Tactile reproduction of paintings: the experience of the Department of Industrial Engineering of Florence

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Abstract. Within the T-VedO project, financed by Tuscany Region, the Reverse Engineering and Virtual Prototyping Lab team of the Department of Industrial Engineering of Florence (Italy) developed a number of methods for the semiautomatic generation of digital 2.5D models starting from paintings. Once such models are prototyped, they can be used to enhance visually impaired people tactile experience of artworks. Such methods, combined into a systematic procedure, allow to solve most of the typical problems arising when dealing with artistic representation of a painted scene. The present paper presents both an overview of the proposed procedure, including most recent updates, and the results obtained for a selected number of artworks of the Florentine Renaissance.

Key words: 3D Reconstruction; CAD; 2.5D models.

1. Introduction

Visually impaired and blind people are quite disadvantaged in enjoying artworks. These limitations can be easily overcome in the case of three-dimensional art pieces, by realizing tactile reproduction of statues or scale models of architectures, for instance by employing Reverse Engineering methods and 3D printing techniques. The translation of artworks into tactile models become impracticable when dealing with pictorial masterpieces, due to the lack of tools easily allowing the conversion of 2D images into 2.5D models.

On the basis of recent literature, a wide range of simplified tactile models can be built to provide visually impaired people with a faithful description of paintings [1, 2]. Among them, the use of 2.5D models has been demonstrated [3] as one of the most readable and meaningful for blinds, who perceive the bas-relief somehow faithful to their mental idea of the original artwork (described by an external guide).

The topic of 2.5D reconstruction starting from a single image is a long-standing issue in computer vision scientific literature and moves from the studies aiming at recovering 3D information from 2D pictures or photographs. Especially to represent complex scenes, in which more than one figure (i.e. human figures or objects) are displaced in a three-dimensional environment (e.g. architecture), the artist makes use two main stratagems to recreate the deepness-effect: perspective and shading. While a number of methods to obtain 2.5D models from perspective scenes are in literature [4, 5], an automatic method able to correctly convert shading information of a single image into 2.5D geometry doesn’t exist, due to concave-convex ambiguity (e.g. a solid sphere and a spherical hollow produce the same image). The most promising method is Shape From Shading (SFS), for which recent studies have proved that moderate user-interaction highly increases the performances in terms of results quality [6-10].
Among the wide variety of methods dealing with bas-relief reconstruction starting from 2D images, a number of effective approach have been proposed by authors within the T-VedO Project, financed by Tuscany Region [11-14]. Such methods, combined into a systematic procedure, allow to solve most of the typical problems arising when dealing with artistic representation of a painted scene. The present paper presents both an overview of the proposed procedure, including most recent updates, and the results obtained for a selected number of artworks of the Florentine Renaissance.

2. Method

With the purpose of providing a robust 2.5D reconstruction of the scene and of the figures reproduced in the painting, the following 5 step computer-based modelling procedure has been developed:

1. Preliminary image processing: this operation is made on a digital image of the painting and it’s devoted to a) image distortion correction, b) segmentation of the image by subjects and by colour, c) RGB to greyscale conversion of the image and d) albedo normalization of each colour segment.

2. Perspective scene reconstruction: this operation allows the reconstruction of the 2.5D virtual model of the scene, as a virtual flat-layered bas-relief. Mainly based on references [4, 11], but modelling also oblique planes, the procedure builds the framework on which subjects and objects are geometrically arranged by using perspective-related information (when available).

3. Volume reconstruction: this step allows the 2.5D reconstruction of the shape of each figure by exploiting shading related information of the image. In order to overcome incorrect shading issues, an approach based on SFS, image inflating and image embossing has been appositely devised [12].

4. Virtual bas-relief reconstruction: in this step, the definitive shape of the virtual bas-relief is retrieved by combining the results obtained in steps 2 and 3.

5. Rapid prototyping of the virtual bas-relief: in this step, the tactile model is 3D printed.

For sake of clarity, the description of each step will be described with reference to an exemplificative case study i.e. the reconstruction of “The Healing of the Cripple and the Raising of Tabitha” fresco by Masolino da Panicale (see Figure 1). This masterpiece is a typical example of Italian Renaissance paintings characterized by single-point perspective and is located in Brancacci Chapel (Church of Santa Maria del Carmine, Florence).

