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Quality Assurance Based on Descriptive and Parsimonious Appearance Models

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Abstract

In this positional paper, we discuss the potential benefits of using appearance models in additive manufacturing, metal casting, wind turbine blade production, and 3D content acquisition. Current state of the art in acquisition and rendering of appearance cannot easily be used for quality assurance in these areas. The common denominator is the need for descriptive and parsimonious appearance models. By 'parsimonious' we mean with few parameters *so that a model is useful both for fast acquisition, robust fitting, and fast rendering of appearance. The word 'descriptive' refers to the fact that a model should represent the main features of the acquired appearance data. The solution we propose is to reduce the degrees of freedom by greater use of multivariate statistics.*

Categories and Subject Descriptors (according to ACM CCS): I.4.1 [Image Processing and Computer Vision]: Digitization and Image Capture—Reflectance

1. Introduction

Much work has gone into formulating radiometric models of surface reflectance for believable photorealistic rendering of material appearance. This has led to a number of physically plausible models with intuitively meaningful parameters that are appropriate for direct manipulation [MHH*12]. In this positional paper, we discuss the use of appearance models in a different context, namely in quality assurance of physical and digital products. We argue that this area of application requires models with few parameters, or parsimonious models. Through our example use cases, we further argue that there is a significant need for such parsimonious models, and that effort should be put into their development.

The need for parsimonious radiometric models manifests itself when we need to estimate the radiometric properties of surfaces in practice, e.g. when doing industrial inspection to ensure that the products have the specified visual properties, or when we would like to acquire photorealistic models from images. In such cases, the number of measurements is limited, maybe 5 to 20 per surface patch. This should be seen in light of the number of measurements needed to reliably estimate a general bidirectional reflectance distribution function (BRDF). A BRDF is modeled by a 4D manifold and is typically measured using a spherical gantry (a gonioreflectometer). This means that a very large number of measurements is required, which in many cases is practically infeasible.

According to the philosophy associated with Occam's razor, the formulation of descriptive and parsimonious models will also force us to better model and understand the underlying radiometric phenomena. Thus, in the end, our models should hopefully lead to physically plausible models with few intuitively meaningful parameters as is needed for the more classical applications of appearance models. We believe that it is possible to make large advances in this direction, meaning that the task of formulating parsimonious models does not seem to be a frugal one.

2. Relating to existing models

Previous work has shown that the classical empirically and physically based computer graphics reflectance models cannot fit all measured reflectance data well [NDM05]. This has led to a quest for models that provide a better fit [BSH12, LKYU12]. The cost of a better fit is an increase in the number of model parameters, and the simplest model (the Phong model [Pho75]) already has two parameters per color band and one parameter to describe the material glossiness. As such, the simplest model requires at least seven measurements although ideally many more to robustly fit measured reflectance data. In applications of real-time reflectance acquisition, this quickly becomes infeasible.

The fitting of most parametric models is far from triv-

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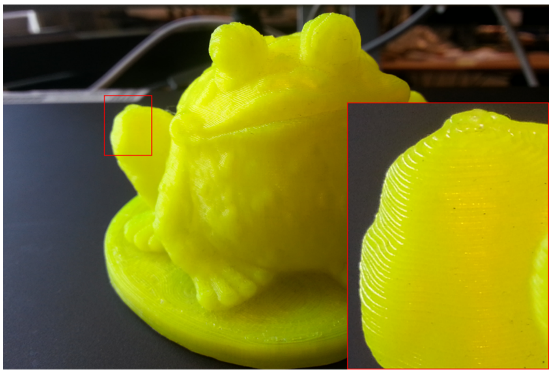

Figure 1: *Frog printed out of Polylactic acid (PLA) plastic using a Fused Deposition Modeling (FDM) printer.*

ial. Major challenges include determining what optimizers to use and what objective functions they should minimize. For the latter, various suggestions have been proposed including L_1 minimization [NFCA14] and log-transformation with cosine-weighting of observed data [NDM05]. To address the issues of non-linear model fitting, alternative approaches have been proposed where reflectance is modeled by linear combinations of basis functions. Suggestions to basis functions include spherical harmonics [WAT92], wavelets [SS95], and densely sampled reference reflectances [MPBM03]. The advantage here is that fitting models to observations becomes extremely easy as this corresponds to solving a linear system of equations. The challenge however, which is an unsolved problem, is identifying a *sparse* set of basis functions that model a wide variety of material appearances well. We need, as a community, to work on this.

