Microfacet-Based Normal Mapping for Robust Monte Carlo Path Tracing

Non-Separable Masking-Shadowing

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1 Introduction

In the main paper we made the assumption of separable-masking shadowing, i.e. \( G_2(\omega_o, \omega_i) = G_1(\omega_o) G_1(\omega_i) \). This has the intuitive meaning of light being uniformly distributed on the facets. In fact, it is the only approximation of our model compared to ray tracing the microsurface. In order to visualize the impact of this assumption, we extend our algorithm to a true ray tracing simulation and thus incorporate effects of height correlation.

2 Importance Sampling

To importance sample our BRDF, we simply trace a ray on the microsurface that is not masked using Algorithm 1. Like before, we choose the facet on which the first intersection occurs based on the intersection probability. Additionally, we randomly choose a valid height for this intersection using the masking function. Starting from this initial point on the microsurface, we repeatedly sample a direction from the micro-BRDF and intersect the opposite facet to obtain the next path vertex. When a ray leaves the microsurface, we take its direction and accumulated energy throughput as the sampling result.

Algorithm 1 Importance Sampling Algorithm

\[
\begin{align*}
\omega_r & \leftarrow -\omega_i & \triangleright \text{ray direction} \\
e & \leftarrow 1 & \triangleright \text{ray throughput} \\
\omega_m & \leftarrow [U < \lambda_p(\omega_i) \ ? \ \omega_p : \ \omega_l] & \triangleright \text{first facet} \\
h & \leftarrow 1 - U G_1(\omega_r, \omega_m) & \triangleright \text{first height} \\
\text{while true do} & \\
(\omega'_r, w) & \leftarrow \text{sample } f_m(-\omega_r, \omega'_r) (\omega'_r, \omega_m) & \triangleright \text{sample} \\
e & \leftarrow we & \triangleright \text{update throughput} \\
h' & \leftarrow \text{intersect(other facet(\omega_m), \omega'_r, h)} & \triangleright \text{intersect other facet for new height} \\
\text{if } h' > 1 \text{ then return } (\omega'_r, e) & \triangleright \text{leave microsurface} \\
\text{else} & \\
\omega_m & \leftarrow \text{other facet(\omega_m)} & \triangleright \text{continue on other facet} \\
h & \leftarrow h' & \triangleright \text{update height} \\
\omega_r & \leftarrow -\omega'_r & \triangleright \text{update direction} \\
\text{end if} & \\
\text{end while} & \\
\end{align*}
\]

3 Evaluation

Evaluation of the BRDF could be performed like in the main paper by adding next-event estimation to Algorithm 1. We would have to introduce a binary shadowing test, because we can no longer use the masking function for this.
Instead, we employ a more efficient approach in Algorithm 2 (visualized in Figure 1) that results in less variance. The inefficiency of the naive approach stems from the early determination of an initial height. In this way, only one path on the microsurface is considered at once. Our algorithm is able to trace parallel paths simultaneously by tracking an interval of unmasked heights on the facets. The initial interval, which we used in our sampling algorithm for choosing the first height, is given by the masking function. Since we consider only parallel rays, the resulting distribution of heights on the opposite facet after one bounce is also a uniform interval. We update this interval by tracing rays from both the lowest and the highest point of the interval on the facet. For next event estimation, we compute a masking-shadowing value by intersecting the interval of unmasked heights with the interval of not-shadowed heights given by the masking function. Note that to simplify notation of our algorithm, we set the microfacet height to 1, which is in contrast to the convention of assuming an area of 1m² for the geometric surface.

**Algorithm 2 Evaluation Algorithm**

```latex
\begin{algorithm}
  \begin{algorithmic}
    \State $L_o = 0$
    \State $\omega_r \leftarrow -\omega_i$
    \State $e \leftarrow 1$
    \State $\omega_m \leftarrow [\mathcal{U} < \lambda_p(\omega_i) \ ? \ \omega_p : \omega_i]$
    \State $H \leftarrow [1 - G_1(\omega_r, \omega_m), 1]$
    \While {true} 
      \State $G_2 \leftarrow |H \cap [1 - G_1(\omega_o, \omega_m), 1]|$
      \State $L_o \leftarrow L_o + e f_m(-\omega_r, \omega_o) \langle \omega_o, \omega_m \rangle \frac{G_2}{|H|}$
      \State $(\omega'_r, w) \leftarrow \text{sample } f_m(-\omega_r, \omega'_r) \langle \omega'_r, \omega_m \rangle$
      \State $e \leftarrow w e$
      \State $H' \leftarrow \text{intersect(other facet(} \omega_m \text{), } \omega'_r, H\text{)}$
      \If {$\mathcal{U} < \frac{|H' \cap [1, \infty]|}{|H'|}$} \textbf{return } $L_o$
      \Else 
        \State $\omega_m \leftarrow \text{other facet}(\omega_m)$
        \State $H \leftarrow H' \cap [0, 1]$
        \State $\omega_r \leftarrow -\omega'_r$
      \EndIf
    \EndWhile
  \end{algorithmic}
\end{algorithm}
```

