Computer-Aided Design of Tactile Models

Taxonomy and Case Studies

Andreas Reichinger[1], Moritz Neumüller, Florian Rist, Stefan Maierhofer[1], and Werner Purgathofer[1]

[1] VRVis Forschungs-GmbH, Donau-City-Str. 1, 1220 Wien, Austria
reichinger@vrvis.at

Abstract. Computer-aided tools offer great potential for the design and production of tactile models. While many publications focus on the design of essentially two-dimensional media like raised line drawings or the reproduction of three-dimensional objects, we intend to broaden this view by introducing a taxonomy that classifies the full range of conversion possibilities based on dimensionality. We present an overview of current methods, discuss specific advantages and difficulties, identify suitable programs and algorithms and discuss personal experiences from case studies performed in cooperation with two museums.

Keywords: accessibility, design for all, blind people, visually impaired people, tactile graphics, tactile models, CAD, CAM, 3D scanning

1 Introduction

Tactile models are an important tool for blind and visually impaired people to perceive images and objects that otherwise are incomprehensible for them. Of course, verbal description or use of residual sight are always favorable, but may often be greatly complemented by the sense of touch. While touching the original objects would be best, this is not always feasible due to inappropriate scale, lack of tangible features or conservatory and safety concerns. For a long time, tactile models have mostly been created manually by skilled people (e.g. [2, 5]). Today, the availability of digital scanning and production tools opens possibilities for automation—shifting from a manual to a computer-aided design process. In order to open its full potential for faster, easier and more accurate creation we investigate the optimization of digital workflows (i.e. the conversion and adaption from scanned input to data required by rapid prototyping tools).

To date many publications [8, 9, 15] deal with the creation of raised line drawings or tactile diagrams from images or the reproduction of 3D objects [14]. In the present work we specifically include cross-dimensional conversions in a common taxonomy embedded in the continuum of spatial dimensions.

2 Continuum of Dimensions

Our taxonomy is based on spatial dimensionality, which has the largest impact on the required workflow. We categorize *objects to be converted* (input) and *generated tactile media* (output) based on the dimensionality they can express. The continuum ranges from two-dimensional (2D) objects such as paintings to full three-dimensional (3D) objects like sculptures. In between we can find the limited three-dimensional spaces: 2.5D and 2.1D—a terminology borrowed from visual computing. 2.5D denotes height fields, surfaces that can be represented by a function $z = f(x, y)$, giving every point above a plane a single height value. 2.1D representations pose a further limitation on 2.5D, in that only a correct ordering of depth-layers is imposed, but no actual height values are given.

2.1 2D Objects

The 2D *input* category is formed by paintings, drawings, maps, photographs and so forth. They have in common that they are inherently flat with no elevation that would give meaningful tactile input. The optical channel is the only source of information and has to be interpreted and transformed into adequate tactile sensations. Despite being physically two-dimensional, the depicted content can have higher dimensions encoded in various visual cues that can be decoded by the human brain [1]. For instance, occlusion cues induce a depth-ordering of depicted objects, creating a 2.1D impression. Additional cues like shading, shadows, focus or haze, can lift the content to 2.5D. These circumstances may influence the choice about the optimal output medium for a particular image.

Strictly speaking, there are no 2D tactile *output* media. However, we categorize media like *swell paper* and embossed paper [5] as 2D, because they are mainly limited to display 2D-lines, curves and shapes, although their output is strictly speaking 2.1D. Several companies offer hardware and printing services, making 2D tactile media the easiest and cheapest to produce. However, due to limited expressiveness and resolution, careful design is required [2].

2.2 2.1D Objects

2.1D input objects hardly occur in nature, but are rather a visual phenomenon. Artists, however, often use layering techniques, e.g. in image processing software, in animations or physically as dioramas or paper-on-paper build-up cards.

Build-up techniques using various materials (paper, plastic, fabric) are often used as 2.1D tactile media [5]. To simplify the production, computer-aided tools like vinyl- or laser-cutters can be used to cut the individual layers [11]. Some Braille embossers can also produce 2.1D output by varying embossing strength.

