FACULTY OF MATHEMATICS AND PHYSICS
Charles University

HABILITATION THESIS

Alexander Wilkie

Predictive Rendering

Computer Graphics Group
Department of Software and Computer Science Education (KSVI)

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In .... date ....

Author's signature

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Chapter 1

Introduction

This habilitation thesis highlights five core publications from the author's scientific work in the last few years, which was conducted in the field of *Predictive Rendering*. This first chapter is devoted to outlining the context and the global aims that guided this particular research effort, and to defining the problem domain. Also, the individual publications that make up the remainder of this thesis are briefly discussed.

An unusual feature of this thesis that it is, in fact, the *second* habilitation thesis handed in at a university by the author. Twelve years ago, he already successfully defended a first habilitation (Wilkie [2007]) about a very similar topic at Vienna University of Technology in Austria. The reasons for a second habilitation in the Czech Republic are of a purely legal nature: as it turned out after many years of productive work as an employee of the Faculty of Mathematics and Physics in Prague, an Austrian habilitation is apparently no longer considered valid by the Czech authorities. And while having to undergo the habilitation process once again could be seen as a nuisance, it actually offers an interesting opportunity to comment on the last twelve years of research work: how Predictive Rendering, the area the author works in, has developed over the years, and whether the problem definition given in the 2007 thesis has stood the test of time. Overall, this can be answered in the affirmative: in the time since then, the field has gone from a theoretically interesting variant of computer graphics to an emerging discipline with increasing industrial support. The thesis author has done his share to make the concept known, both via teaching (Wilkie et al. [2009]), as well as targeted research work that goes beyond they key papers shown in this thesis (e.g. Weidlich and Wilkie [2009], Wilkie and Weidlich [2009], Wilkie and Weidlich [2010], Wilkie and Weidlich [2011], Happa et al. [2012], Mojzik et al. [2016], Wang et al. [2017]).

In the next section, we briefly given an overview of what Predictive Rendering means today. We also briefly discuss which developments in this area were, and which were not, foreseen in the 2007 habilitation thesis. We encourage the reader to refer to the introductory chapter of the 2007 thesis (which is available online at the URL given in the bibliography) for further comparisons, and for a brief discussion of the general cultural and artistic relevance of the concept. These aspects have not changed, and the arguments made there still hold.

1.1 State of the Art in Computer Graphics

Over the last decades, Computer Graphics research has focused on the ability to deliver appealing imagery which satisfies the expectations of a human viewer: we use the expression “believable imagery” for this kind of output, because it accurately describes the intended usage of most current graphics work. And we have been extremely successful in providing these capabilities: graphics output is now pervasive in almost all walks of life that demand visual communication. 3D renderings, from architecture visualisations via furniture catalogs to big-screen movie productions and computer games are ubiquitous. Widespread adoption of photorealistic rendering has enabled a complete change in the way we produce imagery for all these application areas.

