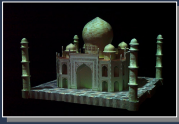

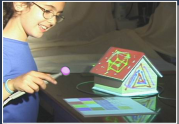






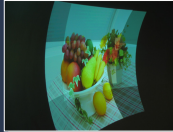

New Directions in Augmented Reality


Ramesh Raskar
 Mitsubishi Electric Research Labs (MERL), Cambridge, MA, USA

New Directions in Augmented Reality

- Spatially Augmented Reality:
 - Alternative approach
- Special effects in real world:
 - Next big graphics challenge
- Location aware RFID:
 - Converging technologies

www.raskar.com

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Parent Organization: MELCO

- Mitsubishi Electric (MELCO), including subsidiaries
 - \$32B in annual sales
 - 125,000 people
 - 10 business sectors:
 - Space Development and Satellite Communications
 - Communications and Information Processing
 - Visual Equipment and Systems
 - Electronic Devices
 - Home Electronics
 - Energy
 - Industrial Equipment
 - Public-Use Systems
 - Transportation

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Non-trivial AR

- Painting with Light
 - [Bandyopadhyay, Raskar, Fuchs 2001]



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MERL

- Mitsubishi Electric Research Laboratories
 - Dick Waters, President & CEO
- Two labs, co-located in Cambridge, MA:
 - MERL Technology Lab
 - Kent Wittenburg, Director
 - Advanced systems development
 - ~35 researchers
 - MERL Research Lab
 - Joe Marks, Director
 - Basic research in applied computing
 - 23 researchers, interns, consultants
 - CV, HCI, Multimedia, CG, AI

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Spatially Augmented Reality (SAR)

HMD-VR

←

Spatially Immersive-VR

→

e.g. CAVE

AR using HMD

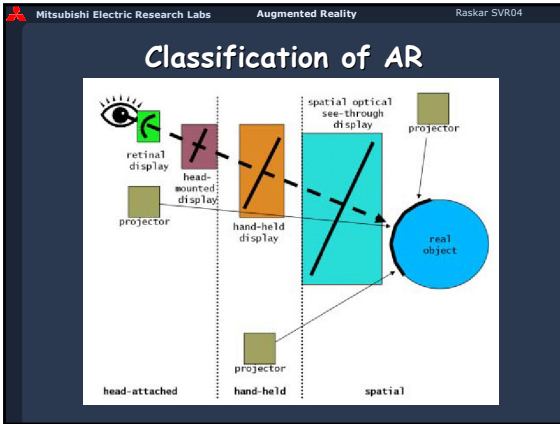
←

Video or Optical see-through

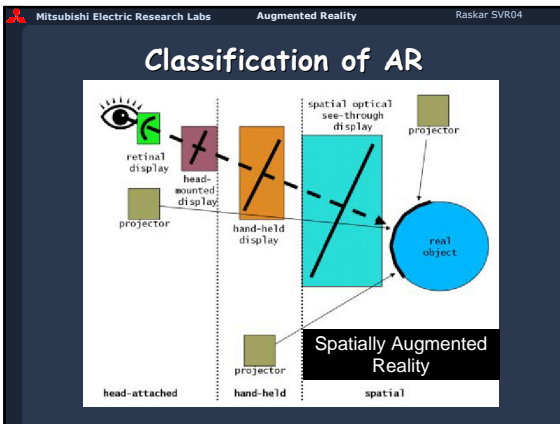
Spatially Augmented Reality

→

SAR, Shaderlamps



- Mitsubishi Electric Research Labs Augmented Reality Raskar SVR04
- ## AR Issues
- Preprocessing:
 - Authoring
 - Runtime:
 - Identification:** Recognition of objects
 - Using markers and visual tags
 - Registration:** Finding relative pose of display device
 - Dynamic estimate of translation and rotation
 - Render/Warp images
 - Interaction:**
 - Widgets, Gesture recognition, Visual feedback



- Mitsubishi Electric Research Labs Augmented Reality Raskar SVR04
- ## Advantages of Projectors
- Size of image
 - Image can be larger than device
 - Combination of images
 - Images can be superimposed and added
 - Shape of display surface
 - Displayed images may be non-planar



- Mitsubishi Electric Research Labs Augmented Reality Raskar SVR04
- ## Disadvantages
- Projector limitations
 - Limited depth of field
 - Shadows
 - Affected by display surface reflectance
 - Challenges
 - Calibration required
 - Rendering involves complex relationships

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Advantages of Spatial Augmentation (SAR)

- Augmentation of objects not view
- Wide area, High resolution

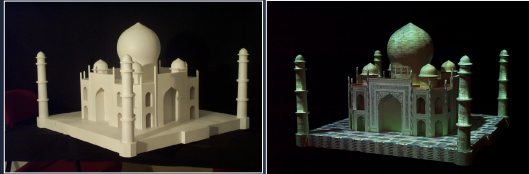
Comparison

- Body-Worn Displays
 - Better ergonomics
 - Reduced tracking requirements
- Hand-held Displays
 - Avoids 'last foot' problem

