Inverse Shade Trees for Non-Parametric Material Representation and Editing

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Complex Appearance

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Appearance Acquisition

- 2,000 Images
- 6 GB

Image courtesy of Stanford Graphics Laboratory
Challenge

- Given: dense set of measurements of light transport function.
- Provide: intuitive representation that is compact and allows editing.

Original Measured Appearance  
Result of Editing Material Properties
Spatially-Varying Reflectance

\( S(u, v, \vec{V}, \vec{L}) \)

Spatially-Varying Bidirectional Reflectance Distribution Function
Observation #1: Represent high-dimensional measured function as tree-structured collection of lower-dimensional parts.

Observation #2: Decomposition at each level is matrix factorization.

Observation #3: Intuitive decomposition achieved using constrained factorization.
Outline

- Introduction
- Prior Work
- Factorization
- Editing
- Conclusions and Future Work
Fitting Parametric Models

- Cluster fits of parametric BRDF: [Lensch et al. 03], [Goldman et al. 05].
- Editable if nice clusters
- Single analytic BRDF limits accuracy

Lensch et al. 2003
Dimensionality Reduction

- Apply rank-reduction algorithms to data matrix: [Dana et al. 99], [Chen et al. 02], [Tsumura et al. 03]
- Compact and accurate
- Cannot be directly edited

HOSVD “Basis Images” from Wang et al. 2005
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Tabulate Raw Data

\[ S(u, v, \vec{V}, \vec{L}) \]
Tabulate Raw Data

\[ S(u, v, \vec{V}, \vec{L}) \]

\[ (\vec{V}, \vec{L}) \]
Factorization of SVBRDF

\((\vec{V}, \vec{L})\) ≈ \((u, v)\) ≈ \(T_1 \ldots T_K\)
6D SVBRDF

\[ \sum \]

\[ \times \]

\[ \times \]

\[ \approx \]

\[ T_1 \ldots T_K \]

\[ f_1 \]

\[ \vdots \]

\[ f_K \]
6D SVBRDF

\[ \sum \]

\[ \times \]

\[ \times \]

2D Spatial Blending Weights
6D SVBRDF

$\sum \times \times$

$\approx$

$\ldots$

$\ldots$

$\ldots$

4D Basis BRDFs

$T_1 \ldots T_K$

$f_1 \ldots f_K$
Providing an intuitive factorization:
Key Idea

Incorporate domain-specific knowledge as constraints of factorization:

Plausible BRDFs

≈

Plausible blending weights.
Factorization Constraints

- **Non-negativity:**
  Reflectance functions are non-negative
- **Sparsity:**
  Few BRDFs at each position
- **Domain-specific:**
  Energy-conservation, monotonicity, etc.
## Factorization Algorithms

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Our Method

Alternating Constrained Least Squares (ACLS)

1. Initialize $W$ and $H$
2. Update $W$
3. Update $H$
4. Iterate until convergence
Our Method

Alternating Constrained Least Squares (ACLS)

\[ \vec{v} \approx \vec{w} \]

Convex QP Problem

\[ \begin{align*}
\min_{\vec{w}} & \quad \| \vec{v} - \vec{w} H \|^2 \\
\bar{l} & \leq \left\{ \begin{array}{c}
\vec{w}^T \\
A\vec{w}^T
\end{array} \right\} \leq \bar{u}
\end{align*} \]

1. Initialize \( W \) and \( H \)
2. Update \( W \)
3. Update \( H \)
4. Iterate until convergence
Appearance Constraints

- Non-negativity
  Value constraint
- Energy conservation
  Constraint on sum
- Monotonicity
  Constraint on derivative

\[ \vec{l} \leq \left\{ \begin{array}{c} \vec{w}^T \\ A\vec{w}^T \end{array} \right\} \leq \vec{u} \]
Appearance Constraints

- Non-negativity
  Value constraint
- Energy conservation
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  Constraint on derivative

\[ \vec{l} \leq \begin{\{ \vec{w}^T \\ A\vec{w}^T \end{\} \} \leq \vec{u} \]
Appearance Constraints

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Appearance Constraints

- Non-negativity
  Value constraint
- Energy conservation
  Constraint on sum
- Monotonicity
  Constraint on derivative

\[ \vec{l} \leq \left\{ \vec{w}^T A \vec{w}^T \right\} \leq \vec{u} \]
Measure of Sparsity

\[ E_{\text{sparse}} = \sum_{i \neq j} w_i \]

\[ \omega_j \geq \omega_i, \ i = 1 \ldots K \]
Measure of Sparsity

\[ \vec{u} \approx \vec{w} \]

\[ H \]

\[ E_{\text{sparse}} = \sum_{i \neq j} w_i \]

\[ w_j \geq w_i, i = 1 \ldots K \]
Season’s Greetings Dataset

5 Camera Positions x 350 Light Positions ~ 1,750 Images

Gold Foil
Silver Foil
White Paper
Blue Paper
Season’s Greetings Dataset

Factorization Computed with **ACLS** (4 Terms)
Wood+Tape Dataset

12 Camera Positions x 480 Light Positions = 6,000 Images

 Oak Wood (Anisotropic)  Semi-Transparent Tape  Retroreflective Bicycle Tape
Wood+Tape Dataset

Blending Weights from ACLS (5 Terms)

Scotch Tape  Dark Grain  Light Grain  Red Bicycle  White Bicycle
SVD

NMF

k-means

ACLS
6D SVBRDF

2D Blending Weights

4D Basis BRDFs
6D SVBRDF

2D Blending Weights

4D Basis BRDFs
Reparameterization and Constrained Factorization

BRDF 4D

“Lobes”

Single Term Factorization

Curves 1D

Specular Highlight

Grazing Effects

$\theta_h (= H \cdot N)$

$\theta_d (= H \cdot V)$
Edits at leaf propagate up the tree.
Specular Highlight Edit
Material Replacement
Blending Weights Edit
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Inverse Shade Trees enable applications with measured appearance data:

- Compression for interactive rendering
- Editing of texture and reflectance
Concurrent Work

Translucent
[Peers et al. 06]

Time-Varying
[Gu et al. 06]
Future Work

- Automatic selection of tree topology
- Additional composition nodes: (e.g. over operators, masks, etc.)
- Higher-dimensional light transport functions
- Other linear decomposition problems
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