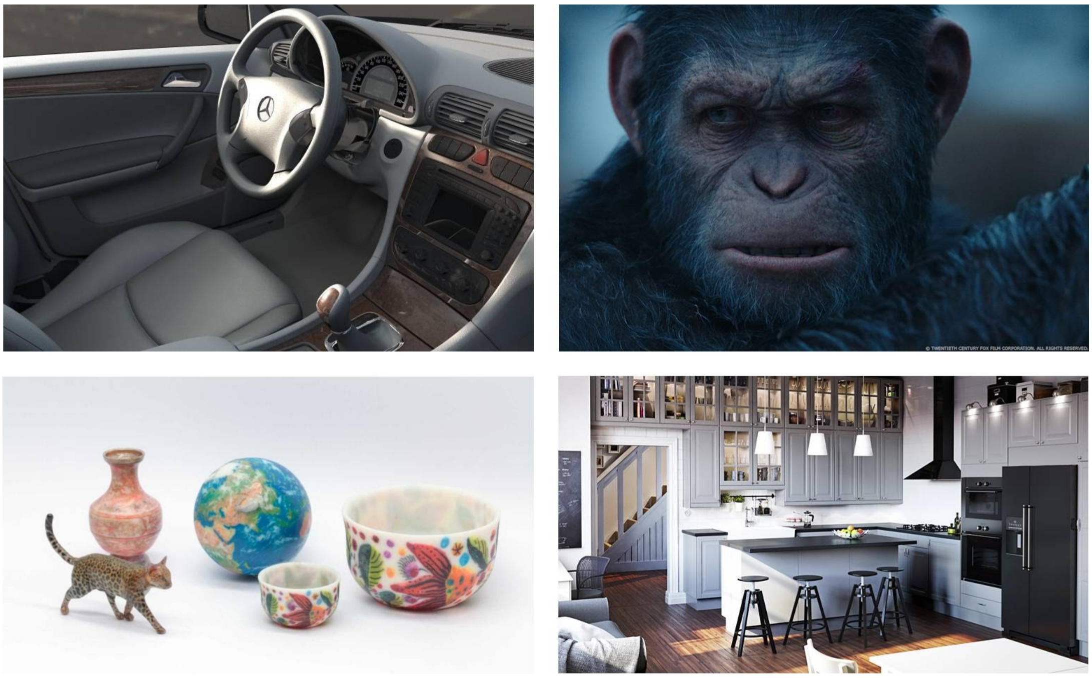

Figure 1.1: Four typical applications for contemporary Predictive Rendering technologies. **Top left**: product previews for appearance critical industries like the automotive sector, or architecture. **Top right**: the VFX industry is increasingly using PR techniques as part of their workflows, as artistic ”faking” of realistic scenes (i.e. not simulating everything from first principles) is both increasingly expensive in terms of invested effort, but also not capable of yielding the last few percent of realism that are needed to convince viewers of total realism. The virtual ape characters in the movie ”Dawn of the Planet of the Apes”, were rendered by Weta Digital using a spectral path tracer which used a technique developed by Wilkie et al. [2014]. **Bottom left**: in this emerging technology example by Sumin et al. [2019], predictive rendering technologies were at the core of the optimisation loops used to refine the appearance and contrast of full-colour 3D print-outs. Such optimisation loops can only be created if one has the ability to authoritatively assess what a given model would look like, if it were printed with a particular set of production parameters. **Bottom right**: Marketing images for IKEA furniture are cost-efficiently mass produced using PR technology.

An important aspect of this is that adoption of 3D Computer Graphics techniques has only been made possible by avoiding full simulations of light transport: these were, up to now, usually infeasible to compute. Instead, this was replaced with visually acceptable approximations. Such “believable” rendering workflows adhere only to some of the fundamental concepts of optics and physics, giving the 3D artists who use them far reaching freedoms to break hard laws of nature. ”Difficult” illumination effects (such as indirect lighting and caustics) can be entirely or partially omitted, and approximate (but quickly computable) models of scene appearance are in widespread use. A good example of this is wood: the common ”believable” approach is to use a simple textured BRDF for this. However, real-world wood has a complex multi-scale volumetric structure, with multiple layers and even weak fluorescence. All such shortcuts, of course, incur varying penalties with regard to visual accuracy; however, as the trade-off between realism and computation time can be tuned by the 3D artist, such inadequacies have, in the past, been considered worthwhile, as they actually allowed one to generate such believable imagery within a reasonable amount of time.

To summarise, the current industry standard in Computer Graphics is practically always only to convince and immerse a viewer, but not to offer an actual prediction of the appearance of a 3D scene. This state of affairs has not really changed since the first habilitation thesis was written: but as we discuss in the next section, this is now finally changing, and genuinely predictive rendering has the potential to be a game changer for several industries, way beyond Computer Graphics proper.

