Multi-Projector Techniques for Real-Time Visualizations in Everyday Environments
Outline
Outline

Introduction
Motivations and Applications

Geometric Correction
Planar, Non-Trivial, Complex Surfaces

Radiometric Compensation
Local and Global Light Effects

Advanced Techniques
View-Dependence, Multi-Focal Projection, Light Transport

Outlook
Limitations and Future Work

these slides:
www.uni-weimar.de/medien/AR
Introduction
Evolving Evolution
Evolving Evolution

50s  60s  70s  80s  90s  2k

VR

AR

Spatial

Mobile

O. Bimber

Multi-Projector Techniques for Real-Time Visualizations in Everyday Environments

04/01/06
Motivation: Projection
Motivation: Projection
Application: Historic Sites and Museums
Application: Historic Sites and Museums

360° Surround Projection in Castel Tower
(Running project in coop. with Bennert Group)
Application: Architectural Visualization
Application: Architectural Visualization

Bimber et al, IEEE/ACM ISMAR 2005

On-Site Architectural Visualizations
(Running project in coop. with Architecture Faculty, BUW)
Application: Pocket Projectors
Application: Pocket Projectors

Courtesy: InFocus

Courtesy: Siemens

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Multi-Projector Techniques for Real-Time Visualizations in Everyday Environments

04/01/06
Principle
Principle
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Principle

original image observed projection

O. Bimber Multi-Projector Techniques for Real-Time Visualizations in Everyday Environments 04/01/06
Some Challenges
Some Challenges

color blending
Some Challenges

color blending

geometric warping
Some Challenges

- color blending
- geometric warping
- misregistration
Some Challenges

- color blending
- geometric warping
- misregistration
- regional defocus
Some Challenges

color blending
geometric warping
misregistration
regional defocus

scattering
Some Challenges

color blending  geometric warping  misregistration  regional defocus

scattering  specular reflection, refraction, sub-surface scattering, inter-reflections, dispersion, diffraction, etc.
A Multi-Projector-Camera Approach

real-time image correction
A Multi-Projector-Camera Approach
Geometric Correction
Planar Surfaces
Homography
Homography

- Homography is a mapping between two projections over a plane.
- It can map pixel coordinates from one perspective to another.
- An equation system has to be solved to determine 8 parameters of matrix $A$.
- It can be used directly in transformation pipeline by multiplying the following matrix after projection (without perspective division):

$$A_{4 \times 4} = \begin{bmatrix}
    a_{11} & a_{12} & 0 & a_{13} \\
    a_{21} & a_{22} & 0 & a_{23} \\
    0 & 0 & 1 & 0 \\
    a_{31} & a_{32} & 0 & 1 \\
\end{bmatrix}$$

- Ensure intact depth values with (approximately)
Multi-Projector Registration
Multi-Projector Registration

- registering multiple projectors onto a common planar surface
- map all perspective into a single target perspective via homographies
- target perspective can be camera perspective
  - automatic determination of matrix parameters via structured light
- rendering
  - render image for target perspective (if target perspective is orthogonal to plane, then it can be done with an off-axis projection of an observer!)
  - map pixels into individual projector views (i.e., multiply 4x4 version of homography matrix onto matrix stack [after projection] and ensure that depth values remain intact!)
Example: Tiled Projection Screens
Example: Tiled Projection Screens

Courtesy: Brown, et al., IEEE TVCG, 2005
Non-Trivial Surfaces
Non-Trivial Surfaces
Non-Trivial Surfaces

parametric surfaces: warping can be computed using parametric description (projectors have to be registered)
Projective Texture Mapping
Projective Texture Mapping

- given a geometric definition of the surface
  - scan or model
- determine intrinsic and extrinsic of projectors with respect to surface
  - measure projections of known 3D surface points on image plane of projector and solve equation system to determine parameters of matrix
- define virtual camera with same parameter for each projector
- render 3D model of surface, textured with images, from perspective of projectors/virtual cameras
- texture coordinates can be automatically generated from target perspective via projective texture mapping
Example: Shader Lamps
Example: Shader Lamps

Courtesy: Raskar, et al., EGRW 2001
Complex Surfaces
Complex Surfaces

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Multi-Projector Techniques for Real-Time Visualizations in Everyday Environments
04/01/06
Pixel Displacement Mapping
Pixel Displacement Mapping

- registering projections to such a surface by determining their intrinsic and extrinsic is too imprecise
  - non-linear lens distortion
  - errors in measuring fiducials
- rendering of 3D surface representation from perspective of projector might be too slow
  - high geometric complexity of model
  - many triangles to render
    - project, raster, texture
- measure per-pixel mapping between projector perspectives and target perspective (e.g., camera)
- render image from target perspective and map it (look-up) into perspective of projectors (e.g., pixel-shading)
Pixel Displacement Mapping

- registering projections to such a surface by determining their intrinsic and extrinsic is too imprecise
  - non-linear lens distortion
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- rendering of 3D surface representation from perspective of projector might be too slow
  - high geometric complexity of model
  - many triangles to render
    - project, raster, texture
- measure per-pixel mapping between projector perspectives and target perspective (e.g., camera)
- render image from target perspective and map it (look-up) into perspective of projectors (e.g., pixel-shading)

**Problem:**
works only for static target perspective!
(but image-based rendering approaches exist)
Example: Stucco Wall
Example: Stucco Wall
Example: Fossil Cast
Example: Fossil Cast

In coop. with Senckenberg Museum
Example: Scruffy Room Corner
Example: Scruffy Room Corner

Bimber et al., IEEE Computer 2005
Radiometric Compensation
Photometric Calibration
Photometric Calibration

- regions of display surfaces that are illuminated by multiple projectors simultaneously appear brighter
- projectors can have different brightness and can cover a different color space
- result: inconsistent image (intensity and color)
- humans can perceive 2% difference in brightness and a color variation of 2nm
- variations in brightness is more critical than variation in color
- solutions: intensity blending and color space mapping
- these techniques are not explained here!
- we assume that projectors and cameras are linearized and color mapped
Compensating Local Light Effects
Compensating Local Light Effects
Single Projector
Single Projector

\[ R = IFM + EM \]