2.3 2.5D Objects

Typical examples are reliefs, embossings on coins, terrain models or building façades. In contrast to full 3D, a 2.5D object only works from a limited set of views. Since only a single height value per position is stored, 3D features like undercuts or backsides cannot be represented. From the technical point of view it has several advantages in acquisition, storage, computation and production.

In fact many 3D scanners generate 2.5D depth images as intermediate results. Stereo photography is also a 2.5D medium, since it captures not only an image but also the depth of a scene. Several algorithms [12] and software (e.g. *Stereo-Scan*, `www.agisoft.ru`) can decode the depth in the image pairs, as long as the depicted objects feature sufficient non-similar texture and have diffuse surfaces.

2.5D reliefs of appropriate size can be very helpful touch tools, adding a perception of depth while being comparably flat and easier to handle than full 3D sculptures. Since no undercuts are possible, reliefs are more robust and easier to mount because of their flat backside. This fact also makes production easier: simple 3-axis CNC-milling machines can be directly used, there is no need for artificial support structures in additive production methods, and thermoform or similar embossing techniques may be used to create low-cost copies.

2.4 3D Objects

All kinds of objects, sculptures, architecture and so on can be acquired in full 3D by a wide range of 3D scanners. Recent low-cost alternatives [10] or photogrammetric multi-view reconstruction algorithms [13] and software (e.g. *123D Catch*, `www.123dapp.com` or *PhotoScan*, `www.agisoft.ru`) open scanning to the general public. The latter require no special hardware but only a number of photos to create a 3D model of a static scene provided the objects are suitably textured.

Production is more complicated than in the 2.5D case. Subtractive methods like milling are possible depending on the complexity of the object, but require more expensive (polyaxial) machines and careful path-planning or splitting into multiple parts. Additive 3D printing methods do not have these restrictions [7]. Many kinds of professional and DIY printers for different material types of various strengths and several printing services are available. However, 3D printers often have limited build size, less durable materials, high costs, long printing times and/or unwanted printing artifacts. For larger, moderately complex models, (semi)manual model building might still be the most efficient way.

3 Conversion Workflows

In this section we discuss the steps necessary to get from the data of an input class to the data required by an output class. Table 1 summarizes the main challenges for each conversion and rates them based on the automation potential.

In general, not changing the dimensionality is technically less demanding, but correction of scanning errors, and increasing the expressiveness and robustness for touch may still be necessary. Similarly, reduction of dimensionality is easier than increasing it. While in the first case information is omitted, recreation of missing information (e.g. depth, ...) in the second case can get very difficult.

2D output may therefore be generated from all inputs, since rendering a 2D image is always possible using 3D computer graphics. However, in many cases designing 2D tactile media is not trivial, because of their limited expressiveness and often limited resolution. Abstraction of the content is important [5]. Although

Table 1. Challenges and automation potential in conversion workflows

from \ to	2D output	2.1D/2.5D output	3D output
2D input	Abstraction, find semantically important lines.	Needs interpretation of depth and surface.	Needs interpretation of depth, surface and invisible parts.
2.5D input	Like above, but depth may help finding boundaries.	Compress depth.	Needs interpretation of invisible parts.
3D input	Like above. Multiple views possible.	Like above. Multiple views possible.	Directly useable in appropriate scale.

(green)	Automation possible to a large extent.
(yellow)	User interaction necessary for abstraction / depth generation.
(red)	Often difficult. Requires user interaction for content creation ("hallucination" of invisible parts). Exception: multi-view input.

specialized design programs [3, 8, 9, 15] exist, support for abstraction (e.g. tracing semantically important lines, emphasizing essential parts) is rarely available. Higher-dimensional input may help finding important edges in the depth data. From 3D input, generation of multiple 2D views might be beneficial.

Creation of higher dimensional output from 2D input is often desirable (cf. Sect. 2.1), but the missing depth has to be re-created. The computer vision community has proposed algorithms that generate depth based on user input [4, 11, 17] or directly from extracted depth cues (e.g. [1]), but full automation is still very error prone and limited.