1.2 A New Technology Frontier: Reliable Prediction of Appearance

Due to both recent advances in graphics research, and the emergence of new computing hardware, we are now at the brink of a technological revolution insofar as widespread industrial use of predictive rendering is starting to be technically feasible for the first time. When the first habilitation thesis was written, Predictive Rendering was more of a future dream: but now it is actually becoming an industrial reality. And this has a potential impact which goes way beyond just the areas normally associated with Computer Graphics, such as the gaming and VFX industries, and product visualisation, although these areas will of course also greatly benefit from the availability of truly predictive rendering.

However, even though the impact of PR will eventually go way beyond these areas, the ”traditional” graphics industries such as VFX have over the past few years still been incubators for the underlying workflows and technologies. One of the international collaborators of the thesis author, Weta Digital, is on the forefront of this new movement in the VFX industry: instead of attempting to “convincingly fake reality”, outright predictive simulations of scene assets are being used (and as discussed later, one of the components in those simulations was actually introduced by Wilkie et al. [2014]). Apart from the greatly increased realism of the resulting images, a key argument are economic considerations: with predictive technologies, VFX artist time can be focussed on artistic content creation, instead of faking object appearance. An example of how predictive rendering is already in the mindset of appearance-sensitive industries outside graphics proper is the emergence of so-called digital twins of products (in essence, CAD models which include 100% accurate appearance descriptions). These have already, within the limits of existing technology, been introduced in the car industry, and the concept is currently spreading to other manufacturing industries. Such digital twins become significantly more valuable if one can reliably visualise and virtually manipulate them, and use them for authoritative appearance inspection. Not all such use cases have been explored yet, as the graphics technology needed for them is still either lacking (as in the case of e.g. fluorescent materials), or not sufficiently standardised to for widespread industrial use.

There are entirely new usage domains as well. Just like the arrival of desktop publishing has revolutionised the way 2D documents are designed and printed, we are now in the midst of a comparable revolution which targets the manufacturing of 3D objects. In the last decade, tremendous progress has been made in additive manufacturing (3D printing), but our software capabilities are still lagging behind the fast-paced progress in manufacturing hardware. Specifically, for authoritative control over the appearance of manufactured objects, we need to attain a much better control over object color, translucency, and other visual attributes. Predictive simulation of object appearance – the same technology which enables digital twins – is also a keystone technology in achieving this, and the thesis author has made two significant contributions to this as part of Elek et al. [2017] and Sumin et al. [2019].

Taking this further, predictive rendering could even be used for reliable training of learning-based AI systems, such as autonomous driving software, and the calibration of their sensors. In fact, nothing restricts the use of physically accurate simulations to only the visible range of electromagnetic radiation: this is actually a needed feature, as e.g. modern car sensor suites routinely utilise multiple wavelength bands, from visual to radar. A pervasive issue with AI-based autonomous driving software is that its training needs to be done under tightly controlled circumstances, which are hard to achieve if one has to rely on captured real environments only. Instead, it is much better done, in large, with synthetic data. But so far, we were not able to generate synthetic training datasets which meet the necessary quality criteria: and PR tech can help here.

All this means that after the CAD revolution which started in the 60ies, and which completely altered the industrial landscape by providing huge productivity and capability increases, Computer Graphics can now step over its shadow for the second time in history, and again have a huge impact across a variety of industrial disciplines: this time by being able to predictively store, manipulate and display all aspects of object appearance – not just shape. As discussed earlier, current "believable" rendering tech relies on many shortcuts at all stages of the graphics pipeline, which is fine for its current applications. But even though there are some emerging areas where PR technology is already in (partial) use, such as those shown in Figure 1.1, current solutions are far from fulfilling the requirements of truly predictive applications: there are no reliable protocols for appearance capture for significant classes of assets (especially outside the visible wavelength range), there are too many material classes for which only approximative models are available, there are no reliable error bounds, and global illumination is still too fragile and slow for a large number of use cases - especially when it is being used in its most accurate form.