2.1. Preliminary image processing

The acquisition of the digital image \( I_0 \) of the painting to be reconstructed should be performed by means of proper photographic devices and illumination. Since the whole reconstruction process is based on this single input, the quality of the final result directly depends on the quality of the image. For this reason, the picture should be taken by using calibrated lenses and cameras, with a high resolution sensor. Referring to the case study used as example, a Canon EOS 6D camera (provided with a full-frame CMOS sensor with a resolution equal to 5472 x 3648 pixels) and a Canon EF 24-70mm f/2.8 L USM II calibrated lens have been used. The obtained image is then rectified in order to correct lens distortion [15].

Since both scene reconstruction and volumes definition are based on grey-scale information, the colour of such an image has to be discarded. This can be done by using any colour conversion tool available in any image processing software, such as Photoshop or Gimp. In this work, the grayscale image has been obtained by converting the image from sRGB to CIELAB colour space and by extracting \( L^* \) channel. Let’s call \( I_G \) the obtained image.
Successively, the different objects represented in the scene, such as human figures and architectural elements, are properly identified. This operation, called image segmentation, can be carried out by adopting one of the several methods available in literature (e.g. [16]). In the present work an interactive livewire boundary extraction algorithm has been used [17]. Let’s call the segmented image $I_S$.

In a greyscale image, as $I_G$, the grey value of each pixel (i.e. the brightness) is given by two main factors: albedo $\rho$ and shading $S$ (eq. 1).

$$I_G(i,j) = \rho(i,j) \times S(i,j)$$  \hspace{1cm} (1)

The first one depends on the optical characteristics of the surface itself, like colour or material. The second one instead, which will be analysed in the successive SFS operations, directly depends on the orientation of the surface with respect to the light direction. Therefore, in order to isolate shading information, the albedo value of each segmented region needs to be normalized to 1. If the represented surface is somewhere perpendicular to light direction, this is obtained by dividing the grey value of each pixel by the maximum value of that segment. Otherwise, this can be done comparing the analysed segment with the surrounding ones: parallel or tangent areas must have equal grey value. Let’s call the resulting image $I_L$.

Both $I_L$ and $I_S$ will be used for the 3D modelling of the virtual bas-relief.

### 2.2. Perspective scene reconstruction

Starting from the segmented image $I_S$, it is necessary to define the arrangement of each segment in a consistent 2.5D reconstruction of the scene, exploiting information derived from perspective analysis. It is a straight consequence that this kind of reconstruction can be obtained only for those paintings in which the artist used the perspective to simulate the deepness of the scene. The devised procedure starts with the definition of a reference coordinate system with the origin corresponding with the bottom left corner of the image, the $x$-axis parallel to the horizon line, from left to right and the $z$-axis outward pointing with respect to the painting. Each segment is then classified by means of a graphical user interface (GUI) in 4 types of planes: frontal, horizontal, vertical, oblique. Among the horizontal planes it is defined the main plane, which corresponds to the ground level. Successively, a hierarchy among the defined planes is created. Further details are available on [13].

At the end of the procedure, a depth-map $Z_P$ of the flat layered bas-relief is obtained in the form of a depth map (i.e. a greyscale image), as depicted in Figure 2.
2.3. Volume reconstruction

Once the previous step is completed, the 2.5D shape of each depicted subject has to be retrieved. In the flat-layer representation, in fact, each figure is approximated with a plane, therefore no information about the actual shape of the figures (except the silhouette) is given.

First, all objects representing simple geometries, such as columns, arches or vaults, are directly retrieved by using specifically devised tools, implemented in the GUI. These elements can be easily reconstructed without a deep analysis of the shading, since a limited number of measurement on the picture itself and on $Z_0$ are required (i.e. diameter and length for a cylindrical column).

Referring to subjects whose surface is not reproducible with simple geometric entities (e.g. human figures or clothes), the reconstruction is mainly obtained using SFS-based techniques. While this method is able to provide good results dealing with synthetic images, in which the surface is perfectly diffusive and the shading is free from errors, in the case of a handmade representation results can be far from satisfactory. For these reasons, the authors developed a simplified approach where the final solution i.e. the depth map $Z_F$ of all the subjects in image is obtained as a linear combination of three different contributions (see eq. 2): main shape ($Z_S$), rough shape ($Z_R$) and fine detail shape ($Z_D$).

$$Z_M = \lambda_S Z_S + \lambda_R Z_R + \lambda_D Z_D$$

The main shape derives from shading analysis, by means of a specifically developed SFS procedure based on the minimization of a penalty function under wisely set boundary conditions [14]. The minimization approach was preferred to faster direct SFS-approaches (such as Fast Marching Method) due to a better handling of unprecise shading data. The main drawback of this approach is the over-flattening effect, i.e. the final result appears flattened with respect to the ground truth. In addition, this effect is emphasised in presence of ambient light added to a directional illumination, which is quite common in paintings. A secondary issue related to minimization approach is the loss of detail, due to an over-smoothing effect. Both the two auxiliary contribution, $Z_R$ and $Z_D$ are used to come up with these two issues [13] (see Figure 3).
The rough shape definition aims at recovering the gross volume or the final shape. It derives from a two steps image inflating procedure developed by the authors, in which the initial rough inflated surface is then finely iteratively smoothed to avoid sharp edges that would be visible in the final surface.