- \( I \rightarrow \) projected image
- \( B \rightarrow \) black-level
- \( F \rightarrow \) projector-2-surface form factor
- \( E \rightarrow \) environment light
- \( M \rightarrow \) surface reflectance (diffuse)
Single Projector
determining parameters (textures):

\[ R = IFM + EM \]

- I \(\rightarrow\) projected image
- B \(\rightarrow\) black-level
- F \(\rightarrow\) projector-2-surface form factor
- E \(\rightarrow\) environment light
- M \(\rightarrow\) surface reflectance (diffuse)
Single Projector

determining parameters (textures):

1. turn off environment light and project black flood image

\[ R = I \times F + E \]

- \( R \) \rightarrow projected image
- \( I \) \rightarrow black-level
- \( F \) \rightarrow projector-2-surface form factor
- \( E \) \rightarrow environment light
- \( M \) \rightarrow surface reflectance (diffuse)
Single Projector

determining parameters (textures):
(1) turn off environment light and project black flood image
I=0,E=0 \rightarrow BFM

R=IFM+EM

- I \rightarrow \text{projected image}
- B \rightarrow \text{black-level}
- F \rightarrow \text{projector-2-surface form factor}
- E \rightarrow \text{environment light}
- M \rightarrow \text{surface reflectance (diffuse)}
Single Projector

determining parameters (textures):

1. turn off environment light and project black flood image
   \[ I=0, E=0 \rightarrow BFM \]

2. turn on environment light and project black flood image

\[ R=IFM+EM \]

- \( I \rightarrow \) projected image
- \( B \rightarrow \) black-level
- \( F \rightarrow \) projector-2-surface form factor
- \( E \rightarrow \) environment light
- \( M \rightarrow \) surface reflectance (diffuse)
Single Projector

determining parameters (textures):

(1) turn off environment light and project black flood image

I=0, E=0 $\rightarrow$ BFM

(2) turn on environment light and project black flood image

I=0, E=1 $\rightarrow$ EM (incl. BFM !)

$R = IFM + EM$

- $I \rightarrow$ projected image
- $B \rightarrow$ black-level
- $F \rightarrow$ projector-2-surface form factor
- $E \rightarrow$ environment light
- $M \rightarrow$ surface reflectance (diffuse)
Single Projector

determining parameters (textures):

1. turn off environment light and project black flood image
   \( I=0, E=0 \rightarrow BFM \)

2. turn on environment light and project black flood image
   \( I=0, E=1 \rightarrow EM \) (incl. BFM !)

3. turn off environment light and

\[ R = IFM + EM \]

\( I \rightarrow \) projected image
\( B \rightarrow \) black-level
\( F \rightarrow \) projector-2-surface form factor
\( E \rightarrow \) environment light
\( M \rightarrow \) surface reflectance (diffuse)
Single Projector

determining parameters (textures):

(1) turn off environment light and project black flood image
    \( I=0, E=0 \) \( \rightarrow \) BFM

(2) turn on environment light and project black flood image
    \( I=0, E=1 \) \( \rightarrow \) EM (incl. BFM !)

(3) turn off environment light and project white flood image

\[ R = IFM + EM \]

I \( \rightarrow \) projected image
B \( \rightarrow \) black-level
F \( \rightarrow \) projector-2-surface form factor
E \( \rightarrow \) environment light
M \( \rightarrow \) surface reflectance (diffuse)
Single Projector

determining parameters (textures):

1. Turn off environment light and project black flood image
   \[ I=0, E=0 \rightarrow BFM \]

2. Turn on environment light and project black flood image
   \[ I=0, E=1 \rightarrow EM \text{ (incl. BFM !)} \]

3. Turn off environment light and project white flood image
   \[ I=1, E=0 \rightarrow FM \text{ (incl. BFM !)} \]

\[ R = IFM + EM \]

- \( I \rightarrow \) projected image
- \( B \rightarrow \) black-level
- \( F \rightarrow \) projector-2-surface form factor
- \( E \rightarrow \) environment light
- \( M \rightarrow \) surface reflectance (diffuse)
Single Projector

determining parameters (textures):

1. turn off environment light and project black flood image
   \[ I=0, E=0 \rightarrow BFM \]

2. turn on environment light and project black flood image
   \[ I=0, E=1 \rightarrow EM \text{ (incl. BFM !)} \]

3. turn off environment light and project white flood image
   \[ I=1, E=0 \rightarrow FM \text{ (incl. BFM !)} \]
   \[ \rightarrow FM=FM-BFM \]

\[ R=IFM+EM \]

- \( R \rightarrow \) projected image
- \( B \rightarrow \) black-level
- \( F \rightarrow \) projector-2-surface form factor
- \( E \rightarrow \) environment light
- \( M \rightarrow \) surface reflectance (diffuse)
Single Projector

determining parameters (textures):

(1) turn off environment light and project black flood image
   \[ I=0, E=0 \rightarrow BFM \]

(2) turn on environment light and project black flood image
   \[ I=0, E=1 \rightarrow EM \text{ (incl. BFM !)} \]

(3) turn off environment light and project white flood image
   \[ I=1, E=0 \rightarrow FM \text{ (incl. BFM !)} \]
   \[ \rightarrow FM=FM-BFM \]

compensation (per pixel):

\[ R=IFM+EM \]

I \rightarrow \text{projected image}
B \rightarrow \text{black-level}
F \rightarrow \text{projector-2-surface form factor}
E \rightarrow \text{environment light}
M \rightarrow \text{surface reflectance (diffuse)}
Single Projector

determining parameters (textures):

(1) turn off environment light and project black flood image
   \[ I=0, E=0 \rightarrow BFM \]