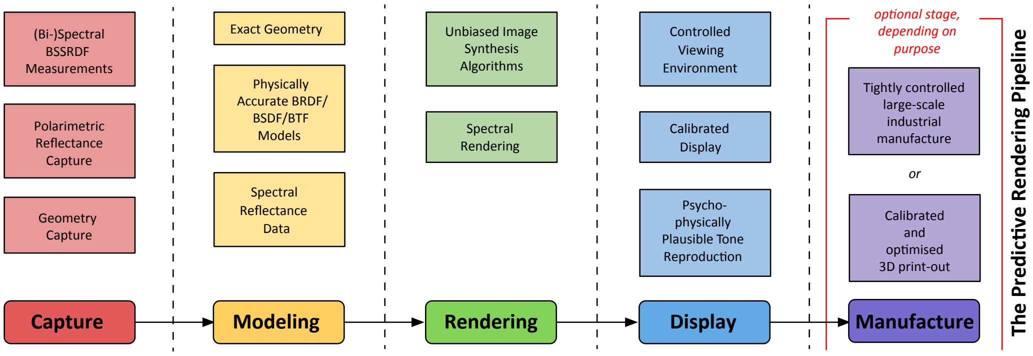

Figure 1.2: The pipeline of Predictive Rendering work, be it for on-screen display, or for accurately controlled manufacturing. It is similar to standard graphics workflows in that it also has the core three stages of Modeling → Rendering → Display. But it has two unusual characteristics: first, it also features a capture step, during which measurementa for the assets one is working with are acquired: while e.g. geometry scans are a standard technique for all graphics purposes, *appearance* capture techniques (especially spectral ones) are very rarely used outside PR workflows. Second, if the end result is to be used for decision-making, it is crucial to realise that this pipeline amounts to a chain which is only as strong as its weakest link. If their impact cannot be properly analysed, any approximations make the obtained results questionable. For instance, the best modelling and rendering is to no avail, if inaccurate display technology or an uncalibrated 3D printer are used afterwards.

1.2.1 The Extended Predictive Rendering Pipeline

Compared to the 2007 thesis, a significant extension of the definition of Predictive Rendering can be seen in figure 1.2, where such a workflow is graphically presented. In 2007, there was neither a mention of the capture stage which needs to stand at the beginning of any such workflow, nor of the optional final production step. While the thesis author has worked with such technologies, e.g. during the collaboration with Berger et al. [2012], or during the work with Wang et al. [2017], capture has (at least so far) not been a main focus of his work. But as his contributions to Elek et al. [2017] and Sumin et al. [2019] showed, research on the precise control of manufactured appearance has become a major part of his research portfolio in the last 12 years. In 2007, the kind of full-colour polyjet 3D printing technology which served as the base for this line of work was still in its infancy, which can explain why this was omitted from the pipeline back then.

1.2.2 First Industrial Use

Something which the 2007 thesis got wrong was the assumption which industry would be the first to make widespread use of Predictive Rendering technologies. All bets were on an industry that deals with appearance-critical high value goods (such as the automotive industry, or architecture) being the first movers. That it would actually turn out to be the VFX industry, with Weta Digital in the lead, was a big surprise. If in 2007 someone had told the thesis author that the first movie with a very substantial portion of path traced scenes would be in cinemas as early as 2014 (”Dawn of the Planet of the Apes”), he would have not considered this to be a realistic prediction. And the adoption of path tracing at Weta Digital was not a fluke: as of 2020, the entire VFX industry has moved solidly in this direction, with actual appearance-sensitive industries lagging behind. But these are catching up, and e.g. the automotive industry now also makes widespread use of path tracing for product development.

