Zone Plate Virtual Lenses for Memory-Constrained NLOS Imaging

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Abstract

Phasor Fields is a wave-based formulation that allows computing time-efficient NLOS reconstructions using Rayleigh-Sommerfeld diffraction kernels. Unfortunately, these kernels are heavy in memory, hampering the integration in memory-constrained devices. We propose alternative kernels based on zone plates that require 16 times less memory to store, offering an attractive trade-off.

Introduction

The non-line-of-sight (NLOS) imaging aims to reconstruct a partially or fully occluded scene. By using transient imaging, which deals with the capture of light transport at vastly high frames per second [1], it is possible to illuminate and capture the scattered light of a hidden scene into a visible surface or relay surface (see Figure 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. Among the variety of proposals to solve the problem is the formulation of *Phasor Fields*, which generalizes the NLOS imaging by treating the relay surface as a virtual lens [2]. This assumption allows us to transform effectively an NLOS problem into a virtual line-of-sight (LOS) problem, and thus, the hidden scene can be imaged using well-known Fourier optic tools.

The Phasor Fields formulation is a wave-based method. In their original work, the authors proposed the Rayleigh-Sommerfeld diffraction (RSD) integral to model the exact diffraction of the light to inverse the propagation of the light and hence obtain the reconstruction. Later work proposes efficient implementations that rely on RSD-based kernels to calculate this propagation with 2D convolutions to image the hidden scene [3]. Unfortunately, the memory required to store these kernels scales with the number of Fourier components used for the propagation, the resolution of the data, and the reconstruction size. The values of the RSD kernels are complex, which increases the storage required if compared to floating precision or integer values.

To overcome this problem we investigate the use of alternative lens operators in the virtual camera of Phasor Fields formulation. Specifically, we propose the zone plates (ZP) as virtual lenses, which use diffraction instead of refraction or reflection to bring a wavefront into focus. These devices are manufactured in a very simple manner: alternating concentric rings of opaque and translucent (an example can be seen in Figure 1). In the computational domain, this traduces into the storage of simple binary values for a lens.

We propose to use ZP-based kernels that require up to 16 times less memory than the RSD-based kernels while being also faster to generate and compute. Our results show that the reconstructions using our ZP provide a valid approximation of the reconstruction for the exact diffraction of the RSD at a much smaller cost. Our approach represents a step forward toward the integration of NLOS imaging systems into embedded and small devices, e.g. in car driving systems, medical imaging, or portable devices.

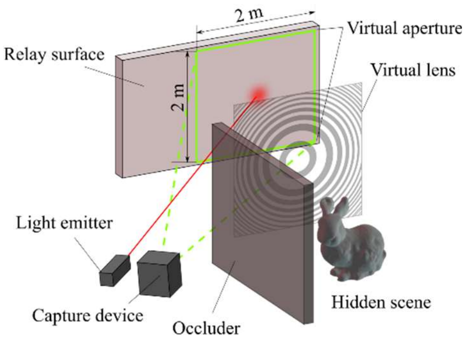

Figure 1: General setup of the NLOS problem. A paired system laser and SPAD (single-photon avalanche diode) illuminate and capture a relay surface, to obtain the time-of-flight of the light scattered from an occluded hidden scene. In this work, we explore the idea of using virtual lenses based on zone plates to reconstruct the hidden geometry from such scattered light.

