A Light Transport Model for Mitigating Multipath Interference in Time-of-flight Sensors

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Continuous-wave Time-of-flight (TOF) cameras represent an increasingly popular method to obtain depth maps. These cameras calculate depth by measuring the phase difference between an emitted and received optical signal. The main source of error in TOF cameras is multipath interference (MPI), which occurs when multiple reflections of light in a scene return to a single pixel on the camera sensor. MPI occurs in natural scenes due to multiple reflections (e.g., concave surfaces), and due to subsurface scattering (e.g., the human face).

Most prior MPI correction algorithms assume sparsity in optical reflections, and recover the true phase with iterative or closed-form solutions using multiple frequency measurements (e.g., [1]). These methods cannot handle scenes with continuous multipath (e.g., subsurface scattering). Our work is more closely related to the emerging trend of incorporating light transport information, using optical and electronic modifications, to correct for MPI [2, 4]. Specifically, we employ the fast method by Nayar et al. [3] for separating the direct component of light transport from the global component and use this information in a closed-form solution for the true phase.

A TOF camera with modulation frequency f_{M} computes the depth of a scene point by estimating the phase delay φ between the the emitted signal $g(t)$ and the received signal $s(t)$. The phase delay is computed from the cross-correlation of these signals, which evaluates to

$$c(\tau) = s(t) \otimes g(t) = \frac{\alpha}{2} \cos\left(f_{\mathrm{M}} \tau + \varphi\right) + \beta. \qquad (1)$$

The Four-bucket principle [1] is used to calculate the phase ($\widetilde{\varphi}$) and amplitude ($\widetilde{\alpha}$) from $c(\tau)$. In the absence of multipath interference and sensor noise, the calculated variables $\widetilde{\varphi}$ and $\widetilde{\alpha}$ are equal to the ground truth. However, in the presence of global illumination, the received signal includes contributions from illumination reflected from multiple scene points, thus corrupting these measurements. In this paper, we model the global illumination using only the lowest order, indirect bounce with phase φ_G and amplitude α_G. The direct bounce has phase φ_D and amplitude α_D. Under this assumption, the received signal can be written as

$$c(\tau) = \underbrace{\frac{\alpha_D}{2} \cos\left(f_{\mathrm{M}} \tau + \varphi_D\right)}_{\text{Direct}} + \underbrace{\frac{\alpha_G}{2} \cos\left(f_{\mathrm{M}} \tau + \varphi_G\right)}_{\text{Approximate Global}} + \beta. \qquad (2)$$

The total projected radiance $\alpha_T = \alpha_D + \alpha_G = 1$, where $0 \leq \alpha_D, \alpha_G, \leq 1$. Using the measurement from Equation 2 into the four-bucket principle equation, we obtain

$$\widetilde{\varphi} = \arctan\left(\frac{\alpha_D \sin\varphi_D + \alpha_G \sin\varphi_G}{\alpha_D \cos\varphi_D + \alpha_G \cos\varphi_G}\right), \qquad (3)$$

$$\widetilde{\alpha}^2 = \alpha_D^2 + \alpha_G^2 + 2\alpha_D\alpha_G \cos\left(\varphi_D - \varphi_G\right). \qquad (4)$$

Accurately estimating φ_D would make it possible to ameliorate MPI and obtain a robust measurement of depth. The Nayar et al. [3] method can be used to obtain the direct (α_D) and global (α_G) radiance. Notice that between Equations 3 and 4 there are four variables, two of which are provided by the Nayar method. Given that there are two equations and only two unknown variables, the direct phase can be computed in closed-form as:

$$\widehat{\varphi}_D = \arctan\left(\frac{\alpha_D \gamma + \alpha_G\left(\sin\left(\varphi_D - \varphi_G\right) + \gamma \cos\left(\varphi_D - \varphi_G\right)\right)}{\alpha_D + \alpha_G\left(\cos\left(\varphi_D - \varphi_G\right) - \gamma \sin\left(\varphi_D - \varphi_G\right)\right)}\right), \qquad (5)$$

where $\gamma = \tan\left(\widetilde{\varphi}\right)$. In short, relaxing the problem to the second bounce approximation provides a closed-form solution for ameliorating multipath interference.

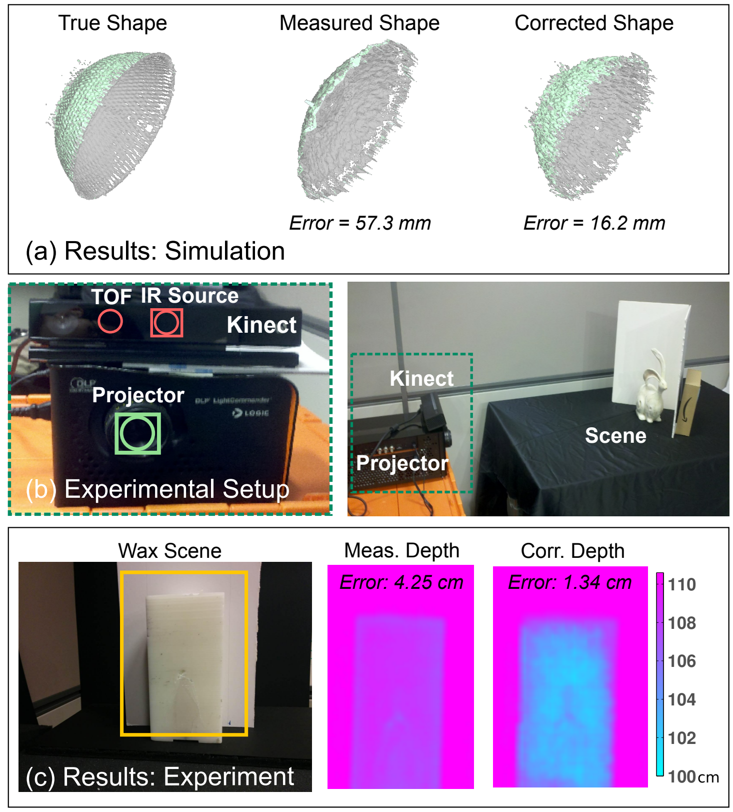

Figure 1: We test our closed-form solution for MPI correction using both simulations (a) and real experiments (b,c), and demonstrate both qualitative and quantitative improvement in depth accuracy (a,c).

We evaluate our solution through simulations (Figure 1a) and captured data (Figure 1c). Our experimental setup (Figure 1b) consists of only a Kinect sensor and an infrared projector. We perform direct-global separation using 25 high frequency illumination patterns, though a more robust implementation could be achieved using better projection systems and real-time methods. Our results show consistent quantitative and qualitative improvement in depth accuracy for a variety of light transport phenomena including interreflections (Figure 1a) and subsurface scattering (Figure 1c). Our method does not require extensive hardware modifications [4] and is not constrained to large scenes or high modulation frequencies [2].

In summary, we propose a new computational photography technique to generate higher quality 3-D scans than the standard TOF sensor. By coupling lightweight optical complexity with a closed-form, mathematical solution, the proposed technique takes a step toward scalable MPI correction.

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This is an extended abstract. The full paper is available at the Computer Vision Foundation webpage.