Digital Bas-Relief From 3D Scenes

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Relief In Sculpture

- Sculpture in limited depth
- Bridges 3D and 2D media

Banteya Srei, Cambodia, 10th c. AD

Ch. Archambault
Relief In Sculpture

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**High relief**
*(alto relievo)*

**Low relief**
*(basso relievo, bas-relief)*

Banteya Srei, Cambodia, 10\(^{th}\) c. AD
Traditional Bas-Relief

Assyrian Bas-Relief, (9th c. BC)

Greek Elgin Marbles (5th c. BC)

Historic Glass Bottles

Coins
Digital Bas-Relief From 3D Scenes

Input Scene

Output Relief
Contributions

- Automated technique for relief generation
  - From arbitrary input scenes
  - Depth-range compression
  - Preservation of visual cues
  - For a wide range of physical materials
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• Gradient-domain editing framework
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- Gradient-domain editing framework

- Promotion of bas-relief as a digital medium
Outline

- Problem statement
- Related work
- Automated bas-relief generation
- Results & Applications
Bas-Relief’s Constraints

• Limited height range
  – Relief resembles scene geometry
  – Possible because of the bas-relief ambiguity
    [Belhumeur et al. 1999]

• Pure height field (no “undercuts”)

• No depth discontinuities
Guidelines For The Sculptor

- *Depth Illusion*: mainly by 2D perspective
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- *Depth Compression*
Guidelines For The Sculptor

- **Depth Illusion**: mainly by 2D perspective
- **Depth Compression**:
  - Shape compression

Object

Back Plane
Guidelines For The Sculptor

- *Depth Illusion:* mainly by 2D perspective
- *Depth Compression:*
  - Shape compression
Guidelines For The Sculptor

- **Depth Illusion:** mainly by 2D perspective
- **Depth Compression:**
  - Shape compression
  - Silhouette collapse (at depth discontinuities)
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- *Object Order*: preserve where objects overlap
Guidelines For The Sculptor

- **Depth Illusion:** mainly by 2D perspective
- **Depth Compression:**
  - Shape compression
  - Silhouette collapse (at depth discontinuities)
- **Object Order:** preserve where objects overlap
- These goals may be conflicting
- Trade-offs have to be found
Objective
Objective

- Given a 3D scene + camera settings
Objective

- Given a 3D scene + camera settings
- Automated generation of bas-relief geometry
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Bas-Relief

• From a technical point of view:
  – Dynamic-range compression
  – Perceptual preservation
Bas-Relief

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  – Dynamic-range compression
  – Perceptual preservation

• Both aspects relate to tone-mapping and high-dynamic-range (HDR) compression
Related Work

- Range compression in images
  - Global tone-reproduction curves (TRC), e.g., histogram adjustment \[\text{[LARSON ET AL. 1997]}\]
  - Local tone-reproduction operators (TRO) \[\text{[TUMBLIN AND TURK 1999]}, \text{[ASHIKHMIN 2002]}, \text{[DURAND AND DORSEY 2002]}, \text{[FATTAL ET AL. 2002]}\]
Related Work

• Range compression in images
  – Global tone-reproduction curves (TRC), e.g., histogram adjustment [LARSON ET AL. 1997]
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• Not trivially applicable to relief height-fields
  – Global techniques cannot collapse silhouettes
  – Local operators preserve steps at silhouettes
  – Designed for image intensities, not surface shading
Related Work

- Bas-relief
  - Initial steps in bas-relief generation [CIGNONI ET AL. 1997]
  - Simulation of 3D sculpting tools [SOURIN 2001]
  - Concurrent work [KERBER ET AL. 2007]
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The Algorithm

- Formulation on height fields
The Algorithm

- Formulation on height fields
- Framework: non-linear gradient-domain compression
  - Similar to use in tone mapping [Fattal et al. 2002]
  - Compresses shape, not intensities
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- Formulation on height fields
- Framework: non-linear gradient-domain compression
  - Similar to use in tone mapping [FATTAL ET AL. 2002]
  - Compresses shape, not intensities
- Gradient-domain operators
  - Depth compression and silhouette collapse
  - Artistic editing operations
The Algorithm

Four-step procedure:
The Algorithm

Four-step procedure:

1. Depth image from input scene
The Algorithm

Four-step procedure:

1. Depth image from input scene
2. Gradient-domain depth compression
The Algorithm

Four-step procedure:

1. Depth image from input scene
2. Gradient-domain depth compression
3. Optionally: Further gradient editing
The Algorithm

Four-step procedure:

1. Depth image from input scene
2. Gradient-domain depth compression
3. Optionally: Further gradient editing
4. Integration yields final relief heights
Input Depth Image

- Depth buffer part of most rendering systems
- Homogeneous mapping ("perspective z")

\[ z_{\text{buf}} = C + \frac{D}{z} \]

- Intrinsic properties desirable for relief
  - Plane preservation
  - Range attenuation of distant features
Input Depth Image
Input Depth Image

- Input depths may already be interpreted as a relief
Input Depth Image

• Input depths may already be interpreted as a relief

• Linear scale to meet range constraints?

