Watercolor Illustrations of CAD Data

Thomas Luft[1] and Frank Kobs[2] and Walter Zinser[2] and Oliver Deussen[1]

[1] Department of Computer Science, University of Konstanz, Germany
[2] Palette CAD GmbH, Stuttgart, Germany

Abstract

In this paper we describe a project that integrates a non-photorealistic rendering pipeline into an existing CAD system. The pipeline enables the customers of the CAD company to create aesthetically appealing renderings in addition to the classical CAD output. Since these customers are operating in the high-quality segment of furniture and interior design, the visual style of the sales brochure is highly important. We concentrate on watercolor drawings, since they are a traditional medium to present artistic interpretations of architectural and CAD data. To create a convincing and aesthetic reproduction of this style, we propose two techniques: First, we introduce a tone-based lighting to separate the traditional shading of a rendering into tone and intensity, which supports traditional color palettes for watercolor paintings, and second, we exploit ambient occlusion information to render traditional stylistic means such as abstraction and indication.

1. Introduction

In the last decade non-photorealistic rendering (NPR) has become a mature research area. Many artistic styles have been explored and imitated, many surprisingly simple algorithms have been found to describe artistic artwork. One important next step in NPR is to apply and integrate the methods into modeling and rendering systems in order to create powerful tools that help users to create images, illustrations and video with a variety of styles beyond traditional photorealistic rendering.

In this paper we describe a project that aims at this goal. The basis is a CAD system that is specialized for designing furniture and infrastructure for private houses such as ovens and fireplaces. The target market for these individually designed products is a high-quality segment where private persons have to spend tens of thousands of Euros. Companies use the CAD system for designing the furniture and presenting the results to the customers. In this high-quality market it is traditionally done by printing out CAD models and manually redrawing, coloring and beautifying them, a process that is quite expensive and depending on the artistic skills of the people in these companies.

In our project we aim at integrating NPR into an existing CAD system to assist users by rendering aesthetically pleasing drawings directly from the CAD data (see Fig. 1). We decided to use a watercolor style because coloring of

Figure 1: *Watercolor illustration of a CAD model created with our pipeline. The tonal lighting model is used to realize a traditional color contrast scheme, while ambient occlusion introduces a perceptual level-of-detail, which is similar to stylistic means found in hand-made illustrations.*

CAD models is very often done with this painting technique. Hereby, a sketchy line drawing is colorized with more or less abstract watercolor washes. In the following we discuss related work, then describe the system design, followed by the techniques we developed during the integration pro-

cess. Lastly, we present and discuss results and sketch future works.

2. Related Work

As this paper describes a whole pipeline, related work can be found in many computer graphics areas. We concentrate on techniques that render watercolors, consider technical illustrations, or explicitly treat abstraction as a stylistic means.

The rendering of watercolor has been explored by a number of authors. Curtis et al. [CAS*97] introduced one of the earliest approaches to simulate watercolor on a virtual canvas. They use a three-layer model to simulate the diffusion and absorption of the water and color pigments. While their approach achieves convincing watercolor paintings, it is computationally expensive. Similar approaches based on hardware shaders were implemented by Van Laerhoven et al. [LLR04] and Chu and Tai [CT05] allowing for real-time watercolor painting.

Beside the canvas simulations, efficient image filter-approaches have been implemented. Thereby, a convincing visual appearance of watercolor layers is produced by a combination of image filter effects rather than a simulation. For example Lei and Chang [LC04] utilize a Sobel filter to mimic the edge darkening effect. Burgess et al. [BWK05] produce brush-like structures using Wyvill noise in their watercolor renderings. Luft and Deussen [LD06] describe such a watercolor rendering approach especially adapted for botanical data. Bousseau et al. [BKTS06] introduce a watercolor rendering pipeline that processes 2d and 3d data. Since our pipeline is intended to efficiently create watercolor illustrations of 3d CAD data, we decided to use a similar approach for our watercolor effects.

Technical illustrations have a long history in computer graphics. The pioneer work by Saito and Takahashi [ST90] introduces the metaphor of G-buffers, which is the basis of many other approach such as the blueprints by Nienhaus and Döllner [ND04]. Beside image space techniques, object space approaches [HZ00, DFRS03] and volume illustrations [LME*02] have been explored. Although our approach uses a combination of different line drawing algorithms, we concentrate in this paper on the expressive shading and lighting. A related work is the lighting model for technical illustrations by Gooch et al. [GGSC98]. This publication explicitly treats a color contrast scheme instead of the bright-to-dark shading from photorealistic rendering. We further develop this important feature and introduce a tonal lighting model that combines traditional contrast schemes with multiple, colored lights. The above cited work by Bousseau et al. [BKTS06] also describes a simple procedure to compute a color value of a layer with certain pigment density. Although, their approach is completely different, the motivation behind is the same.

