. The integration is based on accurate but low cost digital close range photogrammetry as a "global reference" for the 3D model and a procedure for repositioning some key range maps is that global reference system.

2. Range camera

The range camera used in this work is based on optical triangulation with fringe pattern projection and is produced by Optonet Srl, Italy. Similar projection systems are described in the literature [4]. The main components of this system are a LCD pattern projector, a 576x768 CCD camera, multiple camera lenses (FOV dependent), a variable baseline support, and a calibration fixture. Depending on the type of surface imaged (small or large), the field of view and accuracy of the 3D camera are reconfigured. This process allows one to adapt the modeling process to different situations found on the field. Verification objects are used to check the accuracy of any given measurement session.

3. Acquisition strategy

Since the goal of this work was to obtain a high-resolution 3D representation of the sculpture by Donatello, a preliminary survey established a lateral resolution of 0.25 mm as optimal for capturing all the sculpture important details. The range camera CCD sensor gave a field of view of 192 mm (0.25 mm x 768) in width and 144 mm in height (0.25 mm x 576). With such small area the full height of the statue would have been covered with a very large number of images (>500) and thus would have made error propagation in the alignment phase a major problem not counting the problem of missing data. In order to solve these important problems, it was decided to follow a double step strategy:

Step 1: acquisition of the whole statue at twice the optimal lateral resolution (i.e. 0.5 mm) with a consequent framed area 4 times the previous one (384x288 mm). The full coverage of the whole surface was reached in this way with less than 200 images that were easily aligned to generate a reference;

Step 2: acquisition at the optimal resolution of all the surfaces already acquired but too rich of details to be properly represented with a 0.5 mm resolution, and of all those areas not covered in the previous step.

The small images were then aligned over the reference, and finally most of the low-resolution images were deleted leaving only those not re-acquired at higher resolution. In this way, the total number of range maps was limited to 384.

Despite this optimized procedure some residual errors held, due to the peculiar nature of the sculpture. In particular, during the two phases it was noticed that the complex shape of the surface to be acquired involved heavy shadowing effects; each range map was therefore not as dense as in a more conventional application; the dark wooden surface forced us to use a scanner set-up giving range maps noisier than usual; some sections of the statue (e.g. the legs) were characterized by small and locally flat surfaces more difficult to align with respect to other parts. For these reasons and after completing the model, the 3D model was submitted to further measurements in order to check the actual effects of all the aforementioned problems.

4. Model accuracy survey

Numerous tests have been performed at NRC Canada over the years that validate this procedure on closed objects like sculptures using NRC 3D range cameras [1, 2]. Close range photogrammetry techniques can yield very accurate measurement (up to 1 part over 100000) on well-defined feature points [5]. This means that over the full statue height 0.2 mm of overall measurement error could be expected. On the other hand, the point clouds acquired with the range camera had approximately 0.1 mm of measurement uncertainty involving a potential alignment error between adjacent range maps of the same order. Since it was planned to do approximately 20 passages around the statue in order to cover its full height, a potential error of 20 x 0.1 mm = 2mm, was expected. Giving an overall uncertainty more than 10 times lower, photogrammetry was chosen as reference measurement system. In the first survey, fully reported in [6], several test distances were measured both on the digital model and through classical photogrammetry based on a metric camera, revealing some dimensional errors. The main deviations between photogrammetry and 3D model are synthesized in Table 1. This survey has shown that the height of the model (d_1, d_2, d_3) and the distance between the knees (d_{12}), are not correct. Quasi-planar surfaces in some areas of the statue, led to misalignment and hence cumulative error as seen by distances (d_1, d_2, d_3). The distance between the knees (d_{12}), that on the 3D model is wider than in the reference, is probably due to the lack of locking surfaces in that part of the statue, where the two thin legs are separately aligned starting from the upper unique block. In conclusion, although optical 3D with a projection system gives high local accuracy, the registration of different range maps led to large errors on the final 3D model depending on the nature of the surface, or on the lack of points on image overlaps due to the impossibility to access some surface portions.

Table 1. Absolute distances and their differences, obtained from photogrammetry and 3D model (mm)

	Photogrammetry	3D Model	Δ
d_1	1267.0	1236.6	3.4
d_2	1643.0	1638.8	4.2
d_3	1272.5	1270.8	1.7
d_{12}	258.3	262.6	-4.3

