Virtual Mirrors: Non-Line-of-Sight Imaging Beyond the Third Bounce

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Abstract
Non-line-of-sight (NLOS) imaging methods reconstruct scenes hidden around one corner using indirect third-bounce illumination on a visible relay surface. We show how diffuse hidden objects may exhibit specular behaviour in NLOS methods, and how fourth- and fifth-bounce illumination can encode useful information, such as imaging objects hidden around two corners.

Introduction
Non-line-of-sight (NLOS) imaging methods are able to reconstruct scenes hidden around a corner, with many applications in autonomous driving, remote sensing, or medical imaging. NLOS methods have presented promising advances with ultra-fast imaging devices, capturing light in motion with up to picosecond resolution [1] (Fig. 1a and Fig. 1b). Under this regime, time-gated NLOS imaging methods generate detailed reconstructions of hidden scenes by triangulating geometric positions using the time of flight of round-trip third-bounce illumination paths between a visible relay surface and scene [2].

Time-gated methods operate under the assumption of third-bounce-only illumination, with higher-order illumination degrading their reconstructions due to ambiguities in the time of flight of captured light, thus higher-order illumination is typically discarded. The phasor-field formulation [3], which we use throughout our work, uses third-bounce illumination in two steps. First, it computes the response of the scene to an arbitrary illumination function, based on the captured impulse response (Fig. 1c). Second, it computes an image of the hidden scene from the previous response at the relay surface, based on an imaging paradigm that interprets the time-resolved illumination captured at the relay surface as light arriving at the virtual aperture of a computational camera. This effectively converts the relay surface into a virtual line-of-sight (LOS) imaging system (Fig. 1d). Here it is key to understand that there are two domains, real and computational, where surfaces may exhibit different reflectance properties.

Diffuse surfaces as virtual mirrors
A key observation in our work is that diffuse surfaces may exhibit specular properties in the computational NLOS wave imaging domain. In wave-based methods, time-resolved light transport \( P(x, t) \) at any point \( x \) in the scene (\( t \) represents time) becomes a complex-valued phasor \( \hat{P}(x, \Omega) = \mathcal{F}\{P(x, t)\} \), which represents the amplitude and phase of the light wave, for frequencies \( \Omega \) by applying a Fourier transform. When light travels from point \( x_0 \) to point

![Image](image_url)
\[ \hat{P}(x_b, \Omega) = \hat{P}(x_a, \Omega) e^{ik|x_b - x_a|} \]

where \( |x_b - x_a| \) is the optical distance between \( x_a \) and \( x_b \), and the wavenumber \( k = 2\pi\Omega/c \) (where \( c \) is the speed of light) is the conversion factor from optical distance to phase. The phase shift (numerator) and attenuation (denominator) form the RSD operator. Using this base, consider a point light at \( x_l \) whose emission is defined by the phasor \( \hat{P}(x_l, \Omega) \), and illuminates points \( x_m \) on a planar diffuse surface \( M \), resulting in the phasors \( \hat{P}(x_m, \Omega) \). We can then compute the resulting phasor at any point \( x_l \) in a volume \( V \) as a superposition of phasors reflected from \( x_m \) using Eq. 1 from \( x_l \) to all points \( x_m \in M \), and then from each \( x_m \) to all \( x_v \in V \). For a surface that is planar with respect the illumination wavelength \( \Omega^{-1} \), the phasors \( \hat{P}(x_v, \Omega) \) follow the specular reflection of \( \hat{P}(x_l, \Omega) \) on \( M \) as per Huygens’ principle.

During the NLOS capture process (Fig. 2a, which corresponds to light transport Fig. 1a and 1b), the surface \( x_m \) scatters light from \( x_l \) in all directions. In the computational domain (Fig. 2b, using Eq. 1 in the process shown in Fig. 1c and 1d), the computed light transport now follows the specular direction.

We leverage virtual mirrors to address the missing-cone problem, a long-standing issue in NLOS imaging where certain surfaces in the scene have limited visibility [4]. We explain the missing-cone behaviour using virtual mirrors, and show a procedure to directly image hidden surfaces that have limited visibility when imaged using third-bounce methods. We refer the reader to our full paper for a detailed explanation of this procedure. We also use virtual mirrors to compute images of objects hidden around a second corner.

**Looking around two corners**

We also leverage our virtual mirror reflections in the wave domain to image objects around a second corner using fifth-bounce illumination. Our key observation comes from the fact that diffuse planar surfaces may exhibit specular behaviour only in the computational domain. Thus, a planar surface creates a mirror image of objects in the hidden scene, behind such surface (like a real mirror). We image the region where this mirror image is formed, using the confocal camera model [3]. This is similar to third-bounce methods; but now uses fifth-bounce illumination by shifting the imaged region.

We design an experiment with a geometry \( G \) hidden around two corners from an ultra-fast laser and camera, both which are pointed towards the relay surface. A diffuse surface \( M \) is positioned and oriented such that the specular reflection of points in the relay surface on \( M \) reaches \( G \), and vice-versa. We image the region \( V \) (Fig. 3), which shows the mirror image \( G' \) of \( G \) seen from the relay surface.

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