Abstraction plays an important role in non-photorealistic rendering. Beside the abstraction of shape and shading when reproducing a natural painting medium or technique, we think of abstraction as a stylistic means, for example, a visual level-of-detail or the selective abstraction of a rendering to introduce regions of interest. Santella and De-Carlo [SD02] describe such an abstraction approach for photographs controlled by eye-tracker data. An earlier work is the approach by Winkenbach and Salesin [WS94] that uses roughly-sketched user input to guide the perceptual level-of-detail in their pen-and-ink renderings. Our approach works completely automatic by exploiting ambient occlusion information to achieve a meaningful abstraction within our rendering pipeline.

3. System overview

Our pipeline design depends on the system design of the given CAD software that provides our input data. In addition to the geometry and the material, we obtain a camera and light setup. Beyond this, the system defines also meta information such as object categories, which allows us to further tune the rendering, for example, it is possible to render important objects of the scene with higher detail, while ambient objects and the background are rendered with a restrained style.

To produce an appropriate lighting that especially reflects the desired soft lighting situation in a living room we use ambient occlusion and area light sources to compute shadows. Additionally, we use a tone-based lighting and shading for the watercolor rendering. Both techniques are discussed in the following section.

Our renderings consist of three layers that are combined to form the final result:

- **Detail Layer**
  This watercolor layer represents the illuminated portions of the scene; it contains the scene colors and textures.
- **Ambient Layer**
  This second watercolor layer represents portions of the scene that are lit indirectly.
- **Stroke layer**
  This layer represents object contours and cross hatching strokes.

We distinguish two watercolor layers to achieve a finer granularity and to avoid an image filter-like appearance by introducing small gaps between them due to a individual stylization. While this is a quite traditional setup for a NPR pipeline, it allows us to produce accentuated and dynamic results in a visually convincing watercolor style.

4. Integration of NPR

As already mentioned the integration of our techniques within the given CAD software depends on the system structure. This section focuses on two techniques we found especially interesting for achieving aesthetic results in our setup.
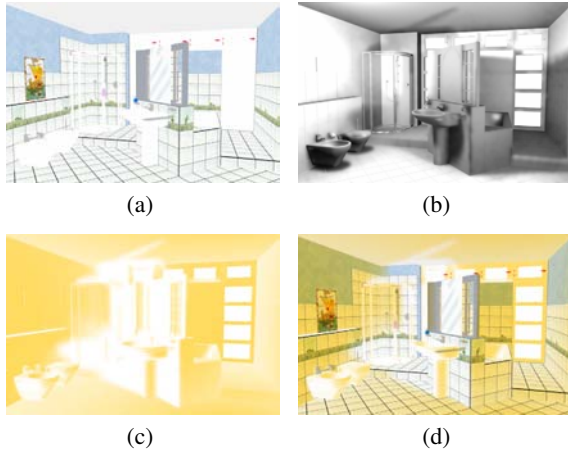
(a)   (b)

(c)   (d)

Figure 2: *Tone based lighting. The scene contains one white and one orange point light. Rendering of the material reference M (a), the lighting intensity L_I^* (b), the lighting tone L_T^* (c), and the final tone $M \cdot (1 + L_T^*)$ (d). Please note that the value range of these renderings is usually beyond $[0,1]$, so we have to apply tone mapping for presenting them in this paper, which causes slight color failures.*

4.1. Tone-based lighting for watercolor rendering

It is a common practice that NPR rendering algorithms use standard real-time and photorealistic lighting models to create the tonal input. However, artwork usually shows contrasts beyond a simple bright-to-dark shading: Harmonic or complementary color palettes are especially appealing to the human visual perception and thus, are often recognizable in paintings. An overview and application of well-known contrast schemes can be found in [COSG*06].

Especially in watercolor paintings, a bright-to-dark shading is usually avoided. Instead illumination effects are achieved by variations of tone and saturation. To provide such a methodology, our approach distinguishes two reference maps: a material reference map and a lighting reference map.