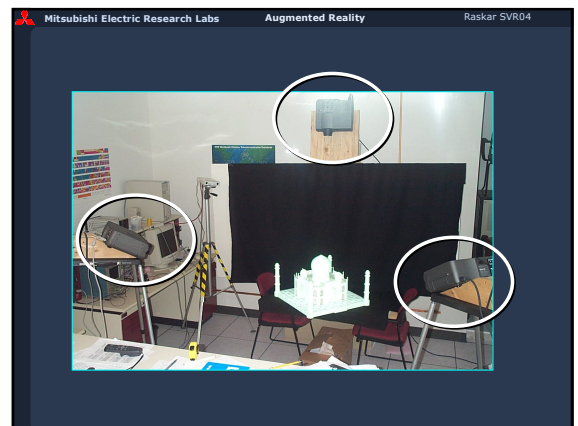
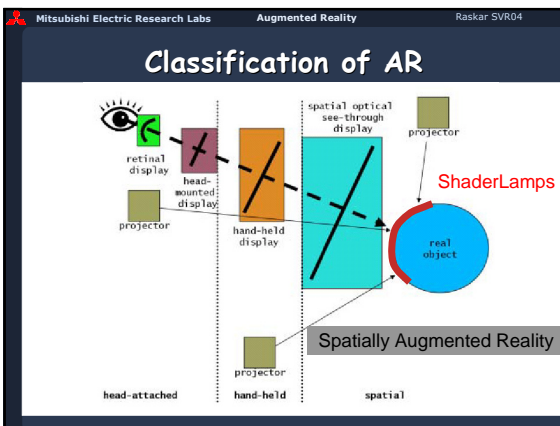
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Shader Lamps Image based Illumination

- Basic Idea
 - Render images and project on objects
 - Multiple projectors
 - View and object dependent color



Raskar, Welch, Low, Bandyopadhyay, "Shader Lamps: Animating Real Objects with Image Based Illumination," Eurographics Rendering Worksp (EGRW 2001)



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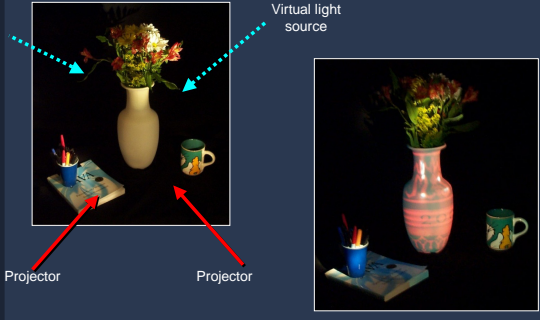
Shader Lamps Motivation

View-dependent Appearance



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Changing Appearance




Virtual light source, Projector, Projector

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Examples

- **Son et Lumiere**
Projecting slide of augmented photo




Copyright © Bernard Fay 1998

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Challenges


- Complete illumination
 - Image alignment
 - Special effects
 - Changing appearance and lighting
 - Complex geometry, self-occlusions
 - Merging multiple projectors




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Examples

- **Disney's Haunted Mansion**
Pre-recorded video



Singing busts



Madame Leota

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Steps

- Preprocessing
 - Scan 3D object and create model
 - Approximately position projector(s)
 - Compute pose, P
 - Find features
 - Find pixels that illuminate them
 - Compute intensity correction
- Run time
 - Render images of 3D model
 - Intensity correction for object shape
 - Feathering for projector overlap

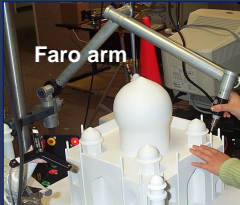
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<ul style="list-style-type: none"> • <u>Old</u> - Large, rigid installations - A 2D image or video projection - Single projector - Texture 	<ul style="list-style-type: none"> • <u>New</u> - Easy setup, Non-trivial objects - Real time 3D animation - Multiple projectors - BRDF
-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------	--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------

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Steps

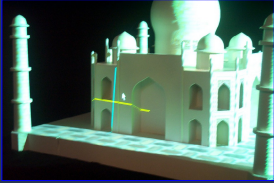
- Preprocessing
 - Scan 3D object and create virtual model, \mathcal{G}



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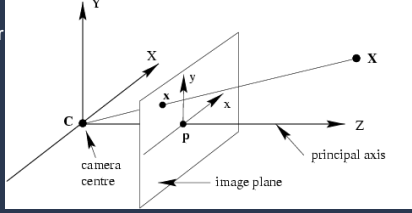
Steps

- Preprocessing
 - Scan 3D object and create model, \mathcal{G}
 - Approximately position projector(s)
 - Find pose, P



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Camera (and Projector) anatomy




Camera center
Image plane
Principal point
Principal axis

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Motivation

- Projector - a 3D projection device
 - Projector is a dual of a camera
 - Relates 3D space and image in framebuffer
 - A useful abstraction : geometric projection model



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Steps

- Preprocessing
 - Scan 3D object and create model
 - Approximately position projector(s)
 - Compute pose, P
 - Find fiducials
 - Find pixels that illuminate them
 - Compute intensity correction
- Run time
 - Render images of 3D model using matrix P
 - Intensity correction for object shape
 - Feathering for projector overlap

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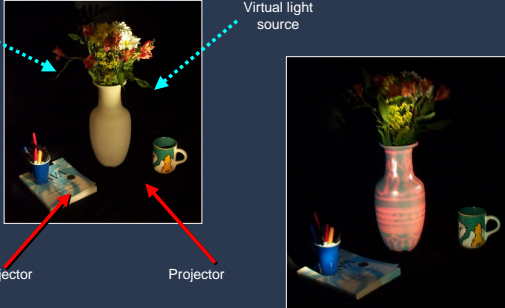
Projector Model

- Pin hole model
 - Equations for perspective projection
 - Relationship between 3D and 2D
 - Intrinsic and Extrinsic Parameters



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Changing Appearance



Virtual light source
Projector
Projector

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Steps

- Preprocessing
 - Scan 3D object and create model
 - Approximately position projector(s)
 - Compute pose, \mathcal{P}
 - Find fiducials
 - Find pixels that illuminate them
 - Compute intensity correction
- Run time
 - Render images of 3D model using matrix \mathcal{P}
 - Intensity correction for object shape
 - Feathering for projector overlap