The fine detail shape instead aims at recovering the loss of details due to over-smoothing effect. Inspired by some well-known techniques [18], a simple but effective strategy to recover the fine detail is to consider the brightness of the input image ($I_G$) as a depth map.

### 2.4. Virtual bas-relief reconstruction

Once the three contribution ($Z_S$, $Z_R$ and $Z_D$) are obtained for each figure, a GUI based procedure helps users in defining the proper set of weights to achieve the better $Z_M$ for each one of the $n$ figures and, therefore, the better $Z_F$. An appositely devised GUI allows the user to regulate each weight value and to see in real time the effect on the 2.5D virtual bas-relief.

$$Z_F = \lambda_P Z_P + \sum_{i=1}^{n} \lambda_{S,i} Z_{S,i} + \lambda_{R,i} Z_{R,i} + \lambda_{D,i} Z_{D,i}$$

(3)

### 2.5. Rapid prototyping of the bas-relief

Once $Z_F$ has a satisfying quality, the procedure allows the user to export the STL file, ready to be manufactured by means of CNC milling machines or with rapid prototyping techniques, such as stereolithography (SLA), selective laser sintering (SLS), fused deposition modelling (FDM), Polyjet/Multi-jet technology. The main aspect that needs to be considered in order to select the most appropriate technology is the attainable level of details. However, other characteristics are relevant, such as surface finishing and the possibility of post-processing treatments (e.g. surface hardening, to prevent material consumption) [19, 20].

The bas-relief of “The Healing of the Cripple and the raising of Tabitha” was prototyped by milling and is sized about 900 mm x 400 mm x 80 mm (see Figure 4).

**Figure 4.** Tactile bas-relief realized for the artwork "The Healing of the Cripple and the raising of Tabitha".

### 3. Case studies

The described method was shared with both the Italian Union of Blind and Visually Impaired People in Florence (Italy) and experts in cultural heritage field (in particular from Uffizi Gallery, Musei Civici Fiorentini and Villa La Quiete). Under their expert suggestions, author realized several bas-reliefs of some of the best known artworks of the Italian Renaissance.

In chronological order, the first masterpiece to be translated into tactile bas-relief by the proposed procedure was “The Annunciation” fresco by Beato Angelico (see Figure 5). As many of the other ones that have been realised, the bas-relief is permanently displayed next to the original exhibit, in this case in the Museo di San Marco, in Florence.
Figure 5. "The Annunciation" by Beato Angelico (Museo di San Marco, Florence): a) rectified grayscale image; b) clustered image; c) 2.5D model; d) final bas-relief exposed together with the original artwork.

Following this, two paintings from Villa La Quiete (Florence) collection have been converted into tactile models: “Madonna with Child and angels” by Niccolò Gerini (Figure 6) and some characters from “Mystical marriage of Saint Catherine” by Ridolfo del Ghirlandaio (Figure 7).

Figure 6. "Madonna with Child and Angels" by Niccolò Gerini, Villa La Quiete (Florence): a) original artwork; b) rectified grayscale image; c) clustered image; d) 2.5D model; e) tactile bas-relief.

In the case of Niccolò Gerini artwork, also the frame of the painting has been included into the tactile representation, considered an integral part of the exhibit itself. Its 2.5D representation has been obtained by means of 3D laser scanner Romer Absolute Arm 7520-SI. Finally, it has been realised the tactile bas-relief of the painting “Pala di Santa Lucia de’ Magnoli” by Domenico Veneziano, displayed in Uffizi Gallery in Florence (see Figure 8).
Conclusions and discussion

Though technologies like 3D scanning and Rapid Prototyping are nowadays an important part of the digital age and have been successfully introduced to improve the 3D reproduction of sculptures, the research is not as mature as regards the realization of 3D models starting from paintings or photographs. Taking into consideration most recent techniques dealing with this topic, the present paper provided an overview of the procedural CAD-based method developed by authors during the T-VedO project. Such a method was successfully applied to a number of important artworks of the Florentine
Renaissance. Manufactured bas-relief, located at museums that have collaborated in the experimentation, are now available to visually impaired people to enhance their tactile experience.