(2) turn on environment light and project black flood image
   \[ I=0, E=1 \rightarrow EM \text{ (incl. BFM !)} \]

(3) turn off environment light and project white flood image
   \[ I=1, E=0 \rightarrow FM \text{ (incl. BFM !)} \]
   \[ \rightarrow FM=FM-BFM \]

compensation (per pixel):
\[ I=(R-EM)/(FM) \]

\( R=IFM+EM \)
- \( I \rightarrow \) projected image
- \( B \rightarrow \) black-level
- \( F \rightarrow \) projector-2-surface form factor
- \( E \rightarrow \) environment light
- \( M \rightarrow \) surface reflectance (diffuse)
Color Mixing
Color Mixing

\[ V = \begin{bmatrix} V_{RR} & V_{RG} & V_{RB} \\ V_{GR} & V_{GG} & V_{GB} \\ V_{BR} & V_{BG} & V_{BB} \end{bmatrix} \]

\[ R = V \cdot I \]

- \( I \rightarrow \) projected image
- \( V \rightarrow \) color mixing matrix
- \( V \) \((\text{projector/camera/reflectance})\)
Color Mixing

\[
V = \begin{bmatrix}
V_{RR} & V_{RG} & V_{RB} \\
V_{GR} & V_{GG} & V_{GB} \\
V_{BR} & V_{BG} & V_{BB}
\end{bmatrix}
\]

(per pixel)

\[R = V*I\]

- \(I\) → projected image
- \(V\) → color mixing matrix
- \(V\) (projector/camera/reflectance)

Nayar et al, CVPR 2004
Color Mixing

determining color mixing matrix $V$:

$$V = \begin{bmatrix}
V_{RR} & V_{RG} & V_{RB} \\
V_{GR} & V_{GG} & V_{GB} \\
V_{BR} & V_{BG} & V_{BB}
\end{bmatrix}$$

$V$ (per pixel)

red in red   green in red   blue in red

$\Rightarrow$ FM (in un-normalized matrix)

$R = V \cdot I$

$I \rightarrow$ projected image
$V \rightarrow$ color mixing matrix
(projector/camera/reflectance)
Color Mixing

determining color mixing matrix $V$:

for un-normalized matrix: (camera and projector response must be known and linearized):

$$V = \begin{bmatrix}
V_{RR} & V_{RG} & V_{RB} \\
V_{GR} & V_{GG} & V_{GB} \\
V_{BR} & V_{BG} & V_{BB}
\end{bmatrix}$$

$R = V \cdot I$

$I \rightarrow$ projected image
$V \rightarrow$ color mixing matrix
(projector/camera/reflectance)

Nayar et al, CVPR 2004
Color Mixing

determining color mixing matrix $V$:

for un-normalized matrix: (camera and projector response must be known and linearized):

capture 9+ images $\rightarrow$ least squares

$$ V = \begin{bmatrix} V_{RR} & V_{RG} & V_{RB} \\ V_{GR} & V_{GG} & V_{GB} \\ V_{BR} & V_{BG} & V_{BB} \end{bmatrix} $$

$V$ (per pixel)

$R = V \cdot I$

$I$ $\rightarrow$ projected image
$V$ $\rightarrow$ color mixing matrix
(projector/camera/reflectance)

Nayar et al, CVPR 2004
Color Mixing

determining color mixing matrix $V$:

**for un-normalized matrix:** (camera and projector response must be known and linearized):

capture 9+ images $\rightarrow$ least squares

**for normalized matrix** (camera response must be known, projector response can be unknown):

\[
V = \begin{bmatrix}
V_{RR} & V_{RG} & V_{RB} \\
V_{GR} & V_{GG} & V_{GB} \\
V_{BR} & V_{BG} & V_{BB}
\end{bmatrix}
\]

$\rightarrow$ FM (in un-normalized matrix)

\[R = V*I\]

$I \rightarrow$ projected image

$V \rightarrow$ color mixing matrix

(projector/camera/reflectance)
Color Mixing

determining color mixing matrix $V$:

- **for un-normalized matrix**: (camera and projector response must be known and linearized):
  
  capture 9+ images $\rightarrow$ least squares

- **for normalized matrix** (camera response must be known, projector response can be unknown):
  
  diagonals are 1 (unknown scaling)

\[
V = \begin{bmatrix}
V_{RR} & V_{RG} & V_{RB} \\
V_{GR} & V_{GG} & V_{GB} \\
V_{BR} & V_{BG} & V_{BB}
\end{bmatrix}
\]

$\rightarrow$ FM (in un-normalized matrix)

\[
R = V \cdot I
\]

$I \rightarrow$ projected image

$V \rightarrow$ color mixing matrix

(projector/camera/reflectance)

Nayar et al, CVPR 2004
Color Mixing

determining color mixing matrix $V$:

**for un-normalized matrix:** (camera and projector response must be known and linearized):
- capture $9+$ images $\Rightarrow$ least squares

**for normalized matrix** (camera response must be known, projector response can be unknown):
- diagonals are 1 (unknown scaling)
- off-diagonals are $V_{ij} = \Delta C_j / \Delta I_i = \Delta C_j / \Delta R_i$

\[ V = \begin{bmatrix} V_{RR} & V_{RG} & V_{RB} \\ V_{GR} & V_{GG} & V_{GB} \\ V_{BR} & V_{BG} & V_{BB} \end{bmatrix} \]

$\Rightarrow$ FM (in un-normalized matrix)

$R = V*I$

$I \rightarrow$ projected image

$V \rightarrow$ color mixing matrix

(projector/camera/reflectance)
Color Mixing

determining color mixing matrix $V$:

for un-normalized matrix: (camera and projector response must be known and linearized):
- capture 9+ images $\rightarrow$ least squares

for normalized matrix (camera response must be known, projector response can be unknown):
- diagonals are 1 (unknown scaling)
- off-diagonals are $V_{ij} = \frac{\Delta C_j}{\Delta I_i} = \frac{\Delta C_j}{\Delta R_i}$ (since $V_{ii} = 1$, $\Delta I_i = \Delta C_i$)

