Progressive Transient Photon Beams

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300,000 km/s LIGHT TRANSPORT
TRANSIENT LIGHT TRANSPORT
Femto-photography [Velten et al. 2013]
Femto-photography [Velten et al. 2013]
Transient Light Transport - What for?

• Light in motion [*Velten13, Heide13, Peters15...*]
• Visible geometry [*Wu14, OToole14, Marco17...*]
• Transparent Objects [*Kadambi13*]
• Hidden geometry [*Velten12, Buttafava15, OToole18, Liu19,...*]
• Reflectance estimation [*Naik11, Naik13*]
• GI Components Separation [*Wu14, OToole14*]
• Vision through media  [*Heide14, Wu18...*]
• ...

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SIMULATION

- Forward model for inverse problems
- Benchmarking algorithms
- Prototyping
- Machine learning
Transient rendering

- Forward model for inverse problems
- Benchmarking algorithms
- Prototyping
- Machine learning
OUR GOAL

Robust time-resolved participating media

Forward model for inverse problems
Benchmarking algorithms
Prototyping
Machine learning
Transient Rendering
vs.
Steady-state

Steady state
Transient Rendering vs. Steady-state
Finite speed of light $\rightarrow$ Temporal dimension

Transient Rendering

Steady state
Transient Rendering

Finite speed of light $\Rightarrow$ Temporal dimension

Steady state

L

Radiance

time

13
Transient Rendering

  ➔ Application-specific, approximations, point samples

• [Jarabo et al. 2014]
  ➔ Time-resolved path integral formulation
  ➔ Temporal progressive density estimations
  ➔ Time-based importance sampling
  ➔ Point samples: Bidirectional path tracing, photon mapping
Transient Rendering

Challenges

• Monte Carlo methods ➔ Variance is aggravated in time
Transient Rendering

Challenges

• Monte Carlo methods \( \rightarrow \) Variance is aggravated in time
Monte Carlo methods \(\rightarrow\) Variance is aggravated in time

**Transient Rendering**

**Challenges**

- Slow convergence
Transient Rendering

Participating media

Classic RTE in rendering

TIME-INDEPENDENT

\[ L(x, \vec{\omega}) = T_r(x, x_s) L_s(x_s, \vec{\omega}) + \int_0^s \mu_s(x_q) T_r(x, x_q) L_o(x_q, \vec{\omega}) \, dq \]

\[ L_o(x_q, \vec{\omega}) = L_e(x_q, \vec{\omega}) + \int_S f_s(x_q, \vec{\omega}_i, \vec{\omega}) L(x_q, \vec{\omega}_i) \, d\vec{\omega}_i \]
Transient Rendering

Participating media

Classic RTE in rendering

TIME-INDEPENDENT
Transient Rendering

Participating media

Transient RTE

NEED TO ACCOUNT FOR TIME
Transient Rendering

Participating media

Transient RTE

NEED TO ACCOUNT FOR TIME

\[ L(x, \omega, t) = T_r(x, x_p) L_s(x_p, \omega, t - \Delta t_p) + \int_0^p \mu_s(x_q) T_r(x, x_q) L_o(x_q, \omega, t - \Delta t_q) \, dq, \]

\[ L_o(x_q, \omega, t) = \int_{-\infty}^{t} L_e(x_q, \omega, t') \, dt' + \int_{S} \int_{-\infty}^{t} f_s(x_q, \omega_i, \omega, t-t') L(x_q, \omega_i, t) \, dr' \, d\omega_i \]
Transient Rendering

Participating media

Transient RTE

NEED TO ACCOUNT FOR TIME
Transient Rendering

Participating media

[Jarabo 2014] → Point samples (BDPT, photon mapping)

SPARSE SAMPLES IN TIME
Transient Rendering

Participating media

[Jarabo 2014]→ Point samples (BDPT, photon mapping)

⇒ SPARSE SAMPLES IN TIME

NEED DENSER TEMPORAL SAMPLING
Steady-state - Photon Beams

[Jarosz et al. 2011a, 2011b]: Steady-state media rendering
Steady-state - Photon Beams

1. Stores photon trajectories on a BEAMS MAP
Steady-state - Photon Beams

1. Stores photon trajectories on a BEAMS MAP

2. Performs ray-beam density estimations
**Transient Photon Beams**

Why photon beams for transient rendering?