1.3 Focus of the Research in This Thesis

Apart from the 3D printing publication (which, as stated above, is from an entirely new area), the particular subset of the author's research which is being presented in this thesis is rather similar in scope and goals to that presented in the first habilitation thesis (Wilkie [2007]). However, unlike the work presented there, the technologies which were introduced by publications 1, 2, 4 and 5 incorporated in this thesis are either in standard industrial use now (1 and 2), or in the process of being integrated into industrial workflows (4 and 5). As such, the impact of the work presented here is substantially greater than that of the old publications: these served as groundwork, but were by themselves not yet useable for production work. This has now changed, and as discussed above, Predictive Rendering has grown up. And the author has made some contributions to this process. A more detailed discussion of each of the five papers can be found in sections 1.5.1 through 1.5.5, where they are presented one by one.

1.3.1 ART - The Tool for Our Research, Then and Now

The lack of publicly available predictive rendering systems that could be used for our research purposes meant that we always had had to develop our own complete predictive rendering research systems from scratch, in order to conduct a considerable part of the work presented in this thesis. The exception were the second and third papers, although the second paper was later also ported to our own software (and valuable further insights were gained in the process - essentially, this led to the fourth paper featured in this thesis).

Our predictive rendering software – ART, the *Advanced Rendering Toolkit* by Wilkie [2018] – was already prominently mentioned in the first habilitation thesis, and has been substantially improved since then. In the meantime, it has been brought to a reasonably stable state, released as Open Source software, and continues to be used as research tool by our group and others. It still has features that are globally unique, and that are not to be found in any other software. In particular, while Mitsuba 2 by Nimier-David et al. [2019] now also features polarisation rendering (as the one other such software), ART is still the only system that offers fluorescence rendering capabilities. Also, the capability of ART to handle and manipulate fully spectral images, including those that contain polarisation information, is still unmatched, as Mitsuba 2 can still only handle non-polarised images.

In hindsight, the fact that 12 years later there still is no other software which offers all the spectral rendering features found in ART even back in 2007 seems to justify our decision to write this software ourselves. Waiting for someone else to do it would simply not have worked, as we needed the advanced features of ART for our research work.

1.4 List of Selected Papers

This thesis contains the following papers as chapter-level core contributions: Hosek and Wilkie [2012], Wilkie et al. [2014], Elek et al. [2017], Mojzík et al. [2018], Jung et al. [2019].

1. Lukas Hosek, Alexander Wilkie
   An Analytic Model for Full Spectral Sky-Dome Radiance
   ACM Transactions on Graphics, 31(4), July 2012

2. Alexander Wilkie, Sehara Nawaz, Marc Droske, Andrea Weidlich, Johannes Hanika
   Hero Wavelength Spectral Sampling
   Computer Graphics Forum, 33(4), pp. 123-131, July 2014

3. Oskar Elek, Denis Sumin, Ran Zhang, Tim Weyrich, Karol Myszkowski, Bernd Bickel, Alexander Wilkie, Jaroslav Křivánek
   Scattering-aware Texture Reproduction for 3D Printing
   ACM Transactions on Graphics, 36(6), November 2017

4. Michal Mojzík, Alban Fichet, Alexander Wilkie
   Handling Fluorescence in a Uni-directional Spectral Path Tracer
   Computer Graphics Forum, 37(4), pp. 77-94, July 2018

5. Alisa Jung, Alexander Wilkie, Johannes Hanika, Wenzel Jakob, Carsten Dachsbacher
   Wide Gamut Spectral Upsampling with Fluorescence
   Computer Graphics Forum, 38(4), pp. 87-96, July 2019

1.5 Overview of the Selected Papers and Contributions of the Author

In general, computer graphics research is a collaborative effort, where cooperations are necessary to spread the effort usually required to implement complex rendering systems; this is particularly true for predictive rendering with its stringent requirements on the quality of all components in the pipeline. Therefore none of the papers in this thesis is a single-author paper by Alexander Wilkie alone; such papers are the exception, not the rule, in the field of computer graphics. However, the thesis author did not merely act only as academic supervisor, and has made a significant direct contributions to all these publications. The following sections contain more details about the contributions to each of these papers.