$R = V \cdot I$

$I \rightarrow$ projected image
$V \rightarrow$ color mixing matrix
(projector/camera/reflectance)
Color Mixing

determining color mixing matrix $V$:

for un-normalized matrix: (camera and projector response must be known and linearized):

capture 9+ images $\rightarrow$ least squares

for normalized matrix (camera response must be known, projector response can be unknown):

diagonals are 1 (unknown scaling)
off-diagonals are $V_{ij} = \Delta C_j / \Delta I_i = \Delta C_j / \Delta R_i$
(since $V_{ii} = 1$, $\Delta I_i = \Delta C_i$)
capture 6 images $C$ (2 per color channel)

$$V = \begin{bmatrix} V_{RR} & V_{RG} & V_{RB} \\ V_{GR} & V_{GG} & V_{GB} \\ V_{BR} & V_{BG} & V_{BB} \end{bmatrix}$$

$\rightarrow$ FM (in un-normalized matrix)

$R = V \ast I$

$I \rightarrow$ projected image
$V \rightarrow$ color mixing matrix (projector/camera/reflectance)
Color Mixing

determining color mixing matrix $V$:

**for un-normalized matrix:** (camera and projector response must be known and linearized):
- capture 9+ images $\rightarrow$ least squares

**for normalized matrix** (camera response must be known, projector response can be unknown):
- diagonals are 1 (unknown scaling)
- off-diagonals are $V_{ij} = \Delta C_j / \Delta I_i = \Delta C_j / \Delta R_i$
  (since $V_{ii} = 1$, $\Delta I_i = \Delta C_i$)
- capture 6 images $C$ (2 per color channel to determine deltas)

$$V = \begin{bmatrix}
V_{RR} & V_{RG} & V_{RB} \\
V_{GR} & V_{GG} & V_{GB} \\
V_{BR} & V_{BG} & V_{BB}
\end{bmatrix}$$

$\rightarrow$ FM (in un-normalized matrix)

$R = V \times I$

$I \rightarrow$ projected image
$V \rightarrow$ color mixing matrix
(projector/camera/reflectance)
Color Mixing

determining color mixing matrix $V$:

**for un-normalized matrix**: (camera and projector response must be known and linearized):
- capture $9+$ images $\rightarrow$ least squares

**for normalized matrix** (camera response must be known, projector response can be unknown):
- diagonals are 1 (unknown scaling)
- off-diagonals are $V_{ij} = \Delta C_j / \Delta I_i = \Delta C_j / \Delta R_i$
  (since $V_{ii} = 1$, $\Delta I_i = \Delta C_i$)
- capture 6 images $\mathbf{C}$ (2 per color channel to determine deltas)

\[
V = \begin{bmatrix}
V_{RR} & V_{RG} & V_{RB} \\
V_{GR} & V_{GG} & V_{GB} \\
V_{BR} & V_{BG} & V_{BB}
\end{bmatrix}
\]

$\rightarrow$ FM (in un-normalized matrix)

$R = V \ast I$

$I \rightarrow$ projected image

$V \rightarrow$ color mixing matrix

(projector/camera/reflectance)
Color Mixing

determining color mixing matrix $V$:

**for un-normalized matrix**: (camera and projector response must be known and linearized):
- capture 9+ images $\rightarrow$ least squares

**for normalized matrix** (camera response must be known, projector response can be unknown):
- diagonals are 1 (unknown scaling)
- off-diagonals are $V_{ij} = \Delta C_j / \Delta I_i = \Delta C_j / \Delta R_i$
  (since $V_{ii} = 1$, $\Delta I_i = \Delta C_i$)
- capture 6 images $C$ (2 per color channel to determine deltas)

compensation (per pixel):

$R = V \ast I$

- $I$ $\rightarrow$ projected image
- $V$ $\rightarrow$ color mixing matrix
  (projector/camera/reflectance)
Color Mixing

determining color mixing matrix $V$:

**for un-normalized matrix**: (camera and projector response must be known and linearized):
- capture 9+ images $\rightarrow$ least squares

**for normalized matrix** (camera response must be known, projector response can be unknown):
- diagonals are 1 (unknown scaling)
- off-diagonals are $V_{ij} = \Delta C_j / \Delta I_i = \Delta C_j / \Delta R_i$
  (since $V_{ii} = 1$, $\Delta I_i = \Delta C_i$)
- capture 6 images $C$ (2 per color channel to determine deltas)

compensation (per pixel):
- $I = V^{-1} * R$ (does not consider

\[ R = V * I \]

$I \rightarrow$ projected image
$V \rightarrow$ color mixing matrix
(projector/camera/reflectance)
Color Mixing

determining color mixing matrix $V$:

- **for un-normalized matrix**: (camera and projector response must be known and linearized):
  - capture 9+ images $\rightarrow$ least squares

- **for normalized matrix**: (camera response must be known, projector response can be unknown):
  - diagonals are 1 (unknown scaling)
  - off-diagonals are $V_{ij} = \frac{\Delta C_j}{\Delta I_i} = \frac{\Delta C_j}{\Delta R_i}$
    (since $V_{ii} = 1$, $\Delta I_i = \Delta C_i$)
  - capture 6 images $C$ (2 per color channel to determine deltas)

compensation (per pixel):

$I = V^{-1}R$ (does not consider environment light!)