**Full photon trajectories**

Denser sampling the temporal domain
**Transient Photon Beams**

Why photon beams for transient rendering?

- **Full photon trajectories**
  - Denser sampling the temporal domain

- **Closed form density estimations**
  - Arbitrary temporal resolution
1. **Tracing**: Sample Transient RTE

→ **Store beam starting time**
Transient Photon Beams

1. **Tracing:** Sample Transient RTE
   - Store **beam starting time**

2. **Rendering:** Spatio-temporal density estimations
**Transient Photon Beams**

1. **Tracing:** Sample Transient RTE
   - Store beam starting time

2. **Rendering:** Spatio-temporal density estimations

Optical path, IOR, Scattering events

Spatial KDE, Temporal KDE

Radiance vs. time
Transient Photon Beams
Transient Photon Beams

Spatio-temporal slice

time
Transient Photon Beams
Transient Photon Beams

Spatio-temporal slice

Time
Transient Photon Beams

BIAS
PROGRESSIVE APPROACH
Spatial density estimations

Temporal density estimations

Progressive Transient Photon Beams

Radiance

0

time
Progressive Transient Photon Beams

Spatial density estimations

Temporal density estimations

Radiance vs. time
Progressive Transient Photon Beams

Spatial density estimations

Temporal density estimations

Radiance

0
time

Progressive Transient Photon Beams
**Progressive Transient Photon Beams**

Spatial density estimations

1D spatial kernel

Temporal density estimations

1D temporal kernel

Radiance

time

$L$
Progressive Transient Photon Beams

Spatial density estimations

Temporal density estimations

\[ O\left(n^{-\frac{2}{3}}\right) \]

1D spatial kernel

1D temporal kernel
Progressive Transient Photon Beams

Spatio-temporal slice

24 iterations
Progressive Transient Photon Beams

Spatio-temporal slice

24 iterations
Progressive Transient Photon Beams

Spatio-temporal slice

2000 iterations
RESULTS
Soccer

40M beams
(2000 iterations x 20k beams/iteration)
Pumpkin

Progressive transient PT [Jarabo 2014]
vs.
Our method
(equal–time comparison)
Steady state
Pumpkin – Equal-time comparison

[Jarabo et al. 2014]  
Our method
Pumpkin – Equal-time comparison

Steady state

Transient state

Radiance vs. time (ns)

- Ours
- Jarabo 2014
- Reference
Pumpkin – Equal-time comparison

Steady state

Transient state

Radiance vs. time (ns)

- Ours
- Jarabo 2014
- Reference

[Jarabo 2014]

Ours
Pumpkin – Equal-time comparison

Steady state

Transient state

Radiance

time (ns)

Ours
Jarabo 2014
Reference

[Jarabo 2014]

Ours
Pumpkin – Equal-time comparison

Steady state

[Jarabo 2014]

Ours

Transient state

Radiance

Ours
Jarabo 2014
Reference

time (ns)

10

6

7

8

9

12

10

11

$10^{-6}$

$10^{-4}$

$10^{-2}$
Juice

24M beams
(1200 iterations x 20k beams/iteration)
Conclusion

• Robust method for low-variance time-resolved participating media

• Render complex time-resolved effects

• Consistent approach

• Optimal 1D x 1D spatio-temporal kernel reduction ratios
What next?

• Introduce time-based importance sampling [Jarabo et al. 2014]
• Extend to hybrid methods, all volumetric estimators
• Improve temporal reconstruction
Thanks!