3. Relevant Cases

To argue relevance, we now describe four cases where we have identified that the current radiometric models or acquisition methods simply do not suffice. The cases are (1) additive 3D printing, where the 3D microstructures caused by the printing process cannot be modeled well by standard reflectance models; (2) real-time monitoring of reflectance in metal production; (3) estimation of surface reflectance on massive objects (wind turbine blades); and (4) reflectance models to be used with 3D scanners to allow simultaneous acquisition of geometry and appearance. These are all problems that cannot be solved by conventional methods.

3.1. Additive Manufacturing

For the past decade, additive manufacturing (3D printing) has been an accepted production method. Today, it is possible to manufacture products in multiple materials ranging from soft polymers to metals [WC13]. A rapidly growing market of internet printing services is emerging (shapeways.com and i.materialise.com, for example) where users can upload their own 3D models for printing. Fast and realistic material rendering is of great interest to these types of services, allowing users to previsualize the printed outcome of their models prior to committing to purchase. However, accurately obtaining these radiometric models is a challenge. The layer-like nature of the printing process yields surface artifacts, the most prominent known as the ‘staircase effect’ which drastically alters material appearance for some materials. Visually, we observe this as a local anisotropy, often correlated with the surface curvature, see Figure 1. Thus the printing process itself must be considered when producing an accurate model of the printed appearance.

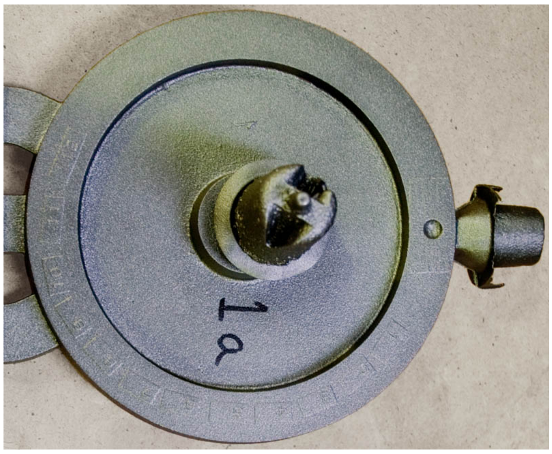

Figure 2: *Example of iron casting [VSRT15], where the mould has introduced a surface roughness affecting the visual appearance of the product. Image is courtesy of Nikolaj Kjelgaard Vedel-Smith.*

Radiometric model acquisition also has an application in the quality assurance aspect of additive manufacturing. So far, most effort has been placed on in-line geometric verification of parts [HNRP14, PH14] and color verification [EPA15]. These optical systems capture each and every layer during the print in order to verify its correctness. Combinations of such systems along with rapid radiometric acquisition could prove beneficial as slight deviations from the material optical properties could indicate failure due to e.g. overheating (color change) or structural collapses (surface normal orientation). In essence, we need to verify the quality of 3D prints, but practical constraints limit the number of measurements that it is possible to acquire.