$R = V*I$

$I$ $\rightarrow$ projected image
$V$ $\rightarrow$ color mixing matrix
(projector/camera/reflectance)
Dynamic Adaptation
Dynamic Adaptation

\[ R_t = \frac{M_t}{M_0} \cdot (E_t \cdot M_0 + V_0 \cdot I_t) \]

- \( t \rightarrow \) time index
- \( I_t \rightarrow \) projected image at \( t \)
- \( V_0 \rightarrow \) un-normalized color mixing matrix at \( t=0 \) (const.)
- \( M_t \rightarrow \) material at \( t \)
- \( M_0 \rightarrow \) material at \( t=0 \)
- \( E_t \rightarrow \) environment light at \( t=0 \)
Dynamic Adaptation

determining color mixing matrix $V_0$:

$$R_t = \frac{M_t}{M_0} (E_t M_0 + V_0 I_t)$$

$t$ → time index
$I_t$ → projected image at $t$
$V_0$ → un-normalized color mixing matrix at $t=0$ (const.)
$M_t$ → material at $t$
$M_0$ → material at $t=0$
$E_t$ → environment light at $t=0$
Dynamic Adaptation

determining color mixing matrix $V_0$: similar as before: $V_{ij} = \Delta C_j / \Delta I_i$

\[
R_t = M_t / M_0 \cdot (E_t \cdot M_0 + V_0 \cdot I_t)
\]

- $t$ → time index
- $I_t$ → projected image at $t$
- $V_0$ → un-normalized color mixing matrix at $t=0$ (const.)
- $M_t$ → material at $t$
- $M_0$ → material at $t=0$
- $E_t$ → environment light at $t=0$

---

Fujii et al, CVPR 2005
Dynamic Adaptation

determining color mixing matrix \( V_0 \):

similar as before: \( V_{ij} = \Delta C_j / \Delta I_i \)

(un-normalized!)

\[
R_t = \frac{M_t}{M_0} (E_t * M_0 + V_0 * I_t)
\]

- \( t \) \rightarrow time index
- \( I_t \) \rightarrow projected image at \( t \)
- \( V_0 \) \rightarrow un-normalized color mixing matrix at \( t=0 \) (const.)
- \( M_t \) \rightarrow material at \( t \)
- \( M_0 \) \rightarrow material at \( t=0 \)
- \( E_t \) \rightarrow environment light at \( t=0 \)
Dynamic Adaptation

determining color mixing matrix $V_0$:
similar as before: $V_{ij} = \Delta C_j / \Delta I_i$
(un-normalized!)

determine reflected environment

$$R_t = M_t / M_0 \cdot (E_t \cdot M_0 + V_0 \cdot I_t)$$

$t$ → time index
$I_t$ → projected image at $t$
$V_0$ → un-normalized color mixing
matrix at $t=0$ (const.)
$M_t$ → material at $t$
$M_0$ → material at $t=0$
$E_t$ → environment light at $t=0$

Fujii et al, CVPR 2005
Dynamic Adaptation

determining color mixing matrix $V_0$:

similar as before: $V_{ij} = \frac{\Delta C_j}{\Delta I_i}$

(un-normalized!)

determine reflected environment light $E_0 * M_0$ at $t=0$:

$$R_t = \frac{M_t}{M_0} * (E_t * M_0 + V_0 * I_t)$$

where:

- $R_t$ \rightarrow \text{time index}
- $I_t$ \rightarrow \text{projected image at $t$}
- $V_0$ \rightarrow \text{un-normalized color mixing matrix at $t=0$ (const.)}
- $M_t$ \rightarrow \text{material at $t$}
- $M_0$ \rightarrow \text{material at $t=0$}
- $E_t$ \rightarrow \text{environment light at $t=0$}
Dynamic Adaptation

determining color mixing matrix $V_0$:
    similar as before: $V_{ij} = \frac{\Delta C_j}{\Delta I_i}$
    (un-normalized!)

determine reflected environment light $E_0^*M_0$ at $t=0$:
    $E_0^*M_0 = C - V_0^*I$ (project

$R_t = M_t/M_0^*(E_t^*M_0 + V_0^*I_t)$
    $t \rightarrow$ time index
    $I_t \rightarrow$ projected image at $t$
    $V_0 \rightarrow$ un-normalized color mixing matrix at $t=0$ (const.)
    $M_t \rightarrow$ material at $t$
    $M_0 \rightarrow$ material at $t=0$
    $E_t \rightarrow$ environment light at $t=0$
Dynamic Adaptation

determining color mixing matrix $V_0$:

similar as before: $V_{ij} = \Delta C_j / \Delta I_i$

(un-normalized!)

determine reflected environment light $E_0 * M_0$ at $t=0$:

$E_0 * M_0 = C - V_0 * I$ (project arbitrary I and capture C)

$R_t = M_t / M_0 * (E_t * M_0 + V_0 * I_t)$

$t$ → time index

$I_t$ → projected image at $t$

$V_0$ → un-normalized color mixing matrix at $t=0$ (const.)

$M_t$ → material at $t$

$M_0$ → material at $t=0$

$E_t$ → environment light at $t=0$
Dynamic Adaptation

determining color mixing matrix \( V_0 \):

similar as before: \( V_{ij} = \Delta C_j / \Delta I_i \)
(un-normalized!)

determine reflected environment light \( E_0 \cdot M_0 \) at \( t=0 \):

\[
E_0 \cdot M_0 = C - V_0 \cdot I
\]
(project arbitrary \( I \) and capture \( C \))

compensation (per pixel at \( t \)):

\[
R_t = \frac{M_t}{M_0} \cdot (E_t \cdot M_0 + V_0 \cdot I_t)
\]

\( t \) → time index
\( I_t \) → projected image at \( t \)
\( V_0 \) → un-normalized color mixing matrix at \( t=0 \) (const.)
\( M_t \) → material at \( t \)
\( M_0 \) → material at \( t=0 \)
\( E_t \) → environment light at \( t=0 \)
Dynamic Adaptation

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similar as before: $V_{ij} = \Delta C_j / \Delta I_i$
(un-normalized!)