[CIGNONI ET AL. 1997]
Input Depth Image

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Input Depth Image

- Input depths may already be interpreted as a relief
- Linear scale to meet range constraints?  
  [CIGNONI ET AL. 1997]
- Disadvantages:
  - Linear scale flattens features
  - Depth discontinuities persist
Gradient-Domain Compression

- Derive gradients $\nabla h(x, y)$ from scene depth-map
- Fix gradient direction to preserve shape cues
- Non-linear compression of gradient magnitudes
  - Shape compression by attenuating large slopes
  - Silhouette collapse by eliminating depth discontinuities
- Implemented as a mapping $C(x)$ applied to $\|\nabla h(x, y)\|$
Shape Compression

\[ C(x) = \frac{1}{\alpha} \log(1 + \alpha x), \quad \alpha > 0 \]
Silhouette Collapse

- Elimination of depth discontinuities by thresholding \( \| \nabla h(x, y) \| \):

\[
s(x, y) = \begin{cases} 
C(\| \nabla h \|), & 0 \leq \| \nabla h \| < \theta_{\text{sil}}, \\
0, & \theta_{\text{sil}} \leq \| \nabla h \|
\end{cases}
\]

- Treats large input gradients as silhouettes
- For high sampling rates: clear discrimination from large surface slopes
Integration

- Modified gradient field $g'$ describes relief
- In general, $g'$ is not integrable
- Optimization for height field $h'$ that matches

\[ h' = \arg \min_h \iint \| \nabla h - g' \|^2 \, dx \, dy \, , \]

by solving Poisson equation

\[ \nabla^2 h = \text{div} \, g' \, . \]
Compression Results

1D example: Cylinder cross-section

Compression Functions

Integration Results

- $\alpha = 0$
- $\alpha = 3$
- $\alpha = 1$
- $\alpha = 10$
Compression Results

2D example:
complex input depth-map
Compression Results

2D example:
complex input depth-map
Compression Results

2D example: complex input depth-map

No Compression $\alpha \rightarrow 0.0$

Compression $\alpha = 1.0$

Compression $\alpha = 10.0$
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Relief From Complex Scenes
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Silhouette Constraints
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- Receding background emphasizes silhouettes
Silhouette Constraints

- Receding background emphasizes silhouettes
- Sometimes flat background desirable
Silhouette Constraints

- Receding background emphasizes silhouettes
- Sometimes flat background desirable
- Sea-level constraint at silhouettes flattens back pane
Silhouette Constraints
Silhouette Constraints
Silhouette Constraints
Material Dependence

• **Compression:** glossier materials allow for flatter relief

• **Detail:** must respect medium
  (e.g., translucent media allow for less detail)

• **Steps:** to emphasize depth discontinuities
Material Dependence
Material Dependence
Material Dependence
Gradient-Domain Editing

- Frequency control
  - Independent scaling of frequency decomposition
  - Decomposition uses silhouette-respecting filter
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- Selective application
  - Emphasizes scene elements
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• Integration still leads to seamless reconstruction
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- Integration still leads to seamless reconstruction
Physical Reliefs

- Previous results use realistic shaders and lighting
- Final evaluation using
  - A physical stone relief
  - Real coins showing a 3D scene
Physical Reliefs — Limestone
Physical Reliefs — Limestone

- Transferring height fields to a robotic mill
Physical Reliefs — Limestone

- Transferring height fields to a robotic mill
- Milling a relief from stone
Physical Reliefs — Coins
Physical Reliefs — Coins

- Limestone represents a very diffuse material
Physical Reliefs — Coins

- Limestone represents a very diffuse material
- Second experiment on shiny materials: custom-made coins
Physical Reliefs — Coins

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Physical Reliefs — Coins

• Limestone represents a very diffuse material

• Second experiment on shiny materials: custom-made coins

• Handed out after this session — first-come first served!
Conclusion

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  – From arbitrary input scenes
  – Depth-range compression
  – Preservation of visual cues
  – For a wide range of physical materials

• Gradient-domain editing framework

• Promotion of bas-relief as a digital medium
Future Work

- Formal incorporation of material properties
- Higher-level editing operations
- Bas-relief over general geometry
- *Alto relievo*
- Additional sources of input
Additional Sources

- Scene input not limited to 3D sources
- Only requirements:
  - Gradient field
  - Silhouette locations
- Gradients obtainable from normals
Photometric Normals
Photometric Normals
Relief From Normals
Acknowledgements

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Limitations

• Conflicting goals of guidelines for bas-relief
  – Relative ordering
  – Continuity
  – Shape preservation

• Some scenes impose high strain on optimization
  – Such scenes are generally badly suited for bas-relief
  – Artists have to design scenes that minimize conflicts
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