The material reference map M is obtained by rendering the objects' material color and texture without any lighting computation (see Fig. 2(a)). In contrast to this, the lighting reference map L contains only the lighting information of the scene without any material properties. Thereby we divide the lighting into tone $L_T = \{t : t = (r,g,b) \in \mathbb{R}^3\}$ and intensity $L_I = \{i : i \in \mathbb{R}\}$. This separation allows us to obtain a shading, which solely collects the tone contribution of each light source without any darkening due to the lighting intensity. As an example, this implies that scene objects lit by a red light obtain a reddish tone, while a white light does not influence the scene objects' color at all.

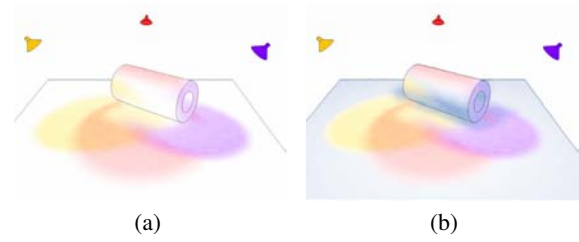We use a flexible multi-pass rendering approach for com-

(a)   (b)

Figure 3: *Application of tone based lighting. A combination of the tonal lighting with the light intensity as opacity causes (slight) variations of saturation, however, ambient or shadowed portions of the scene remain untouched (a), tone variations due to a contrasting user-defined color, which renders the ambient and shadowed regions (b).*

puting the lighting: For each light source (including an ambient light) the scene is rendered and later all render passes are combined by an additive blending. In each pass we render the intensity L_I and the tone L_T produced by a light source with color $\mathscr{L}$ defined in RGB color space. We use a standard illumination model and include shadows and ambient occlusion. The light intensity at a pixel $i \in L_I$ is computed as the mean value of $\mathscr{L}$, the lighting tone $t \in L_T$ is derived as the difference to the intensity:

$$i = \frac{1}{3}(\mathscr{L}_r + \mathscr{L}_g + \mathscr{L}_b) \qquad (1)$$

$$t = (\mathscr{L}_r - i, \mathscr{L}_g - i, \mathscr{L}_b - i) \qquad (2)$$

Applying additive blending, we obtain a final lighting intensity L_I^* and tone L_T^* by accumulating all render passes (see Fig. 2(b) and (c)). Now we are able to compute the final color that contains the objects material and the lighting tone (see Fig. 2(d)). Since L_T^* contains only variance values relative to 0, we have to bias the tone by adding 1:

$$M \cdot (1 + L_T^*) \qquad (3)$$

The result of the tone-based lighting can be applied in many ways. For watercolor layers, it can be directly used as color input, while the opacity should be derived from a lighting term, i.e., lighting intensity or ambient occlusion. Such a watercolor layer reflects the scene illumination via variations of the saturation (see Fig. 3(a)). We use this approach for the detail watercolor layer in our pipeline. To obtain more traditional color schemes such as a warm-to-cold shading, tone variations can be introduced by adding an arbitrary color, for example some dark blue weighted by the lighting intensity (see Fig. 3(b)).

Thus, tone-based lighting computes a map that contains

Figure 4: *Ambient occlusion as stylistic means. Ambient occlusion map (a), masking the detail layer to achieve a dynamic and accentuated rendering (b), shaping the ambient layer to reproduce the dull portions with a contrasting color (c), and the stroke layer (d).*

only the tone of the scene objects and the light sources. It can directly serve as input for a color layer in our NPR pipeline. In addition, the layer can be modulated by a lighting term to achieve light-dependent variations in tone or saturation and to introduce color contrasts.

4.2. Ambient Occlusion as a stylistic means

A lot of NPR techniques consider the reproduction of a certain artistic style, e.g. stroke based rendering, or the reproduction of a certain artistic medium, e.g. painterly rendering, watercolor rendering. However, the artistic medium alone is certainly not enough if the rendering approach shall reproduce the artistic process as a whole.

Artists usually achieve very dynamic results through the application of stylistic means. Stylistic means are tools to emphasize, abstract, indicate, or select information. They are often applied by artists to achieve a vivid and expressive result. Stylistic means appear very differently: They exist in form of abstractions of shape and shading, as a level-of-detail control over different parts of the painting, or as indication of contours, shapes, and details. Abstraction and indication are two very important and often observable stylistic means in traditional watercolor paintings and illustrations. Abstraction is performed by simplifying shape and shading, indication by emphasizing spatial relations or details of interest.