determine reflected environment light $E_0 * M_0$ at $t=0$:

$$E_0 * M_0 = C - V_0 * I$$
(project arbitrary $I$ and capture $C$)

compensation (per pixel at $t$):

$$I_t = V_0^{-1} * (R * M_0 / M_{t-1} - E_{t-1} * M_0)$$

$$R_t = M_t / M_0 * (E_t * M_0 + V_0 * I_t)$$

$t$ → time index
$I_t$ → projected image at $t$
$V_0$ → un-normalized color mixing matrix at $t=0$ (const.)
$M_t$ → material at $t$
$M_0$ → material at $t=0$
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$\rightarrow E_{t-1} * M_0 \text{ approx. } E_0 * M_0$

$R_t = M_t / M_0 * (E_t * M_0 + V_0 * I_t)$

t $\rightarrow$ time index
$l_t \rightarrow$ projected image at $t$
$V_0 \rightarrow$ un-normalized color mixing matrix at $t=0$ (const.)
$M_t \rightarrow$ material at $t$
$M_0 \rightarrow$ material at $t=0$
$E_t \rightarrow$ environment light at $t=0$
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compensation (per pixel at $t$):

$$I_t = V_0^{-1} (R * M_0 / M_{t-1} - E_{t-1} * M_0)$$

$E_{t-1} * M_0$ approx. $E_0 * M_0$

$M_0 / M_{t-1} = C_0 / C_{t-1}$

$$R_t = M_t / M_0 * (E_t * M_0 + V_0 * I_t)$$

$t$ → time index

$I_t$ → projected image at $t$

$V_0$ → un-normalized color mixing matrix at $t=0$ (const.)

$M_t$ → material at $t$

$M_0$ → material at $t=0$

$E_t$ → environment light at $t=0$
Limited Dynamic Range and Brightness
Limited Dynamic Range and Brightness
Limited Dynamic Range and Brightness
Multiple Projectors
Multiple Projectors

\[ R = EM + I_1 F_1 M + I_2 F_2 M + \ldots + I_N F_N M \]
Multiple Projectors

strategy: balance intensity load

\[ R = EM + I_1F_1M + I_2F_2M + \ldots + I_NF_NM \]
Multiple Projectors

strategy: balance intensity load

- assume: total intensity is equally balanced among multiple low-capacity units

\[ I_i = I_1 = I_2 = \ldots = I_N \]

\[ R = EM + I_1 F_1 M + I_2 F_2 M + \ldots + I_N F_N M \]
Multiple Projectors

strategy: balance intensity load

- assume: total intensity is equally balanced among multiple low-capacity units

\[ I_i = I_1 = I_2 = ... = I_N \]

\[ R = EM + I_1 F_1 M + I_2 F_2 M + ... + I_N F_N M \]

\[ EM + I(F_1 + F_2 + ... + F_N)M \]
Multiple Projectors

strategy: balance intensity load

- assume: total intensity is equally balanced among multiple low-capacity units

\[ I_i = I_1 = I_2 = \ldots = I_N \]

\[ R = EM + I_1F_1M + I_2F_2M + \ldots + I_NF_NM \]

\[ \Rightarrow EM + I(F_1 + F_2 + \ldots + F_N)M \]
Multiple Projectors

strategy: balance intensity load

- assume: total intensity is equally balanced among multiple low-capacity units
  \[ I_i = I_1 = I_2 = \ldots = I_N \]

- this is equivalent to the assumption that a single high capacity projector produces the total intensity arriving on the surface virtually

\[ R = EM + I_1 F_1 M + I_2 F_2 M + \ldots + I_N F_N M \]
Multiple Projectors

strategy: balance intensity load

- assume: total intensity is equally balanced among multiple low-capacity units
  \[ I_i = I_1 = I_2 = \ldots = I_N \]

- this is equivalent to the assumption that a single high capacity projector produces the total intensity arriving on the surface virtually
  \[ R = EM + I_i(F_1M + F_2M + \ldots + F_NM) \]
  \[ \Rightarrow EM + I(F_1 + F_2 + \ldots + F_N)M \]
Multiple Projectors

strategy: balance intensity load

- assume: total intensity is equally balanced among multiple low-capacity units
  \[ I_i = I_1 = I_2 = \ldots = I_N \]

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\[ R = EM + I_i(F_1M + F_2M + \ldots + F_NM) \Rightarrow EM + I(F_1 + F_2 + \ldots + F_N)M \]

compensation (per pixel):
Multiple Projectors

strategy: balance intensity load

- assume: total intensity is equally balanced among multiple low-capacity units

\[ I_i = I_1 = I_2 = \ldots = I_N \]

- this is equivalent to the assumption that a single high capacity projector produces the total intensity arriving on the surface virtually

\[
R = EM + I_i(F_1M + F_2M + \ldots + F_NM) \\
\rightarrow EM + I(F_1 + F_2 + \ldots F_N)M
\]

compensation (per pixel):

\[ I_i = (R-EM)/( F_1M + F_2M + \ldots + F_NM) \]

remember: \( F_iM = F_iM-B_iF_iM \) !

or \( BFM = B_1F_1M + \ldots + B_iF_iM \)

Bimber et al, IEEE Computer 2005
Considering Human Visual Perception
Considering Human Visual Perception

threshold map (Ramasubramanian et al. Siggraph’99)

- computes for every pixel of an image $R$ the amount of luminance difference that is imperceptible
- considers contrast, luminance and spatial frequency in local neighborhood

adaptation of un-compensated (original) image $R$:

- compute and apply a single (global) scaling factor $R' = R^\alpha$ that minimizes the perceived error (Wang, et al. 2005, only monochrome, not real-time, single projector)
- coming soon: color, real-time, global and local adaptation, potentially multiple projectors
Example: Curtain
Example: Curtain

Bimber et al, IEEE Computer 2005
Example: Fossil
Example: Fossil

In coop. with Senckenberg Museum
Example: Natural Stone Wall
Example: Natural Stone Wall

Bimber et al, IEEE Computer 2005
In coop. with Bennert Group
Example: Wallpaper
Example: Wallpaper