In most cases, creation of full 3D models from lower-dimensional input is very difficult, because backsides and hidden parts are not present in the input and have to be completed or "hallucinated". Only in some cases (e.g. technical drawings, floor plans) and especially when additional knowledge or multiple views are available, the conversion may be easier.

3D-3D conversion is typically straightforward (e.g. [14]); scaling and reinforcing fragile parts may be considered. Scanners are mostly bundled with software (e.g. *Geomagic*) to process scanning data into printable formats. For more complex corrections, digital sculpting programs (e.g. *ZBrush*) can be useful.

2.5D data can be generated from 3D data by rendering the object from a desired view into a depth-buffer [16]. Compression of depth from 2.5D data may be necessary, a technique perfected by relief artists. Several algorithms (e.g. [16]) have been developed that mimic this step and potentially enhance readability.

In general, correction and manipulation of 2.5D data is easier than 3D data. A 2.5D depth map can be exported as a gray-scale image encoding the height at each location and can therefore easily be shared between applications. Such depth maps may be retouched in image editing software. Better alternatives are special relief-editing programs (e.g. *Delcam ArtCAM*), although their set of editing tools is still rather limited. It is also possible to use manipulation techniques of 3D modeling software, a technique we used in some of our case studies (Sect. 4.2). We created a 3D mesh representation from the height map, manipulated it in the 3D software, and converted it back to the 2.5D representation by orthographic rendering of a depth map.

4 Case Studies

In order to cover the technically most challenging conversion possibilities according to Table 1, and to gain hands-on experience in the different fields, we performed two projects in co-operation with local museums.

Fig. 1. Tactile paintings [11] of Raffael's *Madonna of the Meadow*. From left to right: a) original 2D painting, ©Kunsthistorisches Museum, b) 2.1D layered depth diagram, c) 2.5D textured relief.

4.1 Tactile Paintings (2D-2.1D, 2D-2.5D)

Together with *Kunsthistorisches Museum* (KHM) in Vienna we developed a workflow [11] for converting figural paintings to higher-dimensional output:

2D-2.1D. *Layered depth diagrams* are a layer-by-layer buildup technique (cf. Fig. 1b). We developed a semi-manual design program that quickly allows defining layers on segmented regions and directly outputs data suitable for laser-cutters. After manual assembly a diorama-like image enables visually impaired visitors to quickly get the shape of individual scene elements, and their spatial three-dimensional relation, which is missing in purely two-dimensional media.

2D-2.5D. *Textured reliefs* are an extension of layered depth diagrams (cf. Fig. 1c). We extract texture information from the image and create tactile sensations from it. The design software gives a 3D preview and allows the generation of more complex surfaces. Textured reliefs were produced using milling machines and a subsequent casting process. In addition to layered depth diagrams, blind test persons could also perceive curved surfaces like faces, and painted texture. According to one of the test persons it "opens blind people a new perspective of perceiving images, especially to get a three-dimensional impression".

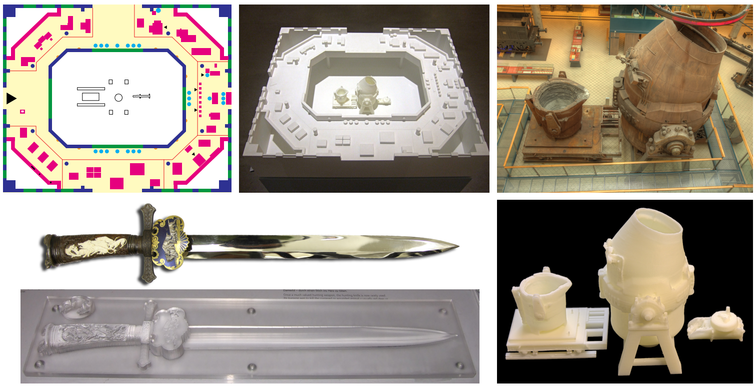

Fig. 2. Top f. l. t. r.: a) exhibition floor plan, b) 1:50 tactile model, c) LD-converter; Bottom f. l. t. r.: d) hunting dagger and its relief, e) 1:50 3D print of LD-converter