1.5.1 Chapter 2: Analytical Sky Dome Models

The thesis author was the Ph.D. supervisor of the first author, introduced him to the problem, and guided the derivation and implementation of the model: in particular, the inclusion of the wavelength-dependent albedo feature was an idea of the thesis author, and proved to be a highly useful property of the finished model. Also, some of the reference renderings shown in the paper were done by the author with ART, as no other rendering software was capable of showing the fluorescence effects that were needed to demonstrate the effect of the ultra-violet radiation that is part of the model.

This paper was a continuation of earlier sky modelling efforts conducted in Vienna which were included in the first habilitation: back then, the focus was mainly on sky dome polarisation patterns. The 2012 model has no polarisation component: but future research will yield an integrated model that finally combines all these features.

The 2012 model was crafted to be as useful as possible for the spectral rendering community. It has found widespread use in commercial products, becoming the de facto standard (as of 2020) in this regard for offline rendering systems. A key reason for becoming so ubiquitous was no doubt the fact that we made source code and date of the model freely available from the get-go, under a permissive Open Source license.

1.5.2 Chapter 3: Hero Wavelength Sampling

This research work was conducted while on a sabbatical in the research department at Weta Digital: the new technique was urgently needed to make the then new production renderer *Manuka* (described in Fascione et al. [2018]), which the studio was in the process of developing for in-house use, practical. The thesis author had the basic idea, and personally implemented the technique to initial production ready status in the system. Since then, HWS has become the de facto standard for inclusion of spectral rendering in path tracers. An Open Source implementation of the technique is made available in ART, our own rendering software.

1.5.3 Chapter 4: Contrast Enhancement for 3D Print Textures

This work was a protracted research effort, as the research group in Prague had not had prior experience with 3D printing technology. The initial idea for the entire project was hatched by the thesis author, after seeing blurry textured 3D print-outs at the labs of the Fraunhofer IGD in Darmstadt during the EGSR 2015 conference. The Prague research group had at the time just started to collaborate with a wider network of other institutions as part of DISTRO, an EU ITN focused on Distributed 3D Object Design. The initial experiments with hand-crafted 3D prints that served as proof of concept were done by the thesis author, and the topic was then further developed by the Ph.D. students who are lead authors. However, the thesis author also continued to contribute research input, and not just supervision: in particular, the measurement of 3D print material parameters was partially done by him, due to his prior experience with ellipsometric methods described in Berger et al. [2012]. These were used to accurately determine the index of refraction of the involved materials, which was an essential ingredient in setting up a predictive simulation.

1.5.4 Chapter 5: Practical Fluorescence Path Tracing

In this paper, we essentially ported Hero Wavelength Sampling (HWS) by Wilkie et al. [2014] to ART: and as ART supports fluorescence, we needed to make HWS compatible with this phenomenon. Which it had not been, in its original form - and this essentially prevented fluorescence from being included in a modern path tracer. This work turned out to be fairly intricately mathematical, and provided the foundation for including fluorescence, both on surfaces and in volumes, in a modern renderer. Volumes in particular post particular challenges in this regard, which were solved by this work. The contribution of the thesis author was supervision, guidance and implementation, as well as refinements of the underlying rendering software.

This work has not yet been duplicated by commercial software, but will serve as a basis for future research in appearance modelling. In a certain way, this paper is the conclusion of many years of work that started with the 2001 paper by Wilkie et al. [2001] about combined fluorescence and polarisation rendering: this paper was also one of those included in the first habilitation thesis. In contrast to the slow and inefficient technique introduced in 2001, this new method is now an actually useful, robust technology that is compatible with state of the art rendering technology. As such, it enables to move the frontiers of appearance modelling to include wavelength-shifting materials.