Radiance Adjustment

$$I_p(x, \theta_p) = \frac{d(x)^2}{k(x) \cos(\theta_p)} L(x, \theta) \quad , \quad k(x) > 0$$

Pixel intensity Intensity correction Desired radiance Reflectance

Radiance Adjustment

$$L(x, \theta) = \int F(x, \theta, \theta_i) L_i(x, \theta_i) d\omega_i$$

Desired radiance BRDF Incident radiance

Intensity Correction

$$I_p(x, \theta_p) = \frac{d(x)^2}{k(x) \cos(\theta_p)} L(x, \theta)$$

Per-pixel factor Rendered Image

- Rendering with
 - Light at c.o.p. : $\cos(\theta_p)$
 - Diffuse reflectance : k
 - Distance attenuation : $1/d(x)^2$
 - $\theta_p > 60^\circ$ cut off

Radiance Adjustment

$$L(x, \theta) = \int F(x, \theta, \theta_i) L_i(x, \theta_i) d\omega_i$$

$$L'(x, \theta) = \frac{k(x) \cos(\theta_p)}{d(x)^2} I_p(x, \theta_p)$$

Resultant radiance Pixel intensity

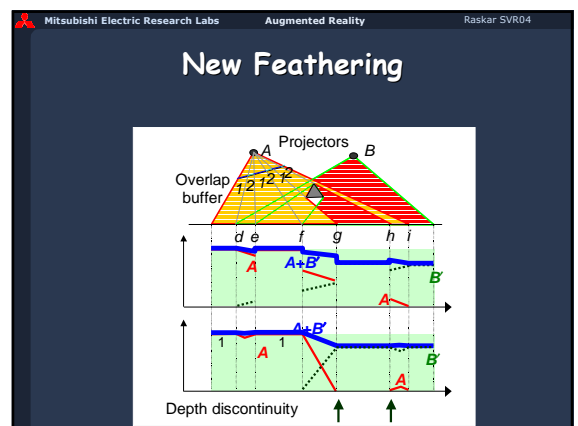
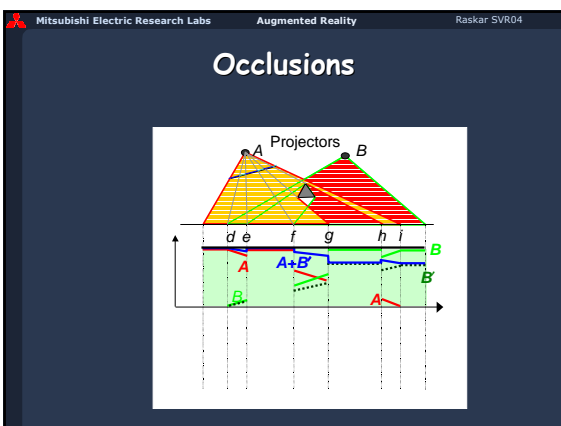
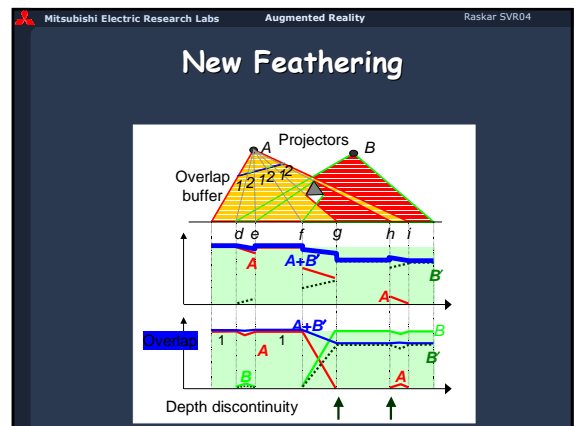
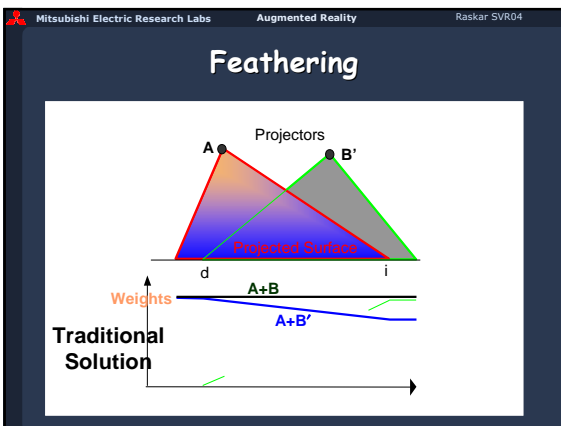
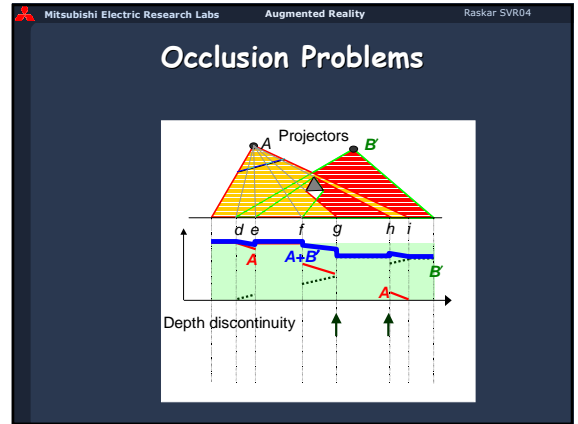
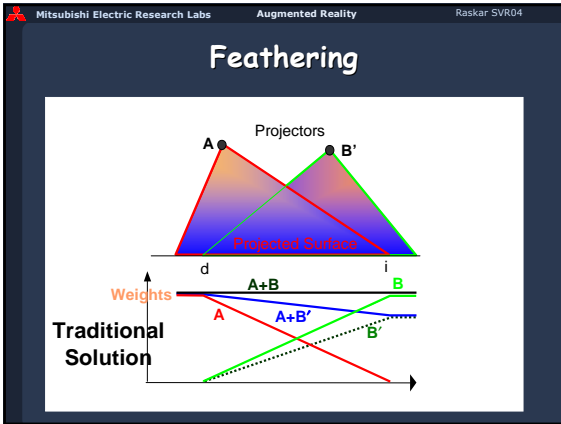
Feathering in Overlap

