Computational Imaging for Inverse Scattering

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Abstract

Scattering materials are ubiquitous: from our skin and food, to every day objects such as wax and soap, to industrial materials such as coatings and soft tissues. Common to all these materials is the complex way in which they interact with light. Their appearance is the result of photons that penetrate the material surface, and perform random walks inside the material before emerging towards a camera. Inverse scattering is, then, the problem of inverting this light transport process, in order to infer scattering parameters from images of a material.

We approach inverse scattering as an appearance matching problem: given a set of measurements (images) of a material, we search for the scattering parameters which, when used to computationally render new images, minimize the difference with the captured ones. In full generality, this is a very challenging optimization problem, due to the high-dimensional search space and the non-linear dependence of images on scattering parameters. We present several contributions for making this optimization problem tractable.

First, we introduce a computational framework for efficiently solving the appearance matching problem. Our framework is based on a combination of operator theory, stochastic gradient descent, Monte Carlo rendering, and material dictionary representations. It allows inverting the light transport process in a broad range of scattering materials, without having to rely on common approximations such as single scattering and diffusion. Additionally, it accommodates rich, high-dimensional material representations, enabling us to accurately measure parameters such as the scattering phase function shape, without having to rely on restrictive low-parameter models. To evaluate this framework, we created an acquisition setup that images thin material slabs under narrow-beam illumination from multiple lighting and viewing directions. Using measurements from this setup, we used our algorithm to infer the parameters of homogeneous scattering materials. Our experiments show that we can accurately recover all scattering parameters of ground-truth materials (reference polydispersions whose scattering parameters are given by Mie Theory). Additionally, using our measured scattering parameters for several common liquids and solids, we can accurately predict their appearance under novel geometric configurations.

Second, we present a computational imaging system that allows capturing rich sets of measurements from scattering materials, to be used as the input in the appearance matching framework. Our system is based on interferometric techniques, and specifically on the optical coherence tomography framework. It collects measurements corresponding to decompositions of photon contributions into subsets, based on the distance they travelled inside the material, or their point of origin on the source illuminating the material, or both. These decompositions are equivalent to the measurements obtained from recently introduced computational photography techniques, such as transient imaging and spatial probing. However, our use of interferometry allows us to capture these decompositions at micron-scale resolutions, two to three orders of magnitude larger than previously possible. Such resolutions are necessary when collecting measurements for inverse scattering applications. We describe how to construct and optimize an optical assembly for this technique, and we build a prototype to measure and visualize scattering materials, as well as other optical phenomena.

Third, we discuss ongoing work where we combine our computational framework and imaging system, in order to perform inverse scattering for more general, heterogeneous materials. We show how this combination can accommodate material representations tailored to very different types of heterogeneities, such as those present in skin, cloth, or jade. We discuss strategies for scaling up both the computational and imaging components of our methods, so that they can tackle the much higher-dimensionality of heterogeneous inverse scattering problems. Finally, we explore possible extensions towards measuring other material properties such as heterogeneous dispersion and birefringence.