1.5.5 Chapter 6: Fluorescence-enabled Spectral Uplifting

This latest work was the result of a second research stay at Weta Digital, and was again direct hands-on research work performed by the thesis author. It was finished by Alisa Jung once the thesis author returned to Prague after the sabbatical, but the basic idea and the core codebase used to generate the results were implemented by him while at Weta in New Zealand.

This work is still quite new, and goes in a still rather uncharted direction: asset development by artists is done in colour space, but rendering engines are increasingly spectral, and require such input data. Spectral uplifting for gamut-limited ”normal” colours was recently decisively solved by a brilliant technique introduced by Jakob and Hanika [2019]: but this still does not include the super-bright colours that fluorescent materials can exhibit. Our new technique offers the possibility to go in this direction for the first time: as such, this is to be considered preliminary work that will be expanded on in the future. The parameter space for spectral uplifting is large, and future refinements will give artists far better control over which aspects of fluorescence end up being used in the material defined by a given highly saturated RGB colour. However, the groundbreaking innovation of being able to do this in the first place has now been made.

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Chapter 2

Realistic Sky Dome Models

Published as:

- Lukas Hosek, Alexander Wilkie
  An Analytic Model for Full Spectral Sky-Dome Radiance
  ACM Transactions on Graphics, 31(4), July 2012

Please note that there were also two follow-up publications which extended the model in various ways, and which are not included here:

- Lukas Hosek, Alexander Wilkie
  Adding a Solar-Radiance Function to the Hosek-Wilkie Skylight Model
  IEEE Computer Graphics and Applications, 33(3), pp. 44-52, 2013

- Alexander Wilkie, Lukas Hosek
  Predicting Sky Dome Appearance on Earth-like Extrasolar Worlds
  Spring Conference on Computer Graphics, SCCG '13, Smolenice, Slovakia, May 2013

Chapter 3

Making Spectral Path Tracing Practical - Hero Wavelength Sampling

Published as:

- Alexander Wilkie, Sehara Nawaz, Marc Droske, Andrea Weidlich, Johannes Hanika
  Hero Wavelength Spectral Sampling
  Computer Graphics Forum, 33(4), pp. 123-131, July 2014

Chapter 4

Using Path Tracing to Enhance Texture Contrast in Full-Colour 3D Printing

Published as:

- Oskar Elek, Denis Sumin, Ran Zhang, Tim Weyrich, Karol Myszkowski, Bernd Bickel, Alexander Wilkie, Jaroslav Křivánek
  Scattering-aware Texture Reproduction for 3D Printing
  ACM Transactions on Graphics, 36(6), November 2017

Note that there was a follow-up publication which extended the initially restricted capabilities of the technique shown in this paper to full 3D objects:

- Denis Sumin, Tobias Rittig, Vahid Babaei, Thomas Nindel, Alexander Wilkie, Piotr Didyk, Bernd Bickel, Jaroslav Krivanek, Karol Myszkowski, Tim Weyrich
  Geometry-Aware Scattering Compensation for 3D Printing
  ACM Transactions on Graphics, 38(4), July 2019

We opted to include the older paper in this thesis, as it shows the underlying concepts more clearly, and as it was the more groundbreaking work: prior to the 2017 paper, no functionality of this sort had been demonstrated before.

Chapter 5

Making Fluorescence Path Tracing Practical

Published as:

- Michal Mojzík, Alban Fichet, Alexander Wilkie
  Handling Fluorescence in a Uni-directional Spectral Path Tracer
  Computer Graphics Forum, 37(4), pp. 77-94, July 2018

Chapter 6

Using Fluorescence in Spectral Uplifting

Published as:

- Alisa Jung, Alexander Wilkie, Johannes Hanika, Wenzel Jakob, Carsten Dachsbacher
  Wide Gamut Spectral Upsampling with Fluorescence
  Computer Graphics Forum, 38(4), pp. 87-96, July 2019