4.2 Tactile Exhibits (2D-2.1D, 2D-2.5D, 2D-3D, 3D-2.5D, 3D-3D)

A temporary exhibition at *Technisches Museum* in Vienna was adapted according to a design-for-all philosophy. Besides preparing an audio guide, a tactile guiding system, embossed diagrams (2D-2.1D) and adapting some exhibits for a multi-sensorial experience, we created several kinds of tactile models as detailed below. A preliminary evaluation was performed with 5 visually impaired experts (4 completely blind) by use of structured interviews after a 2 hour guided tour.

2D-2.5D. A stylized 1:50 model ($81 \times 66 \times 17$ cm) of the whole exhibition space including the view to the lower floor in the center of the model was created based on 2D floor plans (Figs. 2a & b). We conceived a tactile language based on simple forms and height that allows easy differentiation of walls (30 mm high), pillars (30 mm, cylindrical), windows (24 mm), exhibits (12 mm polygonal), chairs (9 mm cylindrical) and doors (0 mm), as confirmed by test persons. Since the lower floor is also included in the model, it can even be seen as a simple form of **2D-3D** conversion. Indeed, all test persons reported to have gained a three-dimensional impression of the architecture, and that it was very helpful to get an overview of the exhibition space. The elements were cut from white Hi-Macs boards and hand assembled, resulting in a very durable model.

3D-3D. 1:50 miniatures of large exhibits on the lower floor—which are important in the exhibition context—were included in the 1:50 exhibition model (Figs. 2c & e). We reconstructed each object with photogrammetric methods from a total of 167 photos, taken from all floors all around the objects during normal opening hours. In order to manage the strong brightness contrast, high-dynamic-range imaging was used by fusing 3 bracketed images each and performing local adaptive compression using *HDRsoft's Photomatix*. Photogrammetric reconstruction was performed using *Agisoft's PhotoScan*. *Geomagic* was used to correct large errors and for hole filling of invisible parts, before using the sculpting program *3D Coat* for further corrections, smoothing and feature enhancement. The resulting models (up to 16 cm high) were augmented with support-structures to increase robustness, printed on a *Dimension BST 768* 3D printer with dense filling for stability and manually sanded to remove printing artifacts. The 3D models were highly appreciated by the test persons. Having the same scale as the rest of the exhibition model helped to get a reference of size, but a standalone touch model could be larger to feel even more details.

3D-2.5D. We produced 2.5D reliefs of three different types of knives (Fig. 2d). The original knives are presented in glass cases for conservation reasons. Therefore, we chose to reproduce them in a 1:1 scale, and to mount them on the showcase in front of the actual exhibit. For reasons of stability we created 2.5D reliefs of one side of the knives, corresponding to the visual presentation of the objects on display. Scanning was performed with a *Nikon ModelMaker MMD50* 3D scanner. Although theoretically straightforward, scanning the knives composed from various shiny materials was very difficult, requiring extensive post-processing. This was performed in 2D, 2.5D and 3D programs (cf. Sect. 3) exploiting the advantages of each representation. The final models were milled out of transparent acrylic glass in correspondence to the exhibition design. Test persons understood the limited 2.5D presentation very well, being "the next best alternative to touching the originals". One design element (a dog at the end of a handle) was difficult to understand in its original orientation and was supplemented by a separate upright copy to improve comprehension (Fig. 2d top left).

In general, our test persons pointed out, that verbal description is still most important in order to get the context, background information and guidance while touching. The chosen plastic materials were reported as pleasant to the touch but sterile, which is however necessary in terms of hygiene. Having different materials than the original objects is no problem, since the true material could be imagined from verbal description or by feeling reachable parts of the original objects. Persons with residual sight would benefit from colored models.

