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Time-resolved reconstruction of scene reflectance hidden by a diffuser

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Abstract: We use time-of-flight information in an iterative optimization algorithm to recover reflectance properties of a three-dimensional scene hidden behind a diffuser. We demonstrate reconstruction of wide-field images without relying on diffuser correlation properties.

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Imaging through scattering media is an important problem in optics, with applications at both macroscopic and microscopic scales, including imaging through atmospheric turbulence, underwater sediment, and biological tissue. For weak scattering, adaptive optics has proven useful, whereas in more strongly scattering media, phase conjugation [1] and generalized wavefront coding via spatial light modulators (SLMs) [2] have provided significant advances. However, SLMs are often limited by the "memory effect," which can constrain significantly the field of view of the scene of interest to the correlation properties of the diffuse material, and phase conjugation requires a double-pass through the material.

A recent method used time-of-flight imaging of multiply scattered light was used to reconstruct three-dimensional scenes [3]. There, consideration was given to only uniform-reflectance objects. Gray-scale reflectance reconstruction, however, is very important, especially for, e.g., pattern recognition and pathology studies, distinguishing signatures between various cells in medical imaging, and measuring properties in astronomical bodies.

Here, we utilize time-of-flight data in an iterative optimization algorithm to reconstruct the spatially varying reflectance values of a scene that is hidden behind a diffuser. We exploit the information contained in the *scattered light*, which is usually ignored or unwanted for time-resolved techniques such as lidar, gated imaging, and optical coherence tomography. The system and algorithm is first calibrated using a single, small square patch object. Then using the calibrated parameters, scenes with varying patches and reflectances are reconstructed.

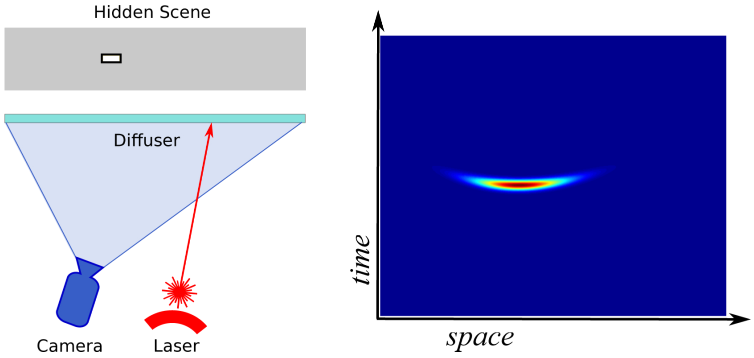

Fig. 1. Setup for time-resolved image acquisition and reconstruction of reflectance of hidden scene behind the diffuser (left). Every scene point generates a hyperbola in the space-time 'streak image', which is shown here in false color (right).

Our experimental setup is shown in Figure 1. Pulses, of 50 fs duration from a Ti:Sapphire laser, are focused onto a ground-glass diffuser. Transmitted light is scattered to a three-dimensional scene, which subsequently scatters light back to the diffuser through the front side. A zoom lens images the front side of the diffuser onto the streak camera (Hamamatsu C5680) aperture. The streak camera has a one-dimensional line of view of the diffuser and generates "streak images," as shown in Figure 1 (right), with a nominal temporal resolution of 2 ps. Using a known, simple scene (1 white, square patch), the physical parameters of the system are first calibrated using nonlinear optimization. We assume that we know approximate geometry of the hidden scene, which can be estimated using methods described in [3].

A single scene points generates a hyperbola in the streak image, while the image for a complex scene is a linear combination of hyperbolas with varying intensities (depending on reflectance and geometry of the scene), position, and scaling (depending on depth of the object). These parameters are fixed and saved for future use.

We now build a forward model for streak images using the geometry information of the scene based on light transport theory and render synthetic streak images. We reconstruct the reflectance of hidden scene points by solving a non-linear optimization problem to reduce the error norm between the real streak images and the rendered streak images. We use multiple streak images captured from different laser spots to improve our reconstruction error. Note that tt is not possible to recover the reflectance of all the scene points in a complex scene using only time-of-arrival information (as in gated imaging); because no pixels might exist which capture light reflected from only one scene point.

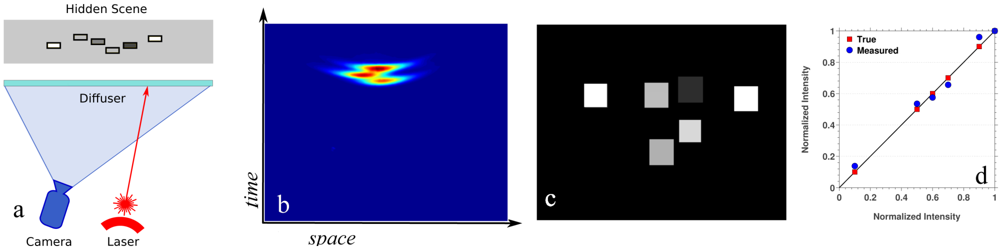

Fig. 2. We reconstruct a complex scene (a), using streak images captured by our setup (b). A fronto-parallel view of the reconstructed scene reflectances is shown in (c) along with a comparison with true reflectance values (d).

We demonstrate our method using a complex scene consisting of six patches (each 15×15 mm) hidden behind a ground glass diffuser. We capture 16 streak images of this scene. Using our forward model and estimated diffuser statistics, we perform non-linear optimization using the interior-point algorithm to solve for the unknown reflectances of scene points. Figure 2(c-d) demonstrates that we successfully reconstruct the varying reflectance of this scene.

We currently assume that the hidden scene comprises only diffuse objects without specularity, though this is not a fundamental limitation of our method; it can be easily modified to reconstruct a four-dimensional reflectance function for the scene points, using methods similar to [4]. Moreover, the spatial resolution of our reconstructed images is limited by the spatial resolution of our streak camera, which is $\sim 400\,\mu m$ axially and and 0.5–1 cm laterally. However, the experiments can successfully scale up to larger scenes using higher power lasers and wider camera aperture, allowing researchers to explore novel applications of this method, such as non-invasive body scanning for security purposes.

In conclusion, we have demonstrated the computational reconstruction of the spatially varying reflected of a wide-field scene using multiple-bounce time-of-flight information. The reconstruction method is general and can be modified so as to include higher order (diffraction) effects. Because of the natural temporal-angular coupling of light propagation, our time-resolved method can be integrated with spatial modulation afforded by SLMs, nonlinear optics, and digital signal processing.

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