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Report on the Doctoral Thesis "Appearance Matching and Fabrication Using Differentiable Material Models " by Dipl.-Ing. Thomas Klaus Nindel

Given a mathematical description of the underlying image formation process, inverse rendering denotes the art of estimating plausible model parameter values from only a single input image. Over the years, this ill-posed, non-convex inverse optimization problem has been addressed by a variety of different techniques. Since Loper and Black's seminal 2014 paper, however, differentiable rendering has become the de-facto standard in how to approach inverse rendering problems.

In his cumulative thesis Thomas Nindel uses differentiable rendering to address the challenge of matching the visual appearance of rendered images as well as 3D-printed objects to input exemplars of real-world images of timber as well as pre-specified translucent volume models exhibiting color-dependent sub-surface scattering properties. The thesis comprises 77 pages plus preface. It is structured into three chapters plus conclusion, futures challenges and coda. The thesis is written in English.

In Chapter 1, Nindel begins by convincingly motivating the importance of the addressed research topic and summarizing the individual contributions of his thesis. He goes on to provide a comprehensive introduction into automatic differentiation and its efficient implementation as the basis for differentiable rendering. He continues by giving the physical background relevant to the simulation of light transport in computer graphics. Touching on path tracing and Monte Carlo simulation, Nindel goes on to describe in considerable depth the intricacies of differentiable light tansport simulation needed for inverse rendering. He reviews the state of the art of existing differentiable renderer implementations before turning to the practical challenges of inverse rendering based on volumetric light transport simulation. Geared towards the specific use cases considered in the subsequent chapters, Nindel then describes different approaches to model visual appearance in computer graphics and how to gauge

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goodness-of-fit for procedural models. He even delves into the growth characteristics and optical properties of wood grain texture. A subsection on the intricacies of color 3D printing concludes the introduction. The chapter demonstrates impressive intellectual depth as well as breadth of the candidate for the topic of his thesis.

Chapter 2 presents the first scientific contribution of the candidate. After a short summarizing introduction the chapter reproduces vertabim a manuscript written by the candidate as first author and apparently submitted to Eurographics 2023. In this work Nindel demonstrates how not only physics-based appearance descriptions but also procedural models are amenable to differentiable rendering, enabling the estimation of procedural model parameter values that yield closely matching visual results to real-world solid wood textures. Challenges to be overcome include estimating wood fiber orientation and location within the original tree stem from the input image as well as coping with discontinuous parametric textures in differentiable rendering. The resulting procedurally modeled wood texture closely mimics the visual appearance of the input wood grain image. Being a solid (3D) texture, it can be directly applied for carving out arbitrary 3D geometry objects. As a side benefit, the Gabor-based wood-grain orientation approach can be used for dendrochronology by automatically aligning different wood specimen to determine the age of wood core samples.

For his second contribution, reproduced in Chapter 3 from his first-authored paper at ACM Siggraph 2021, the candidate presents an end-to-end differentiable modeling and rendering pipeline for colored, translucent 3D volumes that exhibit substantial sub-surface scattering characteristics. The practical motivation behind this work is the problem of matching the output of an ink-jet 3D printer to the desired visual appearance of a previously specified input volume model. Nindel addresses this challenge by inverse volume rendering and proposes a gradient-based framework to the underlying global optimization problem. In addition, he defines a combination of different 3D error metrics to allow for intuitive user control over the process while allowing for a wide range of visual appearances. An intricate hybrid approach between rigorous physical light simulation and heuristic ink deposition modeling allows him to create visually convincing 3D-printed replica of optically complex objects.

Nindel concludes his thesis with a summary of his two considered use cases, contrasting the different pre-requisites and challenges of appearance fabrication vs. appearance matching. He affords a view on future research directions emanating from his work before the bibliography and lists of figures, tables, abbreviations and symbols, as well as his own publications and a link to publicly available source code form the coda of his thesis.

The doctoral thesis is well written. It contains many illustrations and diagrams that further illuminate the presented methods and results. The candidate provides original research results in a promising and active subfield of computer graphics. With his scientific contributions he has broken new ground in appearance modeling and fabrication from example. What distinguishes his work is the insightful development and implementation of practical algorithms from fundamental concepts. With publication at ACM Siggraph 2021 (ToG) and a submission to Eurographics, both contributions of his thesis have been, or are about to be published at top-tier conferences.

In summary, I confirm that Thomas Nindel has shown the ability for original, creative scientific work. He has made significant contributions to the field of computer graphics. I recommend that his doctoral thesis be accepted and be defended by the candidate.

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