5 Conclusions and Future Work

We gave an overview and introduced a new taxonomy for touch tool creation and tested many possibilities in our case studies. General digital tools are already available, making the production of tactile models easier. However, some issues specifically targeted to touch tool design are not covered, such as increasing emphasis on more important parts or automatically making improvements for stability without strongly affecting the content. During our case studies, we started to create some specific tools addressing these issues, but many fields are open for improvement. A further direction of research would be to directly incorporate haptic feedback during the design process using digital force feedback devices, although the usefulness of current devices seems to be limited [6].

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References

1. Assa, J., Wolf, L.: Diorama Construction from a Single Image. Comput. Graph. Forum **26**(3) (2007) 599–608
2. Axel, E.S., Levent, N.S., eds.: Art Beyond Sight: A Resource Guide to Art, Creativity, and Visual Impairment. AFB Press (2003)
3. Breider, J.: TactileView. `http://www.tactileview.com/` (April 2012)
4. Criminisi, A., Reid, I., Zisserman, A.: Single View Metrology. Int. J. Comput. Vision **40** (November 2000) 123–148
5. Edman, P.K.: Tactile graphics. American Foundation for the Blind (1992)
6. Evans, M., Wallace, D., Cheshire, D., Sener, B.: An evaluation of haptic feedback modelling during industrial design practice. Design Studies **26**(5) (2005) 487–508
7. Gibson, I., Rosen, D.W., Stucker, B.: Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing. 1st edn. Springer Berlin / Heidelberg (2009)
8. Hernandez, S.E., Barner, K.E.: Tactile imaging using watershed-based image segmentation. In: Proc. of 4th Int. ACM conference on Assistive technologies. Assets '00, New York, NY, USA, ACM (2000) 26–33
9. Jayant, C., Renzelmann, M., Wen, D., Krisnandi, S., Ladner, R., Comden, D.: Automated tactile graphics translation: in the field. In: Proc. of 9th Int. ACM Sigaccess Conf. on Computers and Accessibility, New York, ACM (2007) 75–82
10. Newcombe, R.A., Davison, A.J., Izadi, S., Kohli, P., Hilliges, O., Shotton, J., Molyneaux, D., Hodges, S., Kim, D., Fitzgibbon, A.: Kinectfusion: Real-time dense surface mapping and tracking. In: 10th IEEE International Symposium on Mixed and Augmented Reality. (October 2011) 127–136
11. Reichinger, A., Maierhofer, S., Purgathofer, W.: High-Quality Tactile Paintings. J. Comput. Cult. Herit. **4**(2) (November 2011) 5:1–5:13
12. Scharstein, D., Szeliski, R.: A taxonomy and evaluation of dense two-frame stereo correspondence algorithms. Int. J. Comput. Vision **47**(1–3) (April 2002) 7–42
13. Seitz, S.M., Curless, B., Diebel, J., Scharstein, D., Szeliski, R.: A comparison and evaluation of multi-view stereo reconstruction algorithms. In: Proceedings of the 2006 IEEE Computer Society Conference on Computer Vision and Pattern Recognition - Volume 1, Washington, IEEE Computer Society (2006) 519–528
14. Teshima, Y., Matsuoka, A., Fujiyoshi, M., Ikegami, Y., Kaneko, T., Oouchi, S., Watanabe, Y., Yamazawa, K.: Enlarged Skeleton Models of Plankton for Tactile Teaching. In Miesenberger, K., Klaus, J., Zagler, W., Karshmer, A., eds.: Computers Helping People with Special Needs. Volume 6180 of Lecture Notes in Computer Science. Springer Berlin / Heidelberg (2010) 523–526
15. Wang, Z., Li, B., Hedgpeth, T., Haven, T.: Instant tactile-audio map: enabling access to digital maps for people with visual impairment. In: Proc. of 11th Int. ACM Sigaccess Conf. on Computers and Accessibility, New York, ACM (2009) 43–50
16. Weyrich, T., Deng, J., Barnes, C., Rusinkiewicz, S., Finkelstein, A.: Digital bas-relief from 3D scenes. ACM Trans. Graph. **26** (July 2007)
17. Zhang, L., Samson, J.S., Seitz, S.M.: Single View Modeling of Free-Form Scenes. In: IEEE Conference on Computer Vision and Pattern Recognition. (2001) 990–997