Looking Around Flatland: End-to-End 2D Real-Time NLOS Imaging

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Abstract

Non-line-of-sight (NLOS) imaging methods reconstruct scenes hidden around one corner using indirect third-bounce illumination with high temporal resolution on a visible surface. Unfortunately, acquiring or simulating this information is expensive. We present a simulation-based NLOS imaging pipeline for scenes with two spatial dimensions to enable fast prototyping and analysis.

Introduction

Non-line-of-sight (NLOS) imaging methods aim to reconstruct partially or fully occluded scenes, with potential medical imaging or autonomous driving applications. By using ultra-fast imaging devices, it is possible to illuminate and capture scattered light at a visible surface with up to picosecond resolution [1]. The captured signal contains the time of flight (ToF) of the photons, and it is possible to reconstruct the hidden scene through software signal processing. One of these solutions is the phasor-field formulation, which poses the visible surface as the aperture of a virtual camera and projector that have direct line of sight towards the hidden scene [2].

However, the development of new time-gated NLOS imaging methods still suffers from three main problems. First, capture hardware is expensive and can require long capture times. Second, setting up scenes in a laboratory and calibrating the system can take hours or days per experiment. Third, the high dimensionality and density of the capture data lead to severe memory constraints. Simulation of transient light transport in synthetic scenes allows researchers to precisely set up scenes in minutes. However, these algorithms suffer from high computational complexity and generated data maintains the same memory constraints. Consequently, NLOS imaging methods deal with high-dimensional data, leading to high computational and memory costs, with high-resolution results taking several minutes or hours to compute.

In our work, we rely on dimensionality reduction to present a simulation-based NLOS imaging pipeline implemented in WebGL that couples physically-based transient rendering in 2D scenes with NLOS imaging reconstruction methodologies, providing real-time results and comprehensive control of scene and imaging parameters. We extend existing formulations of steady-state light transport in self-contained 2D worlds [3] to account for transient light transport, based on the transient path integral formulation [4]. We then couple our 2D transient path integral formulation with our 2D re-formulation of phasor-based NLOS imaging models. We implement this combination in a WebGL-based end-to-end pipeline that simultaneously performs transient rendering and NLOS imaging at real-time rates, thanks to computational speedups of up to five orders of magnitude w.r.t. equivalent 3D counterparts. We observe that NLOS imaging methods in 2D retain known visibility problems [5] and expand on this visibility analysis.

2D NLOS Imaging Pipeline

We formulate transient light transport in 2D based on the transient path integral [4] and 2D radiometry [3], obtaining the 2D transient path integral. We build upon it to modify the 2D steady-state renderer Tantalum [6]. We add support for transient light transport simulation and model an ultra-fast sensor that captures light reflecting off the visible surface. We offer multiple configuration options for flexibility, such as sensor resolution and extent, both spatial and temporal, confocal and non-confocal setups, laser and sensor location and orientation, and a semi-automated tool to create and load new scenes.

We adapt three different NLOS imaging camera models derived from the phasor-field formulation to the 2D domain. These camera models allow us to estimate the geometry in the hidden scene, observe light propagating through the hidden scene, and look at the scene as if using a conventional camera. Additionally, we implement common filtering and tone mapping strategies for better visualization. The resulting image is updated as the rendering runs, showing results in real time.

Results

We validate our system by replicating existing 3D experiments in our 2D simulation system. Third-bounce NLOS imaging methods have limited visibility due to the position and orientation of certain objects with respect to the laser and SPAD baseline on the visible surface [5]. We illustrate this behavior in Figure 1, where we show and replicate their experiment, containing three patches (segments in our equivalent 2D scene) S1, S2, S3 in different locations and orientations. S1 and S2 can be reconstructed while S3 remains invisible.

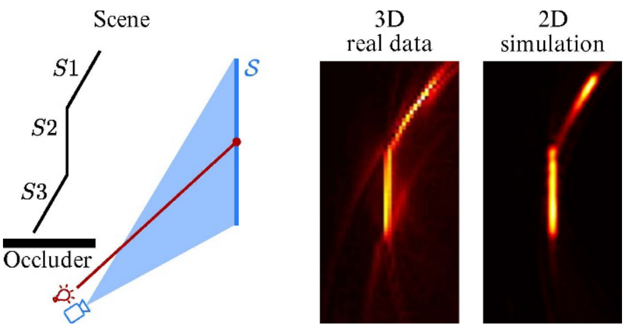

Figure 1. Illustration of the limited visibility problem in NLOS imaging in the 3D scene by Liu et al. and our 2D equivalent, where it prevents S3 from being imaged.

In Figure 2, we extend their analysis by exploring the effect of changing the local structure of the segments so that S1, S2 and S3 have facets of 1.5 cm. Since most facets are not affected by the limited visibility problem, we can now image all three segments.

In Table 1, we demonstrate the benefits of our pipeline in terms of computational speedups and total memory requirements by evaluating two pairs of equivalent 3D and 2D NLOS setups with a hidden Stanford bunny. We evaluate the scenes with two different lateral resolutions: 128×128 and 256×256 sensor points in 3D, and 128 and 256 sensor points in 2D. Our implementation obtains overwhelming NLOS imaging speedups of up to five to six orders of magnitude compared to 3D, which allows us to couple the NLOS imaging process with progressive simulation of light transport samples, showing imaging results in real time. Memory requirements reduce drastically after we remove one spatial dimension.

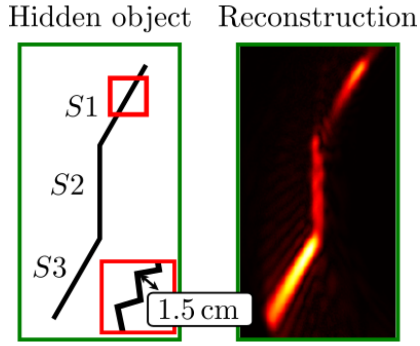

Figure 2. Extension of the visibility analysis by Liu et al. The presence of facets changes the behavior of the object under NLOS imaging methods, and we can image S3.

Table 1. Time and memory requirements comparison between equivalent 2D and 3D scenes with an equivalent number of simulated samples.

		Simulation			Imaging			Memory		
Scene	Δx	3D	2D (Ours)	Speedup	3D	2D (Ours)	Speedup	3D	2D (Ours)	Saving
BUNNY	256	11.12 s	16 ms	694.9	4.8 min	1.6 ms	1.8×10^5	871 MB	6.56 MB	132.77
BUNNY	512	76.27 s	16 ms	4867.5	46.4 min	2.8 ms	9.9×10^5	3.4 GB	12 MB	283.33

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