Projectors A B

Projected Surface

Weights

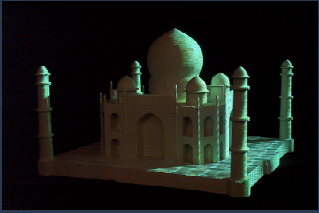
Traditional Solution



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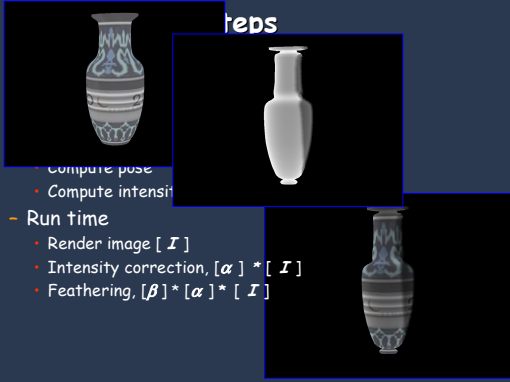
Virtual Illumination

Shadows, Shading and Blending



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Steps




- Compute pose
- Compute intensity
- Run time
 - Render image $[I]$
 - Intensity correction, $[\alpha] * [I]$
 - Feathering, $[\beta] * [\alpha] * [I]$

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Steps

- Preprocessing
 - Scan 3D object and create model, \mathcal{G}
 - Approximately position projector(s)
 - Compute pose, \mathcal{P}
 - Compute intensity correction, α
- Run time
 - Render image $[I]$ using model \mathcal{G} from pose \mathcal{P}



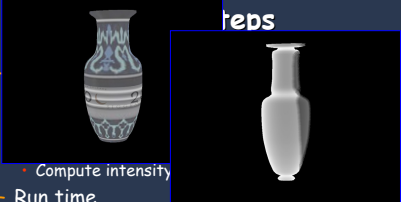
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Steps

- Preprocessing
 - Scan 3D object and create model, \mathcal{G}
 - Approximately position projector(s)
 - Compute pose, \mathcal{P}
 - Find fiducials
 - Find pixels that illuminate them
 - Find projector pose
- Run time
 - Render 3D model \mathcal{G} from \mathcal{P} , $[I]$
 - Intensity correction for object shape $[\alpha] * [I]$
 - Feathering for projector overlap $[\beta] * [\alpha] * [I]$

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Steps



- Compute intensity
- Run time
 - Render image $[I]$
 - Apply intensity correction for object shape $[\alpha] * [I]$
 - Apply feathering for projector overlap, $[\beta] * [\alpha] * [I]$

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Moving Objects



Moving Surface Moving Projector

Moving Viewer

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Apparent Motion

Ramesh Raskar, Remo Ziegler, Thomas Willwacher, "Cartoon Dioramas in Motion," Proc. ACM Symposium on Nonphotorealistic Animation and Rendering (NPAR 2002)

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ShaderLamps

Virtual Reflectance

Virtual Illumination

Virtual Motion

Interaction

www.ShaderLamps.com

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Virtual Motion

Mitsubishi Electric Research Labs Augmented Reality Raskar SVR04

Projector-based Augmentation

Virtual Reflectance

Virtual Illumination

Virtual Motion

Interaction

www.ShaderLamps.com

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Applications

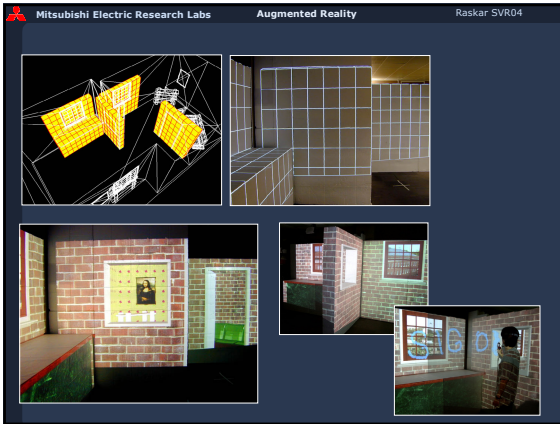
Indoors, under controlled lighting

- Architectural models
 - Augment walk-around scaled model of buildings
 - Project and 'paint' surface colors, textures
 - Lighting, sunlight, seasons
 - Internal structure, pipes, wiring
- Assembly line
 - Instructional text, images and procedures
- Entertainment
 - Live shows, exhibits, demonstrations

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Desired Virtual Model

© Andrei State
Projected Guidance for Placement



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Projection Techniques

- Projection Screen Geometries
 - Planar | Planar Homography
 - Rectilinear |
 - Cylindrical | Quadric image transfer
 - Spherical |
 - Irregular | Discretized Warping

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Projector-based AR

Bimber, O., Fröhlich, B., Schmalstieg, D., and Encarnação, L.M. 'The Virtual Showcase'. *IEEE Computer Graphics & Applications*, vol. 21, no.6, 2001.

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Planar Multi-Projector Display

[Raskar, Jeroen van Baar]

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Steerable Projector

Pinhanez et al 2003

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Planar projective transfer

What is homography?

