APERTURE-AWARE LENS DESIGN

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What makes a good lens?

sharp lens

blurry lens
Lens speed is also important

low speed

high speed
Lens speed is also important

Motion blur

Low light scenes
Sharpness vs speed

Aperture-Aware Lens Design

Wang et al. [2022]
Zemax

best lenses
Sharpness vs speed

Speed

Sharpness

Aperture-Aware Lens Design

Wang et al. [2022]
Zemax

speed optimized

best lenses

sharpness optimized
Autodiff can’t capture lens speed
Autodiff can’t capture lens speed

Finite differencing  Automatic differentiation  Our method
Shape affects speed as well
Representing a lens

- Curvature x4
- Distance x5
- Size x5
Evaluating a lens

- **Point source**
- **Sharpness loss**
  \[ f_{\text{sharpness}} = \| x^s - \hat{x} \|^2 \]
- **Speed loss**
  \[ f_{\text{speed}} = 1 \]
Evaluating a lens

\[ \mathcal{L} = \int_{\Omega(\pi)} f(x^S(\omega, \pi)) \, d\omega \]

Monte Carlo estimator

\[ \frac{1}{N} \sum_{i=0}^{N} \frac{f(x^S(\omega_i))}{p(\omega_i)} \]
Optimizing a lens

\[
\frac{d\mathcal{L}}{d\pi} = \frac{d}{d\pi} \left( \frac{1}{N} \sum_{i=0}^{N} \frac{f(x^s(\omega_i))}{p(\omega_i)} \right)
\]

Monte Carlo gradient estimator (biased)

\[
\frac{1}{N} \sum_{i=0}^{N} \frac{1}{p(\omega_i)} \frac{df}{dx} \frac{dx^s}{d\pi}
\]
autodiff issue: aperture

Monte Carlo gradient estimator (biased)

\[ \frac{1}{N} \sum_{i=0}^{N} \frac{1}{p(\omega_i)} \frac{df}{dx} \frac{dx^s}{d\pi} \]

\[ f_{\text{speed}} = 1 \]

\[ \frac{df}{dx} = 0 \]
autodiff issue: aperture

Monte Carlo gradient estimator (biased)

\[
\frac{1}{N} \sum_{i=0}^{N} \frac{1}{p(\omega_i)} \frac{df}{dx} \frac{dx^s}{d\pi}
\]

\[\frac{dx^s}{d\pi} = 0\]

\(\pi\) : radius of aperture stop
autodiff issue: aperture

\[ \frac{1}{N} \sum_{i=0}^{N} \frac{1}{p(\omega_i)} \frac{df}{dx} \frac{dx^s}{d\pi} \]

\[ \frac{df_{\text{speed}}}{d\pi} = 0 \]

\[ \frac{df_{\text{sharpness}}}{d\pi} = 0 \]

\( \pi \): radius of aperture stop
autodiff issue: curvature

Monte Carlo gradient estimator (biased)

\[ \frac{1}{N} \sum_{i=0}^{N} \frac{1}{p(\omega_i)} \frac{df}{dx} \frac{dx^s}{d\pi} \]
autodiff issue: curvature

\[ \frac{1}{N} \sum_{i=0}^{N} \frac{1}{p(\omega_i)} \frac{df}{dx} \frac{dx^s}{d\pi} \]

\( \Pi : \) curvatures of first element

\( \frac{df_{\text{speed}}}{d\pi} = 0 \)

\( \frac{df_{\text{sharpness}}}{d\pi} = \text{biased} \)
Key insight: variable domain of integration

\[ \mathcal{L} = \int_{\Omega(\pi)} f(x^s(\omega, \pi)) \, d\omega \]

Depends on lens parameters!

Leibniz integral rule

\[ \frac{d\mathcal{L}}{d\pi} = \int_{\Omega(\pi)} \frac{df}{d\pi} \, d\omega + \int_{\partial\Omega(\pi)} f \frac{dg}{d\pi} \, d\omega \]
Finding the boundary is hard

\[
\frac{d\mathcal{L}}{d\pi} = \int \frac{df}{d\pi} \frac{d\omega}{\Omega(\pi)} + \int f \frac{dg}{d\pi} \frac{d\omega}{\partial\Omega(\pi)}
\]
Use the reparameterization trick

\[
\frac{d\mathcal{L}}{d\pi} = \int \frac{df}{d\pi} \Omega(\pi) d\omega + \int f \frac{dg}{d\pi} \partial\Omega(\pi) d\omega
\]
Use the reparameterization trick

\[ \frac{d\mathcal{L}}{d\pi} = \int \frac{df}{d\pi} \Omega(\pi) \, d\omega + \int f \frac{dg}{d\pi} \partial\Omega(\pi) \, d\omega \]

\[ \frac{d\mathcal{L}}{d\pi} = \int \frac{df}{d\pi} \Omega(\pi) \, d\omega + \int \nabla \cdot (f V_g) \Omega(\pi) \, d\omega \]
Unbiased Monte Carlo estimator

\[ \frac{dL}{d\pi} = \int \frac{df}{d\pi} \, d\omega + \int \nabla \cdot (f \nabla g) \, d\omega \]

aperture-aware gradient estimator

\[ \frac{1}{N} \sum_{i=0}^{N} \frac{1}{p(\omega_i)} \frac{df}{d\pi} + \nabla \cdot (f \nabla g) \]
Results

- Speed optimized
- Sharpness

Wang et al. [2022]

Zemax

Speed

Sharpness
We can also optimize zoom lenses
We can also optimize zoom lenses

\[ \mathcal{L}_{\text{zoom}} \]
We get better zoom lenses

- Original: Blue line
- Our method: Red line

**Graphs:**
- **Focal Length vs. Blur**
- **Focal Length vs. Speed**
Summary

aperture-aware gradient estimator

\[
\frac{1}{N} \sum_{i=0}^{N} \frac{1}{p(\omega_i)} \frac{df}{d\pi} + \nabla \cdot (fV_g)
\]
It’s possible to optimize other types of lenses

\[
\frac{1}{N} \sum_{i=0}^{N} \frac{1}{p(\omega_i)} \frac{df}{d\pi} + \nabla \cdot (fV_g)
\]

speed

sharpness

aspherics

mirrors

aperture-aware gradient estimator
Gradient based methods are limited by the topology of the lens.
Aperture-Aware Lens Design

https://imaging.cs.cmu.edu/aperture_aware_lens_design/