5. Integration of digital photogrammetry and 3D scanning

The next goal was to refine the procedure by using the results of digital photogrammetry to lock the 3D images into place so automatic alignment becomes more accurate. The basic idea is to measure spatial coordinates of some calibrated targets located near the surface to be modeled, with both 3D scanning and photogrammetry. Typically 3D range cameras supply small range maps representing a detail of the object to be modeled, while photogrammetry can measure the whole object with the use of large image sensors and large baselines. In the latter case the measured coordinates lie all in the same reference system defined by the digital photogrammetry procedure with an estimated error that, as mentioned above, in our case could be lower than 0.2 mm. The minimum number of points to univocally calculate a roto-translation (pose) of the range-map are of course three, but in this way the possible errors affecting the roto-translation matrix would be directly influenced by the uncertainty of each point measured in both the source and destination reference system. By properly choosing a larger number of points to be employed for calculating the roto-translation, the uncorrelated errors tend to cancel each other, leaving only systematic errors, that can be minimized thanks to calibration. For this reason, a procedure has been developed which employs some specifically designed optical reference, capable of marking a number of points to be used in the roto-translation stage. These references consists of white plates with high planarity, printed with a set of 14 black circular targets 10 mm wide, spaced 40 mm each other. Before applying the procedure on the statue, a test set was arranged in our lab, with a “statue emulator” represented by a tailor’s dummy, 1600 mm tall and 600 mm wide. Four targeting plates, shown on Fig. 1 as **A, B, C** and **D**, were located around the object, in order to fix the position of 4 particular portion of the scanned surface. Such mannequin was first digitized with our fringe projector system. The range maps containing the targets were then processed with a Matlab® program that we developed, for evaluating 3D coordinates of each target centroid with sub-pixel resolution, in the coordinate system of the range map. A text file containing the centroid coordinates is the final output of this stage.

The digital photogrammetric process was then performed using a Minolta digital camera (DImage 7), capable of 2560x1920 pixel, and a commercial software (Shape Capture ver. 3.1 - Shape Quest Inc., Ontario, Canada). The program allows to calculate camera calibration with simple and well defined steps, with a calibration grid that the user can build of proper dimensions, taking into account the extension of the volume to be framed in order to measure the actual subject. The camera model used includes 6 external and 9 internal parameters. After calibration, a set of convergent digital pictures of the object taken from different angles can be registered by first selecting homologous points over them, and then launching a bundle adjustment procedure, as described in [7]. One of these images is represented in Figure 1. Once the images are registered, the 3D coordinates of specific points (the target centroids over each plate) can be easily generated and saved in a text file. A 3D plot of the resulting 3D coordinates in shown in Figure 2a. In order to have an intermediate check over photogrammetry a measurement of distances between adjacent targets was done on plates **A** and **D**, that were supposed to be 40 mm spaced apart. The average of measured values was 40.035 mm on plate **A** and 40.010 mm on plate **D**, with a standard deviation of 0.2 mm and 0.17 mm respectively. The next step was to calculate the roto-translation matrix from two sets of experimental data representing the same point coordinates measured in two different reference systems. For this purpose a few methods are available in the literature [8], essentially based on two alternative approaches: iterative search of the minimal distance between roto-translated source points and destination points; closed form solution not requiring iteration. In order to have a simple and fast processing we choose the second way. A script in the Matlab® environment was written, implementing a procedure based on Quaternions [9].

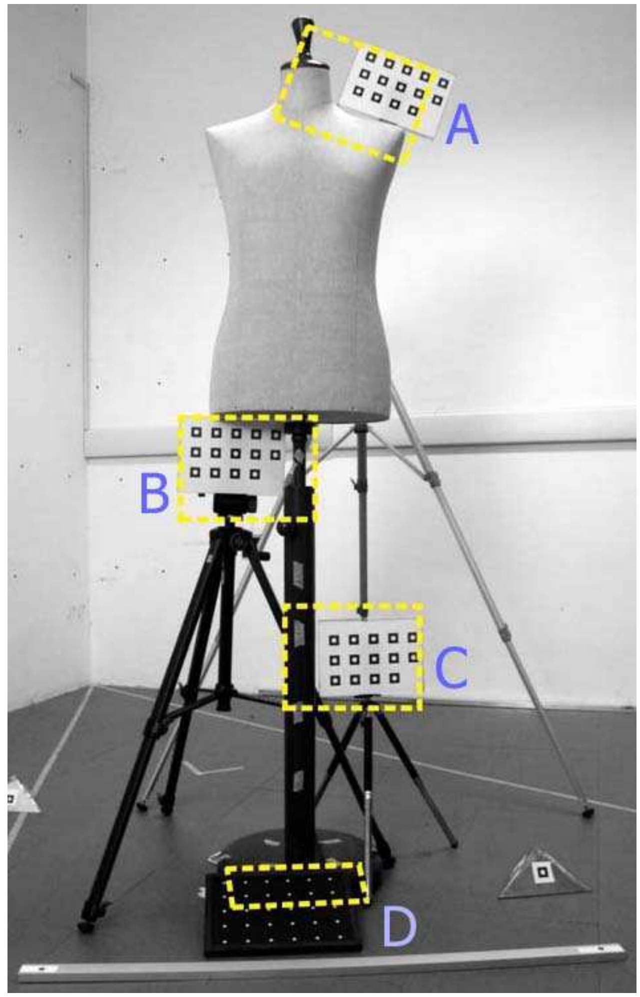
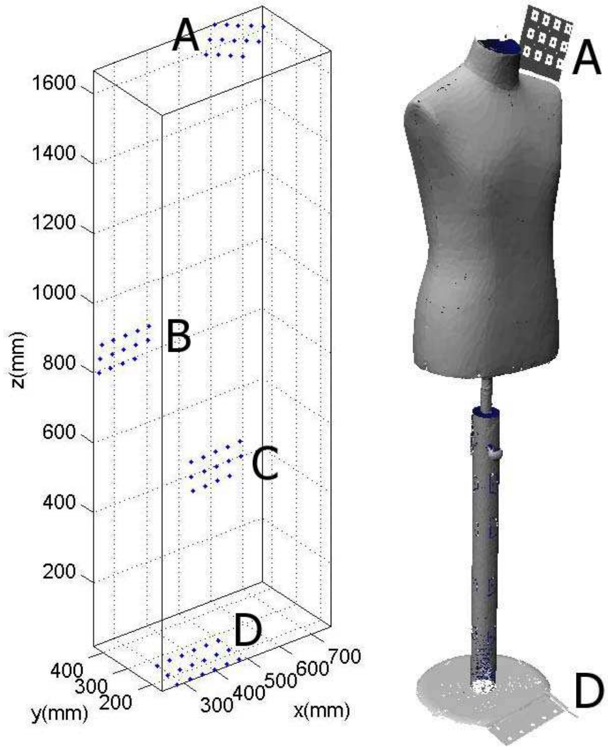