To implement such stylistic means, we found ambient occlusion [ZIK98,Lan02] as a suitable tool. Ambient occlusion is a simple form of a global illumination effect in photorealistic rendering. It approximates a geometry based occlusion as if the scene was placed under a skydome light (in contrast to shadows coming from direct lighting). By integrating the distances from a surface point to nearby occluders within that point's hemisphere, an approximation of the spatial frequency in world space is determined. This characteristic thus represents regions of particular spatial interest. In the following we introduce our way of exploiting this information.

Besides natural shading and illumination provided by ambient occlusion, we utilize this information to achieve an accentuated rendering similar to traditional stylistic means.

Hereby, ambient occlusion provides us a kind of visual level-of-detail – not in the photorealistic sense – to place local accents by emphasizing spatially interesting regions, that is, regions that have a high spatial frequency.

Within our pipeline an ambient occlusion map $A = \{a : a \in [0,1]\}$ (see Fig. 4(a)) is applied in the following ways: First, it masks the detail layer, second, it forms the basis of the ambient layer, and finally, it forms the basis of the cross hatching strokes.

Masking the detail layer

The detail layer shall reproduce the lit parts of the scene including material properties such as color or texture. We render this layer with a watercolor approach similar to the work of Luft and Deussen [LD06] and Bousseau et al. [BKTS06]. In this case, the layer is defined by a color and an opacity map. In our pipeline, the color is computed by the tonal lighting from Eq. 3. The lighting intensity L_I^* is interpreted as opacity.

So far, the result shows a more or less standard rendering of the 3d scene stylized by the watercolor shader. In contrast, artwork contains regions of interest that are emphasized by increasing details and/or using strong colors. To resemble this strategy, we apply ambient occlusion to achieve an accentuated rendering: Since the ambient occlusion map contains information about spatial relations, which can be considered as regions of interest, we restrict the shape of the detail layer to $1 - A$. Consequently, only details within the ambient-occluded areas are rendered. In contrast to using this as an illumination effect, ambient occlusion acts here as a visual abstraction and level-of-detail mechanism (see Fig. 4(b)).

Shaping the ambient layer

While the detail layer represents the lit portions of the scene, the ambient layer represents the dull parts of the scene, which are usually not under direct illumination. The tone of this layer is statically chosen and introduces a certain color contrast scheme. According to our experiences dark blue and dark ochre tones produce appealing ambient accents.
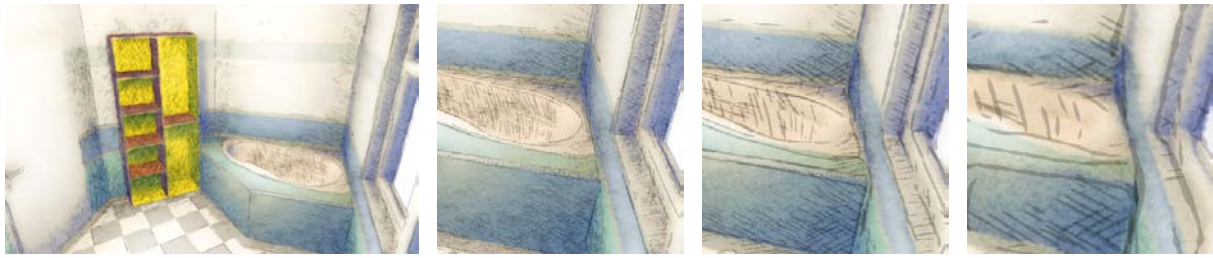
Figure 5: *Scale dependent rendering. The series shows the scale dependent rendering of our pipeline. The close-up views were rendered at 100dpi, 200dpi, and 400dpi.*

The opacity, and thus, the shape of this layer is directly derived from the ambient occlusion values. To exclude illuminated portions, we additionally mask the ambient occlusion map with the lighting intensity by $A \cdot L_I^*$. As a result this layer represents the ambient occlusion areas that are not directly illuminated (see Fig. 4(c)).

Describing the stroke layer

The stroke layer contains a sketchy drawing of the scene including contours and cross-hatching. In contrast to the traditional way of applying cross-hatching strokes to depict shadowed and dark regions, we want to exploit them as an additional indicator for regions of particular interest. Our experiences show that otherwise the shadowed and dark regions, which were already rendered by the watercolor layers, would become over-exaggerated.

Similar to the detail layer we use the ambient occlusion map as a limiter for these cross-hatchings. Together with their individual alignment (which depends on the objects' normal vectors) we achieve a strong indication of edges and object boundaries in our results (see Fig. 4(d)).