- Two images of 3D points on a plane are related by a 3×3 matrix

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Planar Homography (in 2D)

Two images of 3D points on a plane
Related by a 3x3 matrix $j \cong A_{3 \times 3} i$

$$k \begin{bmatrix} j_x \\ j_y \\ 1 \end{bmatrix} = \begin{bmatrix} a1 & a2 & a3 \\ b1 & b2 & b3 \\ c1 & c2 & c3 \end{bmatrix} \begin{bmatrix} i_x \\ i_y \\ 1 \end{bmatrix}$$

$$j_x = (a \cdot i) / (c \cdot i)$$

$$j_y = (b \cdot i) / (c \cdot i)$$

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Automatic Keystone Correction with Camera and Tilt Sensor

[Raskar and Beardsley01]

1. Camera and tilt sensor to find projector pose
2. Compute screen to image homography
3. Pre-warp input image

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Planar projective transfer (homography)

- Two images of 3D points on a plane are related by a 3x3 matrix

Defined by 4 or more corresponding pixels

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Planar display surface Use homography ($A_{3 \times 3}$)

$i \cong P_T V$
 $j \cong A i$

Single Projection Matrix!
 $j \cong [A P_T] V$

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Keystone Correction

1. Compute screen to image homography
2. Pre-warp input image

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Ad-hoc Planar Cluster

Planar Display using ad-hoc Clusters

Self-contained Units, No centralized control
No markers or cameras in environment
Beyond the range of single camera

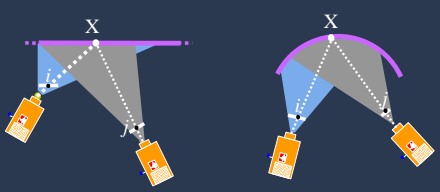
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Projection Techniques

- Projection Screen Geometries
 - Planar  | Planar Homography
 - Rectilinear  | Planar Homography
 - Cylindrical  | Quadric image transfer
 - Spherical  | Quadric image transfer
 - Irregular  | Discretized Warping

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Parametric Image Transfer

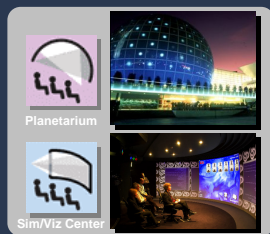


Planar Homography $j \cong A_{3 \times 3} i$

Quadric Transfer $j \cong A_{3 \times 3} i \pm \sqrt{i^T E i} e$

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Quadric curved shape Displays



Planetarium

Sim/Viz Center

Raskar, vanBaar, Willwacher, Rao
 'Quadric Transfer for Immersive Curved Displays',
 EuroGraphics 2004

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Overlap on Quadric Screens

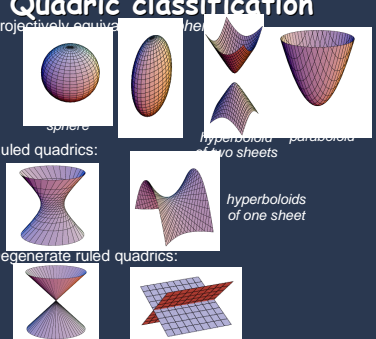


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Curved projective transfer

Quadric classification

Projectively equivalent



sphere

hyperboloids of two sheets

hyperboloids of one sheet

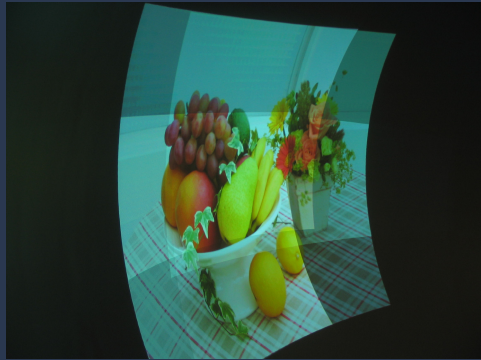
cone

two planes

Ruled quadrics:






Degenerate ruled quadrics:

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Projection Techniques

- Projection Screen Geometries
 - Planar  Planar Homography
 - Rectilinear  |
 - Cylindrical  Quadric image transfer
 - Spherical  |
 - Irregular  Discretized Warping