Bimber et al, IEEE Computer 2005
Compensating Global Light Effects
Compensating Global Light Effects
Compensating Diffuse Scattering
Compensating Diffuse Scattering

Bimber et al, IEEE/ACM ISMAR 2005
Compensating Diffuse Scattering

Bimber et al, IEEE/ACM ISMAR 2005

Bimber et al, IEEE VR, 2006
Compensating Diffuse Scattering

Bimber et al, IEEE/ACM ISMAR 2005

Bimber et al, IEEE VR, 2006

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Multi-Projector Techniques for Real-Time Visualizations in Everyday Environments

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Compensating Diffuse Scattering

Bimber et al, IEEE/ACM ISMAR 2005

Bimber et al, IEEE VR, 2006

details:
IEEE VR talk on Wednesday morning (8:30am), session on tracking and projection displays
see demo!
Advanced Techniques
View-Dependence
Non-Complex Surfaces
Non-Complex Surfaces

- view-dependent geometry correction can be computed if geometry is known
- for example:
  - planar/multi-plane: off-axis projection
  - parametric: warping via parametric description
  - scanned/modelled: projective texture mapping
Example: Life-Sized Projector-Based Dioramas
Example: Life-Sized Projector-Based Dioramas

Courtesy: Low, et al., 2001
Complex Surfaces
Complex Surfaces

- if geometry is unknown image-based rendering helps
- sample geometric and radiometric parameters from multiple (source) camera (perspective)
- for novel (destination) camera
  - compute weighted penalties:
    \[ p_j = \alpha a_j + (1 - \alpha) b_j \]
  - select k best perspectives (lowest penalties) and normalize them:
    \[ w_j = \left( 1 - \frac{p_j}{\max_{p_k} p_k} \right) \frac{1}{p_j} \]
  - interpolate new parameter textures \((P_{i2C_j}, F_{ijM}, E_{ijM})\) and direction vector for destination perspective to render new IP:
    \[ t_d = \sum_{j}^{k} w_j t_j \]
    - lookups in \(F_{ijM}, E_{ijM}\)... interpola...nted \(P_{i2C_j}\)
    - lookups in IP with interpolated \(P_{i2C_j}\)
Example: Tracking and Stereo
Example: Tracking and Stereo

Bimber et al, IEEE/ACM ISMAR 2005
Depth and Occlusion
Depth and Occlusion

Bimber et al, IEEE/ACM ISMAR 2005
Example: Stereo on Wallpaper
Example: Stereo on Wallpaper

Bimber et al, IEEE/ACM
ISMAR 2005
Advanced Techniques
Multi-Focal Projection
Multi-Projector-Camera Technique that Increases Focal Depth
Determining Defocus
Determining Defocus

- structured light projection of grid point samples (2-dimensional phase shift)
  - **pre-correction**: geometric and radiometric correction (corrected grid points must be observed in camera)
    \[ I_{x,y} = \frac{(R_{x,y} - EM_{x,y})}{FM_{x,y}} \]
  - **post-correction**: 
    \[ R'_{x',y'} = fI_{x,y} FM_{x',y'} + EM_{x',y'} \]
    \[ fI_{x,y} = \frac{(R'_{x',y'} - EM_{x',y'})}{FM_{x',y'}} \]
    \[ f = \frac{fI_{x,y}}{I} \]
- the normalized intensity spread texture \( f \) serves as basis to estimate focus measures (e.g., via FFT/DCT, intensity loss, point spread, etc.)
Example: Different Configurations
Example: Different Configurations

Bimber et al, IEEE TVCG 2006
Example: Shifting Focal Plane
Example: Shifting Focal Plane

Bimber et al, IEEE TVCG 2006
Image Composition
**Image Composition**

- using the focus values of each projector’s pixels \( (\Phi_{i,x,y}) \), compose an image with minimal total defocus
  - **exclusive composition**: surface point is covered by a single projector pixel (the one with highest \( \Phi_{i,x,y} \))
  
  \[
  I_i = \frac{w_i (R - EM)}{\sum_j w_j FM_j} \\
  w_{i,x,y} = \frac{\Phi_{i,x,y}}{\sum_j \Phi_{j,x,y}}
  \]

- **weighted composition**: compute normalized weight and multiply it with \( FM \) and \( I \)

\[
I_i = w_i (R - EM) / FM_i, \quad w_i = \begin{cases} 
1 & \Phi_{i,x,y} \geq \Phi_{j,x,y} \\
0 & \text{else}
\end{cases}
\]
Example: Room Corner
Example: Room Corner

Bimber et al, IEEE TVCG 2006
Example: Cylindrical Surface
Example: Cylindrical Surface

Bimber et al, IEEE TVCG 2006
Example: Large Focal Depth
Example: Large Focal Depth

Bimber et al, IEEE TVCG 2006
Advanced Techniques
Light Transport
Acquisition
Acquisition

single camera & projector capture 4D slice of 8D reflectance field

$c = Tp$

$T = \begin{bmatrix} \end{bmatrix}$
Acquisition

single camera & projector capture 4D slice of 8D reflectance field

\[
c = T_p
\]

\[
T = \begin{bmatrix}
\vdots \\
\vdots \\
\vdots \\
\vdots \\
\end{bmatrix}
\]

\[
mn 
\]
Acquisition

single camera & projector capture 4D slice of 8D reflectance field

\[ T = \begin{bmatrix} c \\ \vdots \\ c \end{bmatrix} \]

where \( c = Tp \)
Acquisition

The acquisition process involves a single camera and projector capturing a 4D slice of an 8D reflectance field.

\[ c = T_p \]

\[ T = \begin{bmatrix} \text{element} & \text{element} & \ldots & \text{element} \\ \text{element} & \text{element} & \ldots & \text{element} \\ \vdots & \vdots & \ddots & \vdots \\ \text{element} & \text{element} & \ldots & \text{element} \end{bmatrix} \]

\[ \text{mn} \]
Acquisition

single camera & projector capture 4D slice of 8D reflectance field

\[ c = Tp \]

\[ T = \begin{bmatrix} \vdots \vdots \vdots \vdots \vdots \vdots \vdots \vdots \vdots \vdots \end{bmatrix} \]

\[ mn \times 1 \]

\[ pq \times 1 \]