Figure 1. One of the images processed by the digital photogrammetry procedure. The dashed rectangles represent the position of targets’ 3D images.

The final stage of this process is the generation of a set of roto-translation matrices, one for each 3D image including the targeting plates, in a format compliant with the Polyworks™ software that was used for the final alignment. As a result, in Figure 2 it is shown the model of the mannequin, generated by aligning all the range maps to the roto-translated range maps of two plates **A** and **D**, locked in place during the iterative alignment stage.



a) b)

Figure 2. Model generation: a) results from photogrammetry; b) 3D model obtained by aligning all acquisitions to the locked range maps A and D, positioned by means of the procedure described in the paper.

5. Concluding remarks

After the modeling of the Maddalena by Donatello a photogrammetric survey demonstrated that the usual approach for creating 3D models from small range images hinders metric accuracy even when the single images are highly accurate. The results obtained demonstrate a practical approach to reduce the overall 3D model error by using digital photogrammetry to generate a set of spatial reference in a single coordinate system. Such references allow the translation and the rotation (pose) of some crucial portions of a surface in definite positions and lock them before the following procedure of iterative registration, typical of any 3D modeling platform. The level of accuracy that we have measured on a "photogrammetry driven" alignment may be one order of magnitude better than the alignment with no external reference, especially when hundreds of images are used to generate a 3D model, or when critical situation are encountered (e.g. lack of superposition between adjacent images due to physical constrains or flatness of properly superimposed surfaces). Models of large objects, structures and environments are possible but we are convinced that the combination of the current techniques with other methods that are being explored by our laboratories and others around the world will be required.

6. Acknowledgments

Special thanks go to Sabry El-Hakim from NRC for the many discussions regarding the application of digital photogrammetry technology. This work was in part financed by the Italian National Research Council (CNR) under program for short-term mobility 2001.

7. References

[1] M. Rioux, "Digital 3-D imaging: theory and applications", *SPIE Proceedings, Videometrics III, Int. Symposium on Photonic and Sensors and Controls for Commercial Applications*, Vol. 2350, Boston, MA. October 31 - November 4, 1994, pp. 2-15.

[2] J.M. Taylor and J-A. Beraldin, "Heritage Recording Applications of High Resolution 3D Imaging", *EVA Florence*, 2001, In press.

[3] G. Guidi, M. Pieraccini, S. Ciofi, V. Damato, J.-A. Beraldin, C. Atzeni, "Tridimensional digitizing of Donatello's Maddalena", Proceedings of the *IEEE International Conference on Image Processing (ICIP2001)*, Vol. 1, 2001, pp.578 -581

[4] G. Sansoni, M. Carocci, R. Rodella, "3D vision based on the combination of Gray code and phase shift light projection", *Applied Optics*, 38(31), 1999, pp. 6565-6573.

[5] C.S. Fraser, "Industrial measurement applications" in *Close range photogrammetry and machine vision*, K.B. Atkinson editor, Whittles Publishing, Scotland, 2001, pp. 329-361.

[6] G. Guidi, D. Ostuni, F. Costantino, M. Pieraccini, G. Tucci and J-A. Beraldin, "Photogrammetry and 3D scanning: Assessment of metric accuracy for the digital model of Danatello's Maddalena", *Proceedings of the 2001 Workshop of Italy-Canada on 3D Digital Imaging and Modeling Application of: Heritage, Industry, Medicine, & Land*, Padova, Italy. April 3-4, 2001. (on CD-ROM).

[7] S.-F. El-Hakim, J.-A. Beraldin, G. Godin, P. Boulanger, "Two 3-D Sensors for Environment Modeling and Virtual Reality: Calibration and Multi-view registration", *International Archives of Photogrammetry and Remote Sensing*, Volume 31, Part B5, Commission V, Vienna, Austria, July 9-19, 1996, pp. 140-146.

[8] P.R. Wolf, *Elements of Photogrammetry*, McGraw Hill, New York, 1974.

[9] B.K.P. Horn, "Closed-form solution of absolute orientation using unit quaternions", *J. Opt. Soc. Am. A*, Vol. 4, No. 4, 1987, pp. 629-642.