Vertex Shader for Quadric Transfer in Cg

```

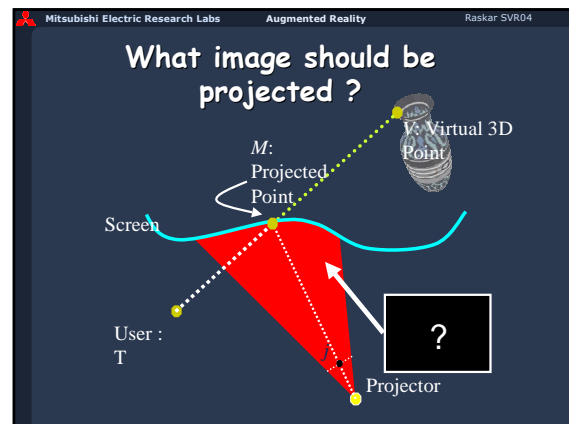
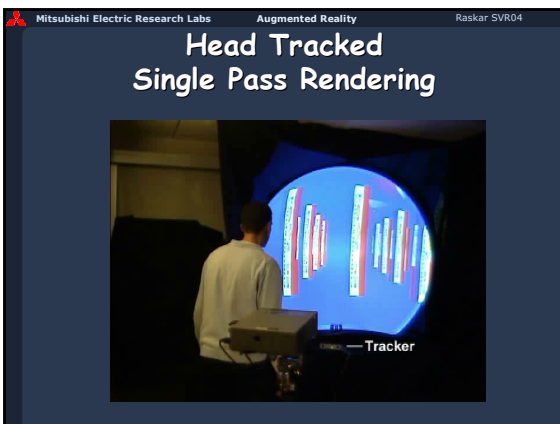
vertout main( appin IN, uniform float4x4 modelViewProj,
uniform float4 constColor, uniform float3x3 A, uniform float3x3 E,
uniform float3 e ) {
    vertout OUT;
    float4 m1 = float4(IN.position.x, IN.position.y, IN.position.z, 1.0f );
    float4 m, mi; float3 m2, mp; float scale;

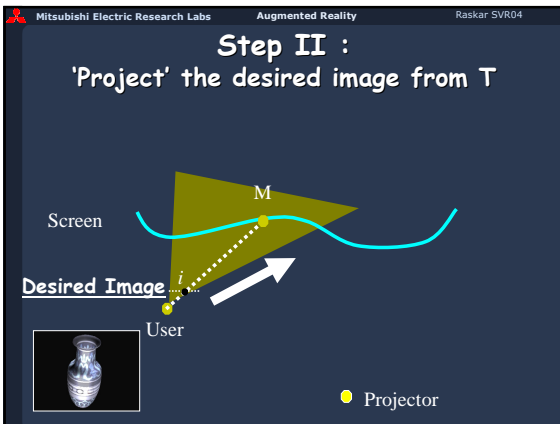
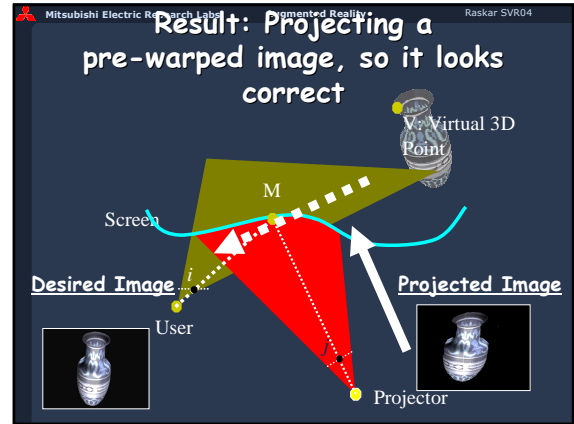
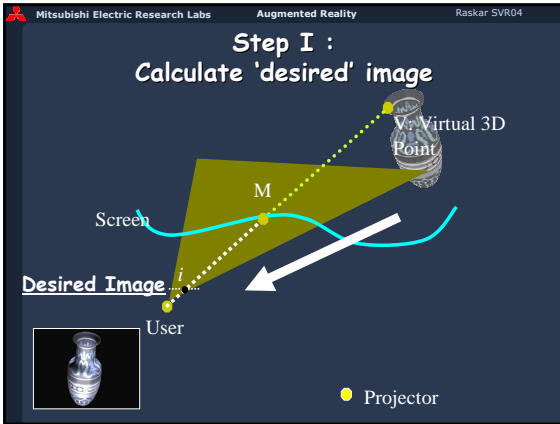
    m = mul( modelViewProj, m1);
    m2.x = m.x/m.w; m2.y = m.y/m.w; m2.z = 1;
    scale = mul(m2, mul(E,m2));
    mp = mul(A,m2) + sqrt(scale)*e;
    mi.x = m.w * (mp.x)/(mp.z);
    mi.y = m.w * (mp.y)/(mp.z);
    mi.zw = m.zw;
    OUT.position = mi;
    OUT.color0 = IN.color0; // Use the original per-vertex color specified
    return OUT;
}

```

(Code in Course Notes)

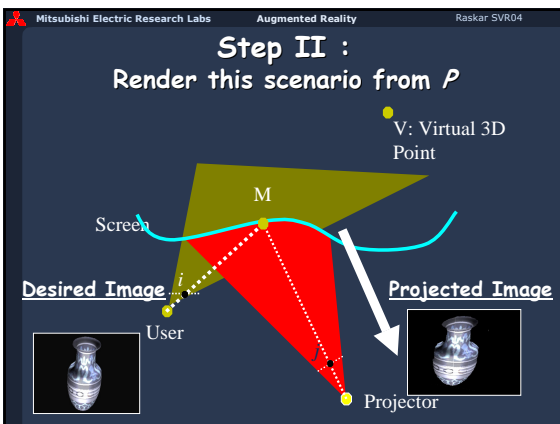
Non-planar Display Video





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AR with location-aware RFID




RFID Lamps : Interacting with a Self-describing World via Photosensing Wireless Tags and Projectors

Ramesh Raskar, Paul Beardsley, Jeroen van Baar, Yao Wang, Paul Dietz, Johnny Lee, Darren Leigh, Thomas Willwacher


Mitsubishi Electric Research Labs (MERL), Cambridge, MA

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Radio Frequency Identification Tags (RFID)




No batteries,
Small size,
Cost few cents



Antenna
microchip

Tagged Books in a Library

✓ Id : List of books in RF range



✗ No Precise Location Data
Are books in sorted order?
Which book is upside down?

