WEP Warwick Evans Publishing

Transactions on Computer Science and Intelligent Systems Research
ISSN: 2960-1800, eISSN: 2960-2238 | Volume 9
AIDML 2025

Analysis of Depth-based and Diffusion Model-based Toon Shading in 3D and 2D Rendering

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Abstract. This paper explores toon shading, a rendering technique widely applied to 3D models to create cartoon or anime-style visuals characterized by flat surfaces and shadows. While toon shading can also be used at the 2D level, it is less common and not as broadly applicable compared to its 3D counterpart. This paper aims to review existing toon shading methods and assess their efficiency in stylization and overall product quality. Specifically, this paper examines depth-based toon shading, which utilizes distance information related to light sources, viewports, geometry, and orientations to group polygons in a desired configuration. Additionally, the paper discusses a newly developed toon shading method using diffusion models. The analysis concludes that current toon shading methods effectively achieve stylized surface coloring and shadow effects central to the cartoon aesthetic. Furthermore, the paper advocates for future research into modifying line-art, enhancing non-photorealistic abstraction, and hand-drawn styles. This research could bridge the gap between 2D and 3D applications, benefiting the animation and gaming industries by improving the integration of toon shading techniques across various production pipelines.

Keywords: Toon Shading; Depth-Based; Diffusion Models; Rendering.

1. Introduction

3D models are three-dimensional virtual objects created through coding or computer software. From 3D models to images and videos, rendering is required to generate a virtual presentation of 3D models through coding computer software after modifications of lighting and texture [1]. 3D and photorealistic effects are relatively immersive and impressive for the audience of games and videos. Corporations, therefore, favour a global illumination rendering method to create immersive scenes to appeal to the audience [2]. On the other hand, photorealistic computer graphics is complex in calculation, which is why individual developers and small studios often struggle to create game or animation scenes with fascinating realism due to budget constraints. Nevertheless, photorealistic rendering may be a standard method to create artistic visual effects, but not a necessity. Non-photorealistic rendering has plenty of opportunities and remains an enormous potential.

Among non-photorealistic rendering methods, toon shading is a method that calculates fewer polygons while demonstrating an arguably stylish 2D effect. The concept of toon shading was first proposed by Decaudin in 1996 as a rendering algorithm to create ‘cartoon-looking’ images. As demands for 3D effects reach saturation, toon shading is increasing in application on video games and animations as it enables 3D models to demonstrate anime-like style while being affordable. Through toon shading, it is possible to render a 3D model in a way that displays a 2D style without a realistic effect. Notably, toon shading can also be applied on a 2D level with or without 3D reconstruction. Most research and experiments on toon shading focus on modifying the shades, such as the stroke-based toon shading system and X-Toon shader based on distance and orientation depth [3, 4]. Moreover, as artificial intelligence advances, editable toon shading via diffusion models, a subset of generative artificial intelligence, becomes a new method of toon shading [5]. While no paper has been published on modifying the line art into toon shading to be non-realistically stylish, interactive tools for line art may inspire such research [6, 7].

Rendering requires geometry data and a light source to visualize 3D models with the desired effect. Such data can be obtained through codes and algorithms that represent and calculate positions and vectors. On top of this, toon shading calculates borders between surfaces and shadows to create flat shading. Unlike global illumination rendering, which aims to render the 3D objects as realistically as possible, the difficulty in toon shading creates the hand-drawn effect, which is primarily unrealistic and abstract according to the artworks from human artists [3]. Therefore, on top of the 3D model analysis, adjusting the shadows and line art in the 2D dimension is required for toon shading methods to achieve a hand-drawn style. This paper's main objective is to summarise the progress on toon-shading and analyse the effectiveness and level of stylization of different modifications in toon shading. The author will summarise the experiments, discuss toon shading via depth-based methods and diffusion models, and argue for future focus on toon shading, such as line art modification.

2. Methodology

This paper aims to investigate toon shading methods and their impact on objects. Toon shading fundamentally involves filtering light and shadow boundaries using RGB values or depth information to apply flat, distinct colors to various regions of objects and characters. While toon shading is commonly applied to 2D images, 3D model reconstruction is often required, making 2D toon shading distinct but still relevant to the application of toon shading on 3D models. This paper introduces two prominent toon shading methods: depth-based cel shading and editable shading using diffusion models. Depth-based cel shading, a widely used technique in video games and animation, applies flat shading based on depth information, providing a stylized appearance for characters and scenes. In contrast, editable shading using diffusion models is a recent technique that directly analyzes real-life images to generate a cartoon-like effect. This paper will explore the advantages and disadvantages of these two methods in rendering objects and characters. Additionally, it will highlight potential areas for future advancements in toon shading technology, focusing on how these methods can be improved and applied in different contexts, as shown in Fig. 1.