5. Results and discussion

For the rendering of a watercolor wash, we combine existing techniques that already create a convincing reproduction of the visual elements of watercolor, such as pigment granulation, edge darkening, (slight) diffusion or the shape simplification due to a paint brush.

Beyond the basic watercolor rendering we concentrated in this project on the reproduction of a natural color palette and traditional stylistic means such as abstraction and indication. Our results demonstrate that these techniques can significantly improve the natural appearance and fidelity of a watercolor rendering (see Fig. 6 and 7).

The tonal lighting was introduced to provide the basis of a watercolor layer. Real watercolor works with harmonic color contrasts rather than bright-to-dark shading as produced by standard illumination. The goal of the tonal lighting is to remove these bright-to-dark shades in a rendering and to replace them with color contrast schemes. Hence, the tonal

lighting is usually combined with a user-defined secondary color providing a contrasting tone for dull and shadowed regions.

In this sense, our approach is similar to the lighting model introduced by Gooch et al. [GGSC98]. However, our tonal lighting can be considered as a further development: While their approach covers the shading defined by a static color contrast, which can be compared to a single, virtual light source, we provide a way to render objects under the illumination of multiple lights. This implies that tonal lighting provides a means to render color contrasts such as a warm-to-cold shading with respect to multiple, even colored light sources.

Ambient occlusion is used in our pipeline as a stylistic means: Beyond the soft illumination effect we use it as indicator for regions of particular interest. Thus, we exploit the fact that ambient occlusion contains geometry-dependent shading information. As a result, ambient occlusion is able to reproduce traditional stylistic means such as abstraction and indication. A natural limitation of this approach is given by single convex objects, for example a single box or sphere: Here the ambient occlusion has no response, and thus, produces no shading information. Possible solutions can be found with algorithms that work on surface normals or depth information, for example the unsharp masking approach of Luft et al. [LCD06].

Another necessary feature of a CAD system is scale-dependent rendering for printing on traditional media. That means, depending on the final output device (screen or printer) we render our results with respect to a given DPI factor. A comparison of different scales is shown in Fig. 5.

Finally, performance plays an important role in a rendering system. We implemented our approach mostly using GPU shaders, which provide interactive rendering of the tonal lighting and the NPR style. Because of greater flexibility and simplicity, we simultaneously implemented a ray tracer for shadows and ambient occlusion. This step is performed when the camera or the scene changed. The ray tracer output in form of intensity maps are integrated into the subsequent pipeline steps. Hence, a complete rendering of a

Figure 6: *Results.*

scene takes typically 20 to 40 seconds for 800×600 pixels, while style and color settings can be altered interactively at about 5 frames per second.

6. Conclusion

We implemented a NPR pipeline within an existing CAD system. The pipeline automatically renders CAD data as watercolor illustration. We concentrated on aesthetic aspects of such a rendering: We aimed at traditional color contrast schemes that are often found in hand-made watercolor illustrations. Furthermore, we reproduced stylistic means that are regularly utilized in artwork to indicate regions of interest, and thereby accentuate the painting.

To achieve this goal we introduced a tonal lighting model that separates intensity and tone of the scene illumination. This procedure allows to reproduce color contrast schemes with multiple, colored light sources. To accentuate our renderings we exploit ambient occlusion by interpreting it as an indicator for spatially interesting regions.

Future work will focus on traditional ways of presenting material properties, for example transparency or reflection. In artwork several typical indicators exist to visualize such material properties – drawing diagonal lines for glass or mirrors is certainly the simplest approach.

References

[BKTS06] BOUSSEAU A., KAPLAN M., THOLLOT J., SILLION F.: Interactive watercolor rendering with temporal coherence and abstraction. In *NPAR 2006: Fourth*
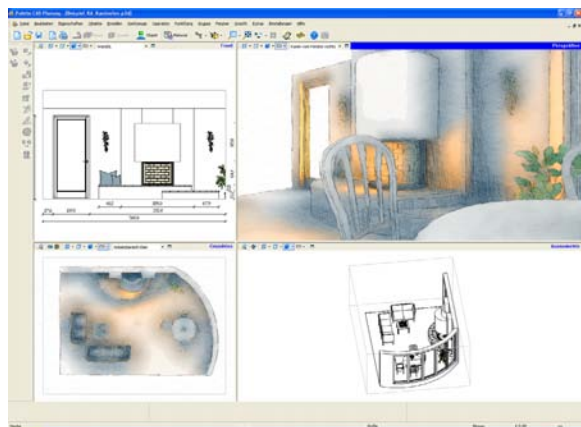
Figure 7: *Screen shot of paletteCAD with different NPR views.*

International Symposium on Non Photorealistic Animation and Rendering (2006), pp. 141–149.