References

[1] A. Reichinger, M. Neumüller, F. Rist, S. Maierhofer, W. Purgathofer, Computer-aided design of tactile models – taxonomy and case studies 2013 *Lect Notes Comput. Sc.*, 7383, 497–504.

[2] M. Carfagni, R. Furferi, L. Governi, Y. Volpe, G. Tennirelli, Tactile representation of paintings: an early assessment of possible computer based strategies 2012 *Lect Notes Comput. Sc.*, 7616 261–270.

[3] Y. Volpe, R. Furferi, L. Governi, G. Tennirelli, Computer-based methodologies for semi-automatic 3D model generation from paintings 2014, *Int. J. Comput. Aided Eng. Technol.* 6 (1) 88–112.

[4] Y. Horry, K. Anjyo, K. Arai, Tour into the picture: using a spiderly mesh interface to make animation from a single image 1997, *Proceedings of the 24th Annual Conference on Computer Graphics and Interactive Techniques*, ACM Press/Addison-Wesley.

[5] A. Reichinger, S. Maierhofer, W. Purgathofer, High-quality tactile paintings 2011, *J. Comput. Cult. Heritage* 4 (2), Art. No. 5.

[6] P. Daniel, J.-D. Durou, From deterministic to stochastic methods for shape from shading 2000, in: *Proc. 4th Asian Conf. on Comp. Vis*, 1–23.

[7] L. Di Angelo, P. Di Stefano, Bilateral symmetry estimation of human face 2013, *Int. J. Interactive Design Manuf.* 7(4), 217-225.

[8] J.D. Durou, M. Falcone, M. Sagona, Numerical methods for shape-from-shading: a new survey with benchmarks 2008, *Comput. Vis. Image Underst.* 109, 22–43.

[9] R.T. Frankot, R. Chellappa, A method for enforcing integrability in shape from shading algorithms 1988, *IEEE Trans. Pattern Anal. Mach. Intell.* 10 (4), 439–451.

[10] T.-P. Wu, J. Sun, C.-K. Tang, H.-Y. Shum, Interactive normal reconstruction from a single image 2008, *ACM Trans. Graphics (TOG)* 27 (5), 119.

[11] R. Furferi, L. Governi, N. Vanni, Y. Volpe, Tactile 3D bas-relief from single-point perspective paintings: a computer based method 2014, *J. Inform. Comput. Sci.* 11 (16), 1–14.

[12] L. Governi, M. Carfagni, R. Furferi, L. Puggelli, Y. Volpe, Digital bas-relief design: a novel shape from shading-based method, *Comput. Aided Des.* Appl. 11 (2) (2014) 153–164.

[13] R. Furferi, L. Governi, Y. Volpe, L. Puggelli, N. Vanni, M. Carfagni, From 2D to 2.5D i.e. from painting to tactile model 2014, *Graph. Models*, 76 (6), 706-723.

[14] L. Governi, R. Furferi, M. Carfagni, L. Puggelli, Y. Volpe, Digital bas-relief design: a novel shape from shading-based method 2014, *Comput. Aided Des. Appl.* 11 (2), 153–164.

[15] Y. Altunbasak, R. M. Mersereau and A. J. Patti, A fast parametric motion estimation algorithm with illumination and lens distortion correction 2013, *IEEE Trans. Image Process.*, 12 (4), 395-408.

[16] E. Nadernejad, S. Sharifzadeh, H. Hassanpour, Edge detection techniques: evaluations and comparisons 2008, *Appl. Math. Sci.* 2 (31), 1507–1520.

[17] W.A. Barrett, E.N. Mortensen, Interactive live-wire boundary extraction 1997, *Med. Image Anal.* 1 (4), 331–341.

[18] K. Salisbury, D. Brock, T. Massie, N. Swarup, C. Zilles 1995, Haptic rendering: Programming touch interaction with virtual objects. In *Proc. of the 1995 symposium on Interactive 3D graphics*, 123-130.

[19] X. Yan, P. Gu, A review of rapid prototyping technologies and systems 1996, *Comput. aided design*, 28(4), 307-318.

[20] M. Carfagni, L. Puggelli, Different strategies for rapid prototyping of digital bas-reliefs 2014, *Appl. mech. mat.*, 510, 163-167.