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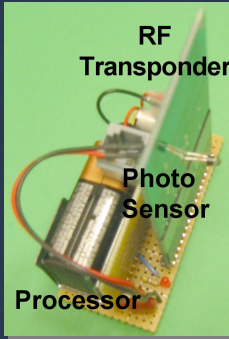
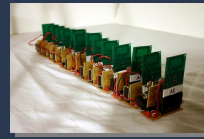
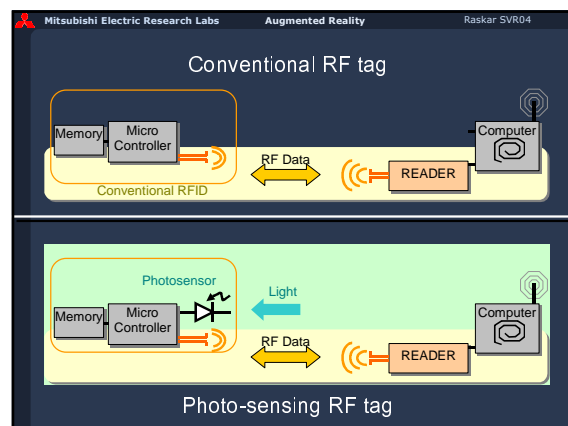
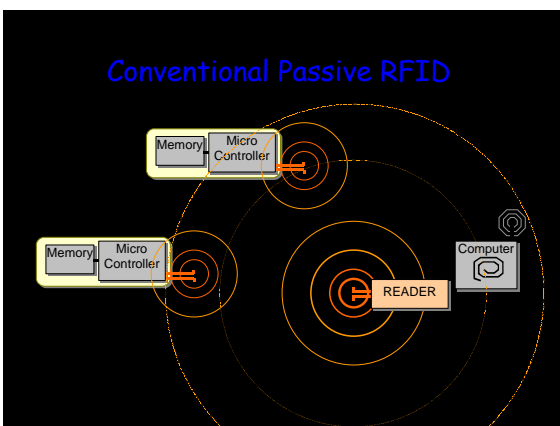


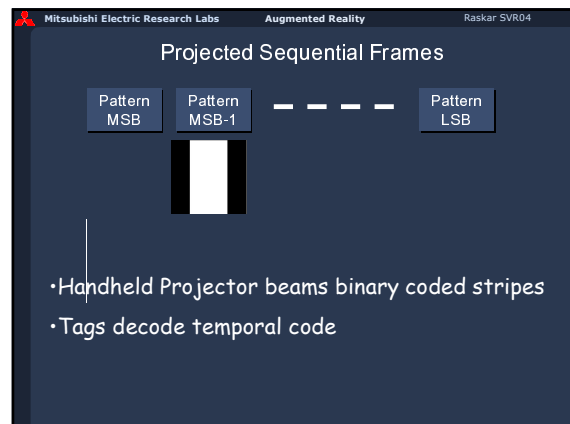
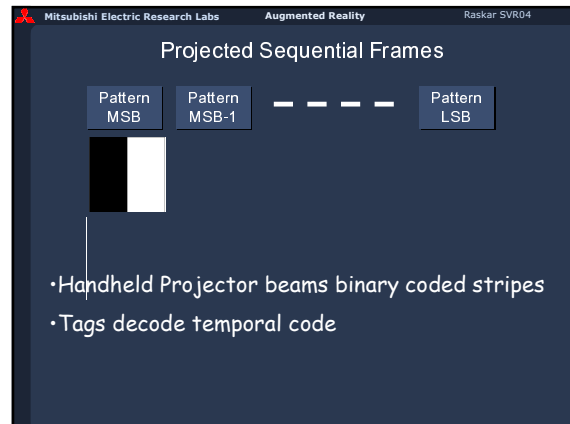
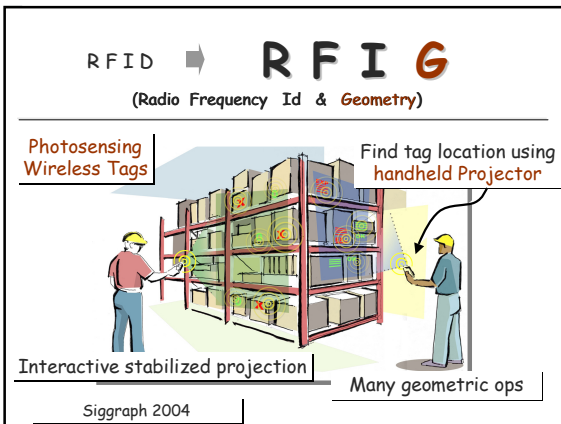
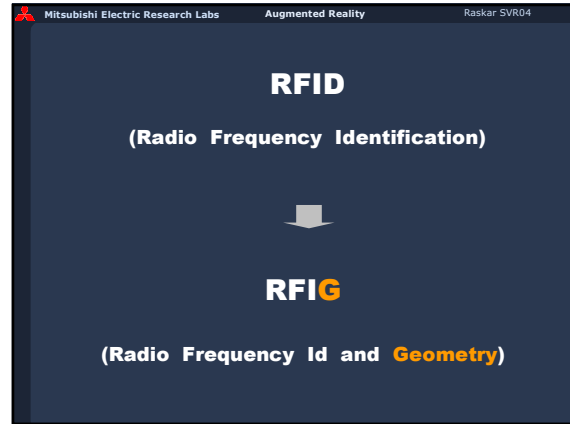
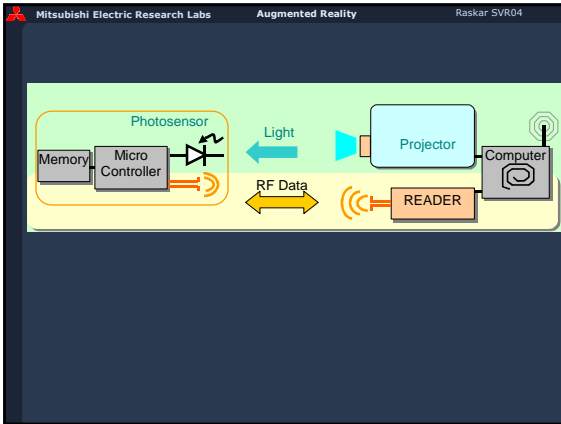
Warehousing
Routing
Livestock tracking
Library
Baggage handling
Currency