3.2. Metal Casting

Metal casting is still an actively used production method. Casting allows for the creation of seamless and rigid structures in various materials. However, post machining of said

Figure 3: *Wind turbine blade right after molding.*

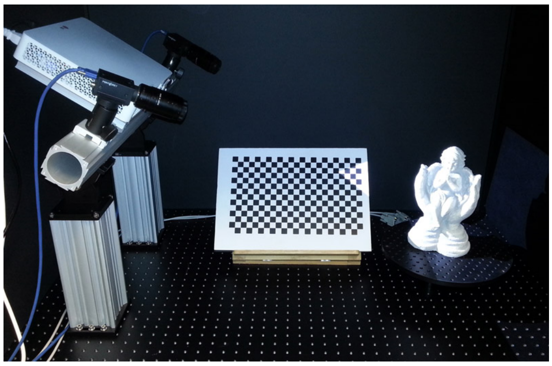

Figure 4: *Structured Light system scanning a statue.*

objects is in many cases required due to the rough surface texture resulting from the casting process, see Figure 2. Measurements of surface roughness parameters are useful for industry and academia in order to optimize the casting procedure as it is related to the overall cast quality. Obtaining surface roughness parameters from optical reflectance is thus of great interest and is an active field of research [NTH13]. As in the case of additive manufacturing, we see a scenario where practical constraints limit the feasible number of measurements, thus creating a demand for accurate parsimonious reflectance models that enable robust fitting.

3.3. Wind Turbine Blades

One of the most important steps in quality inspection of wind turbine blades is to find transverse folds in their longitudinal fiberglass mats. The longitudinal mats run all the way from the root of the blade to the tip and provide the blade with the bulk of its rigidity and strength. Multiple layers of longitudinal mats are needed to provide the necessary strength, and the load must be evenly distributed across the layers. If one layer has a fold, that layer will be tightened harder than the rest of the layers, thus carrying more load when the blade is being operated. Over time, this increased load will wear the fold-layer down to the point where it snaps and thereby compromises the entire structure of the blade. Usually, this sudden release of tension creates a force on the remaining layers so that these also snap. The result is a broken blade.

Before painting, wind turbine blades are translucent due to their composition of transparent epoxy resin and fiberglass (see Figure 3). A fold on a fiberglass mat will create a bulge beneath the surface which alters the optical properties of the material. Currently, specially trained quality engineers shine powerful light parallel to the surface and look for changes in the reflections. An accurate automated measure of surface BRDFs could increase the efficiency and accuracy of the quality assurance by transforming the fold inspection from a qualitative process into a quantitative process.

3.4. Creating 3D Content

Optical 3D scanners are actively used throughout various fields such as archaeology, biology, production, entertainment, medicine, and art. All aiming to capture high resolution 3D models in a relatively short amount of time. However, in order to produce realistic and applicable digitization of scanned objects, their radiometric properties must also be determined. Many commercial systems provide the ability to capture surface textures in order to provide more aesthetically pleasing models, but are often limited to assuming Lambertian behaviour or at most a simple parametric model, such as Phong [Pho75] or Ward [War92]. As indicated in Section 2, these models fail to fit the reflectance properties of many real-world materials. Trouble is that we cannot improve the fit by increasing the number of model parameters as we need to acquire reflectance properties at speeds comparable to the 3D scanning process. This underlines the need for descriptive and parsimonious appearance models.

An interesting property of structured light (SL) scanners is the fixed angle between observer (camera) and lightsource (SL projector). This is illustrated in Figure 4. Using only existing components of such a setup thus poses a constraint on the observable regions in the BRDF domain. Likewise, the geometry also dictates illumination and view directions relative to the surface normal. Hence, again we see a practical limitation on the available observations, which causes a demand for parsimonious models that enable robust fitting.

4. Discussion

From the above, it is evident that there are number of relevant cases where today's methods do not suffice. We believe that the problems in the mentioned cases can be solved, but that they require us to approach material appearance modeling from a new angle. Specifically, we believe that data analysis and multivariate statistics should be involved more than we see it today, and also that we should introduce stronger priors on the data. Such tools are necessary to considerably reduce the degrees of freedom in the problems. A solution of this kind will greatly contribute to streamlining and automating the entire production pipeline, which is an essential part of agile product development.

Conclusively, we would like to reiterate that descriptive and parsimonious reflectance models seem indispensable if we are to use material appearance models in the context of quality assurance of printed, molded, and digitized products.

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