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Acquisition

single camera & projector capture 4D slice of 8D reflectance field

\[ c = Tp \]

\[ T = \begin{bmatrix} \text{pq} \\ \text{mn} \end{bmatrix} \]
Acquisition

single camera & projector capture 4D slice of 8D reflectance field

\[ c = Tp \]

\[ T = \begin{bmatrix} \text{mn} \\ \text{pq} \end{bmatrix} \]
Acquisition

\[ T = \begin{bmatrix}
  t_{00} & \cdots & t_{0pq} \\
  \vdots & \ddots & \vdots \\
  t_{mn0} & \cdots & t_{mnpq}
\end{bmatrix} \]

\( c = Tp \)

Camera image illuminated from single projector pixel.
Dual Photography

\[ c = Tp \]
\[ c' = T^T p' \]

\[ T = \begin{bmatrix} \text{pq} & \text{mn} \end{bmatrix} \]
\[ T^T = \begin{bmatrix} \text{mn} & \text{pq} \end{bmatrix} \]
Dual Photography
Dual Photography

floodlight camera image
Dual Photography

Projected structured light

Floodlight camera image
Dual Photography

dual image

more information on dual photography:
Sen, et al., Siggraph’05

floodlight camera image

projected structured light
Form-Factors from Light Transport Matrix
Form-Factors from Light Transport Matrix

experimental setup
Form-Factors from Light Transport Matrix

\[ M_e = \frac{d^2}{\cos \alpha} L_e \]

Experimental setup

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Form-Factors from Light Transport Matrix

$M_e = \frac{d^2}{\cos \alpha} L_e$

Experimental setup

Measured 16x16 form-factor matrix (computed from light transport matrix)
Global Radiometric Compensation
Global Radiometric Compensation

- traditional radiometric compensation requires direct projector-camera pixel correspondence
- include arbitrary global illumination effects using $T$
- apply inverse light transport $T^{-1}C = P$
- since $T$ is huge, decompose it into clusters and solve in real-time on GPU

$$C = \begin{bmatrix} c_{10} \\ c_{11} \\ c_{12} \\ c_{13} \\ c_{14} \end{bmatrix} = \begin{bmatrix} t_{10}^4 \\ t_{11}^4 \\ t_{12}^4 \\ t_{13}^4 \\ t_{14}^4 \end{bmatrix} \begin{bmatrix} p_4 \\ p_3 \end{bmatrix}$$

$$T^{-1} = \begin{bmatrix} t_{10}^4 & t_{11}^4 & t_{12}^4 & t_{13}^4 & t_{14}^4 \end{bmatrix}^{-1}$$

$$C = \begin{bmatrix} c_{10} \\ c_{11} \\ c_{12} \\ c_{13} \\ c_{14} \end{bmatrix} = \begin{bmatrix} p_4 \\ p_3 \end{bmatrix}$$
Outlook
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geometric warping

complex                        non-trivial                       planar
Multi-Projector Techniques for Real-Time Visualizations in Everyday Environments

- Geometric warping
- Radiometric compensation
- Dynamic adaptation
- Multiple projectors
- Perception
- Global effects

\[ V = \begin{bmatrix} V_{RR} & V_{RG} & V_{RB} \\ V_{GR} & V_{GG} & V_{GB} \\ V_{BR} & V_{BG} & V_{BB} \end{bmatrix} \]
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Multi-Projector Techniques for Real-Time Visualizations in Everyday Environments

04/01/06

radiometric compensation

global effects

view-dependence

geometric warping

complex

non-trivial

planar

single projector

color mixing

dynamic adaptation

multiple projectors

perception

V = \begin{bmatrix} V_{RR} & V_{RG} & V_{RB} \\ V_{GR} & V_{GG} & V_{GB} \\ V_{BR} & V_{BG} & V_{BB} \end{bmatrix}
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Radiometric compensation

Geometric warping

Multi-focal projection

View-dependence

Single projector

Color mixing

Dynamic adaptation

Multiple projectors

Perception

Global effects

Planar

Complex

Non-trivial
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Multi-Projector Techniques for Real-Time Visualizations in Everyday Environments

04/01/06

geometric warping

complex non-trivial planar

radiometric compensation

light transport

multi-focal projection

global parameters dual image global rad. comp.

view-dependence

planar non-trivial complex
Limitations
Limitations

- technological limitations of projectors:
  - brightness, resolution, focal depth
Limitations

- technological limitations of projectors:
  - brightness, resolution, focal depth → can be solved by using multiple projectors (or wait for better ones)
  - black-level and dynamic range
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- technological limitations of projectors:
  - brightness, resolution, focal depth → can be solved by using multiple projectors (or wait for better ones)
  - black-level and dynamic range → wait for HDR light-valve or laser projectors
  - size, cost, portability → wait for (good enough) pocket projectors
Limitations

- technological limitations of projectors:
  - brightness, resolution, focal depth → can be solved by using multiple projectors (or wait for better ones)
  - black-level and dynamic range → wait for HDR light-valve or laser projectors
  - size, cost, portability → wait for (good enough) pocket projectors

- technological limitations of cameras:
Future Work
Future Work

- **new techniques:**
  - consider human visual perception
    - spent computational power only on overcoming limitations that can actually be perceived
  - consider global effects
    - inter-reflections, scattering, etc.
Selected Papers on Geometric Correction
Selected Papers on Geometric Correction


Selected Papers on Radiometric Compensation
Selected Papers on Radiometric Compensation


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Selected Papers Other and Related Techniques
Selected Papers Other and Related Techniques


Thank you!
www.uni.weimar.de/medien/AR
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