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Prototype Tag

RF tag + photosensor



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Projected Sequential Frames

- Handheld Projector beams binary coded stripes
- Tags decode temporal code

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Projected Sequential Frames

0 1 1 0 0 → X=12

For each tag

- From light sequence, decode x and y coordinate
- Transmit back to RF reader (Id, x, y)

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Projected Sequential Frames

- Handheld Projector beams binary coded stripes
- Tags decode temporal code

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Visual feedback of 2D position

- Receive via RF $\{(x_1, y_1), (x_2, y_2), \dots\}$ pixels
- Illuminate those positions

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Projected Sequential Frames

- Handheld Projector beams binary coded stripes
- Tags decode temporal code

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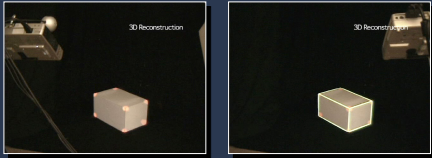
Visual feedback of 2D position

- Receive via RF $\{(x_1, y_1), (x_2, y_2), \dots\}$ pixels
- Illuminate those positions

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3D from 2 Projector Views (Structure from Motion)

- Two+ unknown projector views
- Correspondence is trivial
- Applications
 - Detect 3D deformations
 - Trajectory grouping



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Desktop-like Interaction




Selecting tags

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Change Detection without fixed camera, in any lighting condition

Before



Record coordinates of tags
from one view

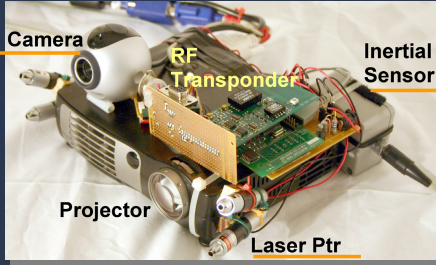
After



Compare with new coordinates
from a different view

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Support for handheld projection



Camera
RF Transponder
Inertial Sensor
Projector
Laser Ptr

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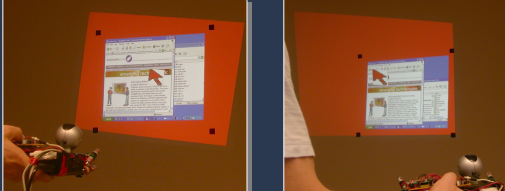
Texture Adaptation



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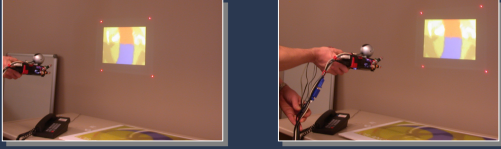
Mouse Simulation

- Cursor follows handheld projector motion
- Pre-warped image remains stable



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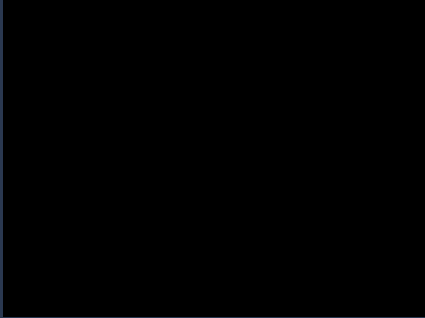
Image Quasi-Stabilization



Eliminate hand jitter using inertial sensors+camera

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Interactive Projection



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Absolute Stabilization

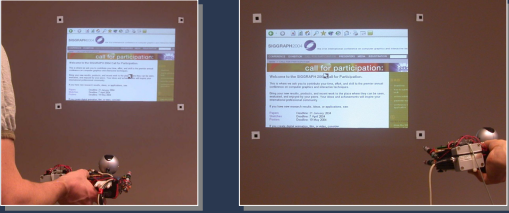


Image stays registered with world features

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Adaptive Projection



'Copy and Paste'
Geometric and Photometric compensation

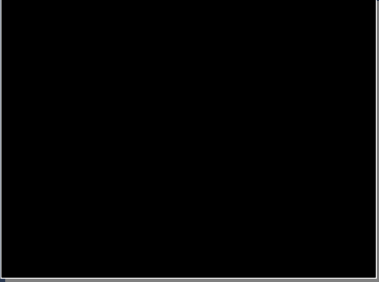
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Image Stabilization



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Prototype Handheld Projector



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Machine AR

- AR for cameras and machines
- Face Dome [Debevec 2001]
- 4D lighting [MPI, MERL]

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- **Projector-Camera Workshop**
June 2005
www.PROCAMS.org
- **Web Page :**
<http://raskar.com/Projector/>
- **Projector mailing list**
majordomo@cs.unc.edu
"subscribe projector"

Robot 'Laser' Guidance Picking and Sorting Tagged Objects

New Directions in Augmented Reality

- **Spatially Augmented Reality:**
 - Alternative approach
- **Special effects in real world:**
 - Next big graphics challenge
- **Location aware RFID:**
 - Converging technologies

www.raskar.com

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- Images
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- SVR, Absolut, Luciano Pereira Soares

New Directions in Augmented Reality

Ramesh Raskar
Mitsubishi Electric Research Labs (MERL), Cambridge, MA

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Shader Lamps Motivation

View-dependent Appearance

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Virtual Motion

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Shader Lamps Image based Illumination

- Basic Idea

- Render images and project on objects
- Multiple projectors
- View and object dependent color

Raskar, Welch, Low, Bandyopadhyay, "Shader Lamps: Animating Real Objects with Image Based Illumination," Eurographics Rendering Workshop (EGRW 2001)

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ShaderLamps

Virtual Reflectance Virtual Illumination

Virtual Motion Interaction

www.ShaderLamps.com

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Prototype Handheld Projector