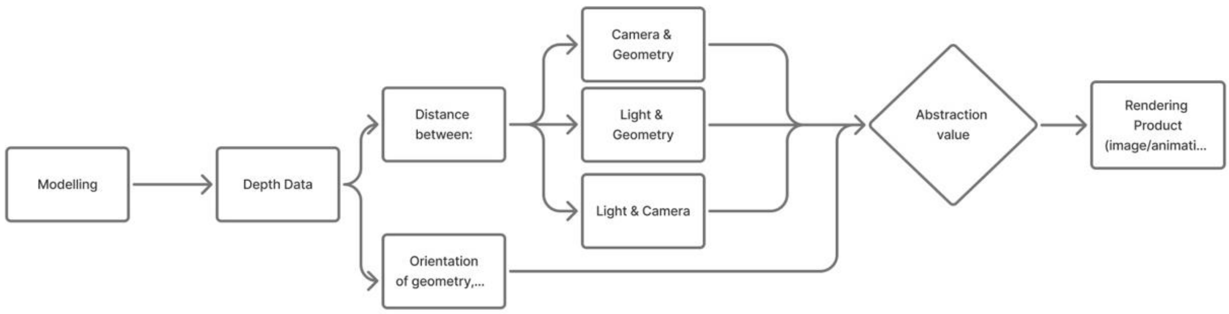

Fig. 1 The pipeline of the study (Picture credit: Original).

2.1. Overview

Research on toon shading has covered depth-based mathematical formulas to calculate the borders and 3D model reconstruction as a side project to support the toon shading process. By integrating artificial intelligence, new toon shading methods via diffusion models have become a new direction. Depth-based toon shading is relatively mature, and its fundamental approach has been advanced and improved in terms of accuracy and level of abstraction through a large quantity of research and shader development. On the other hand, Toon shading via diffusion models starts with great production speed but lacks accuracy and quality, and is difficult in terms of editing and integration with a 3D modelling pipeline.

2.2. Depth-based Toon Shading System

Depth-based toon shading systems are the industry's most common toon shading method. This method is also called cel shading, a subset of toon shading. In this system, the coloring of 3D models employs attribute mapping, which creates clear borders between different layers of light and shadow based on the depth-based attribute. In detail, different colors can be assigned to specific polygons grouped within a range of depth-based attributes. The depth-based attribute used to define different ranges can be the distance between the camera(viewport) and the geometry, the distance between the light source and the geometry, the orientation of the polygons relative to the viewport, and so on. The flat surfaces do not require rich levels of gradient variation and therefore do not require further calculation after grouping the pixels according to depth-based criteria. The fundamental part of face calculation in toon shading is the criteria of defining ranges, which directly decides if the final product is abstract enough to give a hand-drawn effect.

For example, the X-Toon shader developed by Pascal Barla's team uses the distance and orientation of the objects relative to the viewport and observer to apply toon-shading to the rendering targets [4]. There is also a detail value to adjust the level of abstraction in the X-Toon shader. Besides the toon shading system directly applied on 3D models, there is a 2D stroke-based toon shading system developed by Hudou et al., which is noteworthy in terms of approach [3]. This system is completely 2D-based and uses a model of shade deformation to adjust shades. While this system excludes 3D model reconstruction and works on 2D only, its analysis of shades of 2D pictures is depth-based, as it calculates the shades using the distance between the light source and the unshaded flat 2D image. Some mathematical formulas that connect the shadows to be more abstract will likely help render 3D models using toon shading methods.

2.3. Editable Toon Shading via Diffusion Models

Diffusion models, as a branch of generative artificial intelligence, enable the production of videos and images according to the prompts. The application of diffusion models in toon shading starts with image and video input instead of 3D models, hence this method is technically on a 2D level. Current research on toon-shading via generative artificial intelligence focuses on transforming real people's photos and videos into anime-style using pretrained anime-style models. The depth and border information from the image and video input is extracted as a base material, and then the diffusion models are applied to generate toon-shaded content.

The problems of toon shading through diffusion models are the consistency and accuracy of generated content, which are being gradually solved according to the studies and experiments carried out in recent years. For example, Zhongjie Duan's team intervenes in the generating process by obtaining detailed data on the depth, edges, and colors of video input to increase accuracy and adding editing branches to reduce calculation and modify colors [5].

