CamSim illumination model

This describes the illumination model (direct and single-bounce indirect) used in CamSim.

It is based on this paper: M. Lambers, S. Hoberg, A. Kolb: Simulation of Time-of-Flight Sensors for Evaluation of Chip Layout Variants. In IEEE Sensors Journal, 15(7), 2015, pages 4019-4026.

The extension for single-bounce indirect illumination is loosely based on this paper: D. Bulczak, M. Lambers, A. Kolb: Quantified, Interactive Simulation of AMCW ToF Camera Including Multipath Effects. In MDPI Sensors, 18(1), 2018, pages 1424-8220.

1 Symbols

1.1 Radiometric

Q: Radiant energy $[J]$
P: Radiant flux ("power") $[W]$
I: Radiant intensity $[W/\mathrm{sr}]$
L: Radiance ("radiant flux per unit solid angle per unit projected area") $[W/\mathrm{sr}/m^2]$
E: Irradiance $[W/m^2]$

1.2 Geometric

L: Light source position
C: Camera center position
P: Point on object surface seen by camera pixel
$\widehat{n_P}$: Surface normal at P
$\theta_{P\to L}$: Angle between $\widehat{n_P}$ and $\widehat{L-P}$
Q: Another point (on another surface) that may act as a virtual point light
$\widehat{n_Q}$: Surface normal at Q
$\theta_{Q\to L}$: Angle between $\widehat{n_Q}$ and $\widehat{L-Q}$

1.3 Other

$f_P(\widehat{L-P},\widehat{n_P},\widehat{C-P})$: BRDF for $L\to P\to C$
$f_Q(\widehat{L-Q},\widehat{n_Q},\widehat{P-Q})$: BRDF for $L\to Q\to P$

2 Direct Illumination

$I_{L\to P}=\frac{P_L}{4\pi}$ (if L is point light; there are alternatives)
$L_{L\to P}=\frac{I_{L\to P}}{d^2_{L\to P}}$

$L_{P\to C} = f_P(\widehat{L-P}, \widehat{n_P}, \widehat{C-P}) L_{L\to P} \cos(\theta_{P\to L})$
$E_C = L_{P\to C}$ (Note: no factor $\cos(\theta_{C\to P})$ here)
$P_C = E_C \cdot \text{SensorPixelArea}$
$Q_C = P_C \cdot \text{SignalDutyCycle} \cdot \text{ExposureTime}$

3 Indirect Illumination via Virtual Point Lights

Start with the Rendering Equation:
$L_{P\to C} = \int_\Omega f_P(\omega_i, \widehat{n_P}, \widehat{C-P}) L_{i\to P} \cos(\theta_i) d\omega_i$
Approximate this by splitting into direct and indirect parts, and approximating the indirect part with single-bounce RSM VPLs:
$$L_{P\to C} = f_P(\widehat{L-P}, \widehat{n_P}, \widehat{C-P}) L_{L\to P} \cos(\theta_{P\to L}) + \frac{1}{|\text{RSM}|} \sum_{Q\in\text{RSM}} f_P(\widehat{Q-P}, \widehat{n_P}, \widehat{C-P}) L_{Q\to P} \cos(\theta_{P\to Q})$$
The direct part is already computed in the direct step as $L_{P\to C}$. Add the indirect part to it:
$$L^*_{P\to C} = L_{P\to C} + \frac{1}{|\text{RSM}|} \sum_{Q\in\text{RSM}} f_P(\widehat{Q-P}, \widehat{n_P}, \widehat{C-P}) L_{Q\to P} \cos(\theta_{P\to Q})$$
using $L_{Q\to P} = f_Q(\widehat{L-Q}, \widehat{n_Q}, \widehat{P-Q}) L_{L\to Q} \cos(\theta_{Q\to L})$
and $L_{L\to Q} = \frac{I_{L\to Q}}{d^2_{L\to Q}}, \quad I_{L\to Q} = \frac{P_L}{4\pi}$

4 Values to Store in RSM

- Parameters that allow BRDF sampling at Q, e.g. k_d, k_s, s for modified Phong
- Position of Q (to perform shadow test and to compute $\widehat{Q-P}$, $\theta_{P\to Q}$, $\widehat{L-Q}$, $\widehat{P-Q}$, $\theta_{Q\to L}$)
- $\widehat{n_Q}$
- $L_{L\to Q}$