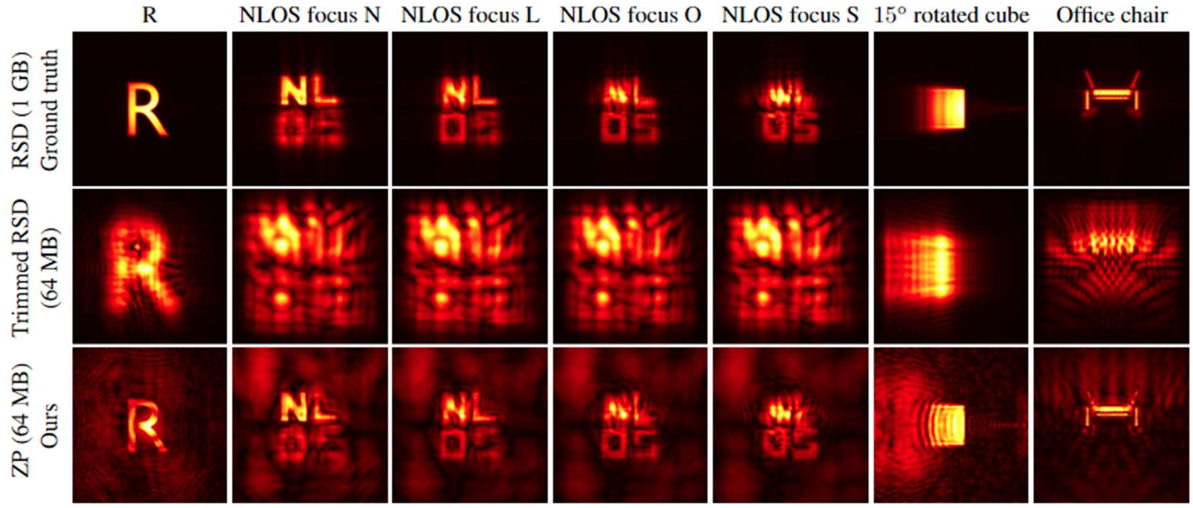

Figure 2: Reconstructions of the hidden scenes using different kernels. From top to bottom: the exact diffraction with the RSD kernel (1GB), a trimmed RSD kernel (64 MB), and our ZP kernel (64 MB). The trimmed RSD kernel fails to properly reconstruct the hidden geometry. In contrast, our ZP kernel allows us to image the hidden scene, with clearly identifiable geometry and sharp edges, despite the residual noise in empty areas, presenting an attractive memory trade-off compared with the RSD.

Methods

Our approach consists of creating kernels based on the ZP to focus the virtual wavefront from the Phasor Fields formulation into a point of space. It is possible to focus on a parallel plane to the relay surface if we apply a 2D convolution instead. Our ZP kernels follow the same structure as the traditional ZP devices. We replaced the RSD kernels of the previous Phasor Fields approach with our kernels, similar to a switch of the lens in a classical camera.

For our experimental validation, we compare the approximate reconstruction of our proposed ZP-based kernel with the exact diffraction obtained with the RSD-based kernel reconstruction. We also defined a trimmed version of the RSD-based kernel in the same memory scenario as our proposal. The data used for the validation is synthetic, obtained with a transient renderer optimized for the NLOS setups [4].

Conclusions and discussion

The Phasor Fields framework allows for transforming theoretically the relay wall into a virtual lens. Exploiting this allows researchers to make use of LOS tools, and specifically, the knowledge of Fourier optics. Thus, previous works reconstruct the hidden scenes of NLOS making use of RSD kernels, at the cost of heavy memory consumtion.

Our proposal overcomes these memory consumption problems by introducing zone plates as virtual lenses. In the results shown in Figure 2, we observe that our ZP kernels are capable to focus on the hidden objects, at the cost of adding noise in the empty areas. We observe the sharp edges of the objects in our approach that perfectly match the exact diffraction of the RSD kernel, using only 64 MB of memory for the first one, in contrast to the 1 GB required to obtain the second. Furthermore, we observe that trimmed versions of the RSD kernel are incapable to reconstruct the hidden scenes, obtaining out-of-focus artifacts due to the smaller relay surface used to reconstruct. In conclusion, our proposal offers an attractive trade-off between quality and needed resources, making it a viable option for devices with strong memory constraints.

There are still many interesting avenues of research for the application of lenses or kernels in the virtual camera system. Future work could try new operators to focus on non-parallel planes or reduce the memory and time required for reconstructions.

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