- $\mathcal{U}$: radiance collected from $\omega_o$
- $\omega_i$: ray direction
- $\omega_i$: ray throughput
- $\lambda_p(\omega_i)$: first facet
- $\omega_p$: initial interval of heights
- $\omega_m$: intersect intervals of valid heights on $\omega_m$
- $G_1(\omega_r, \omega_m)$: eval
- $\langle \omega_o, \omega_m \rangle$: sample
- $f_m(-\omega_r, \omega'_r)$: update throughput
- $\omega'_r$: intersect other facet for new heights
- $\langle \omega'_r, \omega_m \rangle$: leave microsurface
- $H' \cap [0, 1]$: continue on other facet
- $H': \text{update heights}$
- $\omega'_r$: update direction
4 Evaluation with Specular Tangent Facet

We modify our algorithm in the same way as with the separable model, resulting in Algorithm 3. To avoid the singularity at the specular tangent facet $\omega_t$, we evaluate the BRDF on $\omega_p$ in direction $\omega'_o = \text{reflect}(\omega_o, \omega_i)$ instead. The height of rays starting on $\omega_p$ in direction $\omega'_o$ that are reflected on $\omega_t$ in direction $\omega_o$ is contained in an interval $H_r$. We use this interval to determine shadowing and compute it by intersecting rays from $\omega_t$ in direction $-\omega'_o$.

Algorithm 3 Evaluation Algorithm with Specular Tangent Facet

\begin{align*}
L_o &= 0 & \triangleright \text{radiance collected from } \omega_o \\
\omega_r &\leftarrow -\omega_i & \triangleright \text{ray direction} \\
e &\leftarrow 1 & \triangleright \text{ray throughput} \\
\omega_m &\leftarrow \begin{cases} U < \lambda_p(\omega_i) \ ? \ \omega_p : \omega_i \end{cases} & \triangleright \text{first facet} \\
H &\leftarrow [1 - G_1(\omega_r, \omega_m), 1] & \triangleright \text{initial interval of heights} \\
\omega'_o &\leftarrow \text{reflect}(\omega_o, \omega_t) & \triangleright \text{heights on } \omega_p \text{ reflected towards } \omega_o \\
H_r &\leftarrow \text{intersect}(\omega_p, -\omega'_o, [1 - G_1(\omega_o, \omega_l), 1]) & \triangleright \text{heights on } \omega_p \text{ reflected towards } \omega_o \\
\text{while true do} & & \\
\text{if } \omega_m = \omega_p \text{ then} & & \\
G_2 &\leftarrow |H \cap [1 - G_1(\omega_o, \omega_p), 1]| & \triangleright \text{intersect intervals of valid heights on } \omega_p \\
L_o &\leftarrow L_o + e \ f_m(-\omega_r, \omega_o) \langle \omega_o, \omega_p \rangle \frac{G_2}{|H|} & \triangleright \text{eval} \\
G'_2 &\leftarrow |H \cap H_r| & \triangleright \text{intersect intervals of valid heights on } \omega_p \\
L_o &\leftarrow L_o + e \ f_m(-\omega_r, \omega'_o) \langle \omega'_o, \omega_p \rangle \frac{G'_2}{|H|} & \triangleright \text{eval} \\
(\omega'_r, w) &\leftarrow \text{sample } f_m(-\omega_r, \omega'_r) \langle \omega'_r, \omega_m \rangle & \triangleright \text{sample} \\
e &\leftarrow w e & \triangleright \text{update throughput} \\
\text{end if} & & \triangleright \text{reflect} \\
H' &\leftarrow \text{intersect}(\text{other facet}(\omega_m), \omega'_r, H) & \triangleright \text{intersect other facet for new heights} \\
\text{if } U < \frac{|H'|}{|H|} &\text{ then return } L_o & \triangleright \text{leave microsurface} \\
\text{else} & & \triangleright \text{continue on other facet} \\
\omega_m &\leftarrow \text{other facet}(\omega_m) & \triangleright \text{update heights} \\
H &\leftarrow H' \cap [0, 1] & \triangleright \text{update direction} \\
\omega_r &\leftarrow -\omega'_r & \\
\text{end if} & & \\
\text{end while} & & \\
\end{align*}

5 Results

We compare the appearance of the separable model to the non-separable model with specular material tangent facet (Figure 2 and Figure 3) and with same material tangent facet (Figure 4 and Figure 5). We also provide a Mitsuba plugin (normalmap_microfacet_nonseparable) that implements our non-separable model.
Figure 2: *Appearances of our model with specular material tangent facet.*

Figure 3: *Our specular material tangent facet model applied on a more complex geometric model (20000 triangles) with textured GGX roughness.*
Figure 4: **Appearances of our model with same material tangent facet.**

Figure 5: **Our same material tangent facet model applied on a more complex geometric model (20000 triangles) with textured GGX roughness.**