Nevertheless, the stylization is also widely limited as the training of diffusion models relies on many artworks to remain consistent in style. For diffusion models to achieve larger potential in toon shading, evolution in their algorithm is required to train stable stylization models using fewer art materials. While researchers are trying to improve prompt and weight calculation, toon shading via diffusion models has not been effectively implemented on 3D models. Research on connecting diffusion models to the 3D rendering pipeline remains an ample space for progress.

2.4. Application

In general, toon shading creates flat layers through depth-based attribute mapping, in which the attribute can be distances relative to the geometry, light source, and the viewport, or relative orientations of polygons to the viewport. Different ranges will be defined through computation and correspond to a specific colour, so that pixels can be grouped to be coloured the same and clear borders can be demonstrated. This method is commonly applied on a 3D level, but can also be achieved on a 2D level to reduce calculation [8, 9].

Toon shading via diffusion model is based on pre-trained models using anime-style artworks and is fundamentally 2D-based. This method does not require calculating the accuracy of shades, but rather directly utilises light-depth data and edge data from the realistic image or video input and converts them into anime style, with possible editing branches to modify general attributes like colours and improve consistency.

3. Results and Discussion

3.1. Results Analysis

Depth-based toon shading has been integrated into the animation and video game pipeline [10]. Fig. 2 shows the application of toon shading in the animation industry, and Fig. 3 shows the application of toon shading in the game industry. The characters are 3D modeled, and toon shading is applied to 3D geometries to give flat surfaces and shades. In both Fig. 2 and Fig. 3, the flat shades are well-rendered to be anime style, while the line art is notably consistent with no variation in the thickness. This shows that depth-based shading has achieved an impressive effect on shades and surfaces, while line art modifications remain with enormous potential. The products of depth-based toon shading in these examples can be easily spotted as 3D models, possibly due to a lack of thoroughness in toon shading. Nevertheless, Fig. 2 and Fig. 3 show significant improvement in style via toon shading.

Fig. 2 Screenshot from Japanese Anime series "Ave Mujica" created by Bushiroad (Picture credit: Original).

Fig. 3 Screenshot from the Chinese video game "Genshin Impact" created by Hoyoverse (Picture credit: Original).

3.2. Discussion

In future research on toon shadings, the author proposes further study of line-art modification. Aside from the shades, line art is also a fundamental part of the hand-drawn effect, especially in anime and cartoon styles of high abstraction. For example, hand-drawn artworks may have thicker lines when depicting corners, or thinner lines when the surfaces of characters or objects are close to the light source. The line art in hand-drawn art is also significantly stylised in textures. For example, line art using pencil and ink texture gives a greater sense of a non-realistic cartoon effect. On the other hand, toon-shading methods that only modify the shades are highly likely to be spotted as 3D-model-based despite the flat surfaces, and the reason is precisely the lack of modification in line art. Whether the audience prefers the toon-shading to be more hand-drawn or prefers toon-shading on shades only, even if it has a sense of photorealistic effect, is undefined. Nonetheless, the author believes that the ability to modify line-art through 3D methods remains an enormous potential in applications beyond toon-shading once achieved, as it means extending branches of precise editing and modification of 3D rendering and computer graphics in general.

For 3D-based modification of line art, the author suggests taking inspiration from a depth-based system when modifying line art. For example, researchers may map the thickness of the line following the distance between the geometry and the light source. The author also recommends researching modifying line-art on a 2D interface, which may require less calculation while achieving a similar hand-drawn effect compared to the 3D-based method. Diffusion models have the potential to be more accurate by adding editing branches. However, they are still highly limited in accuracy and consistency compared to a 3D rendering pipeline and non-automatic 2D-based toon shading. The author supposes that an ideal way to achieve breakthroughs in toon-shading via diffusion models will be to improve the efficiency of diffusion models, which is to develop diffusion models that require fewer artworks to be trained into constant stylization models.

4. Conclusion

This paper reviews existing toon-shading methods, focusing on depth-based toon shading and toon shading via diffusion models. It analyzes the efficiency of surface and shading coloring in depth-based methods and explores the potential for improving the applicability of toon shading through diffusion models. Depth-based shading techniques utilize depth-related data, such as camera distances, geometry, and light source orientations, to group polygons and create stylized yet accurate surfaces and shadows. However, research on the abstraction of line art remains underexplored. Diffusion models, a more recent approach, face challenges in consistency and accuracy due to their reliance on pre-training with artwork data. Moreover, diffusion models currently lack integration with the 3D shading pipeline, limiting their scope of application. Real-life applications of toon shading in 3D environments have demonstrated significant stylization, although further refinement is needed. Future research will focus on enhancing line-art modification, a key objective in advancing toon shading techniques.

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