[BWK05] BURGESS J., WYVILL G., KING S. A.: A system for real-time watercolour rendering. In *In Proceedings of Computer Graphics International* (2005), pp. 234–240.

[CAS*97] CURTIS C. J., ANDERSON S. E., SEIMS J. E., FLEISCHER K. W., SALESIN D. H.: Computer-generated watercolor. In *SIGGRAPH '97: Proceedings of the 24th annual conference on Computer graphics and interactive techniques* (1997), pp. 421–430.

[COSG*06] COHEN-OR D., SORKINE O., GAL R., LEYVAND T., XU Y.-Q.: Color harmonization. *ACM Transactions on Graphics (Proceedings of ACM SIGGRAPH) 25*, 3 (2006), 624–630.

[CT05] CHU N. S.-H., TAI C.-L.: Moxi: Real-time ink dispersion in absorbent paper. *ACM Trans. Graph. 24*, 3 (2005), 504–511.

[DFRS03] DECARLO D., FINKELSTEIN A., RUSINKIEWICZ S., SANTELLA A.: Suggestive contours for conveying shape. In *SIGGRAPH '03: ACM SIGGRAPH 2003 Papers* (2003), pp. 848–855.

[GGSC98] GOOCH A., GOOCH B., SHIRLEY P., COHEN E.: A non-photorealistic lighting model for automatic technical illustration. In *SIGGRAPH '98: Proceedings of the 25th annual conference on Computer graphics and interactive techniques* (1998), pp. 447–452.

[HZ00] HERTZMANN A., ZORIN D.: Illustrating smooth surfaces. In *SIGGRAPH '00: Proceedings of the 27th annual conference on Computer graphics and interactive techniques* (2000), pp. 517–526.

[Lan02] LANDIS H.: Production-ready global illumination. In *ACM SIGGRAPH Course Notes. Course 16: RenderMan in Production* (2002), pp. 87–101.

[LC04] LEI S. I. E., CHANG C.-F.: Realtime rendering of watercolor effects for virtual environments. In *In Proceedings of IEEE Pacific-Rim Conference on Multimedia* (2004), pp. 474–Ű481.

[LCD06] LUFT T., COLDITZ C., DEUSSEN O.: Image enhancement by unsharp masking the depth buffer. *ACM Transactions on Graphics 25*, 3 (jul 2006), 1206–1213.

[LD06] LUFT T., DEUSSEN O.: Real-time watercolor illustrations of plants using a blurred depth test. In *NPAR 2006: Fourth International Symposium on Non Photorealistic Animation and Rendering* (2006), pp. 11–20.

[LLR04] LAERHOVEN T. V., LIESENBORGS J., REETH F. V.: Real-time watercolor painting on a distributed paper model. In *CGI '04: Proceedings of the Computer Graphics International* (2004), pp. 640–643.

[LME*02] LU A., MORRIS C. J., EBERT D. S., RHEINGANS P., HANSEN C.: Non-photorealistic volume rendering using stippling techniques. In *VIS '02: Proceedings of the conference on Visualization '02* (Washington, DC, USA, 2002), IEEE Computer Society, pp. 211–218.

[ND04] NIENHAUS M., DÖLLNER J.: Blueprints: Illustrating architecture and technical parts using hardware-accelerated non-photorealistic rendering. In *GI '04: Proceedings of Graphics Interface 2004* (2004), pp. 49–56.

[SD02] SANTELLA A., DECARLO D.: Abstracted painterly renderings using eye-tracking data. In *NPAR '02: Proceedings of the 2nd international symposium on Non-photorealistic animation and rendering* (2002), pp. 75–ff.

[ST90] SAITO T., TAKAHASHI T.: Comprehensible rendering of 3-d shapes. *SIGGRAPH Comput. Graph. 24*, 4 (1990), 197–206.

[WS94] WINKENBACH G., SALESIN D. H.: Computer-generated pen-and-ink illustration. In *SIGGRAPH '94: Proceedings of the 21st annual conference on Computer graphics and interactive techniques* (1994), pp. 91–100.

[ZIK98] ZHUKOV S., INOES A., KRONIN G.: An ambient light illumination model. In *Rendering Techniques '98. Eurographics workshop* (1998), pp. 45–56.