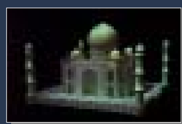
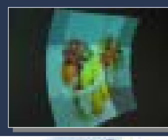
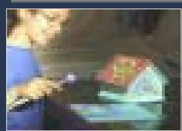
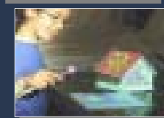
New Directions in Augmented Reality


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

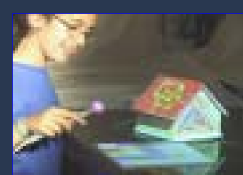
www.raskar.com

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

Non-trivial AR

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



MERL

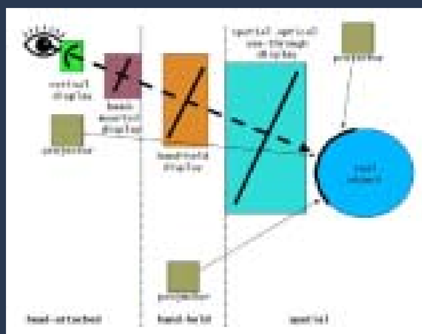
- Mitsubishi Electric Research Laboratories
  - Dick Waters, President & CEO
- Two labs, co-located in Cambridge, MA:
  - MERL Technology Lab
    - Kent Wittenburg, Director
    - Advanced systems development
    - ~35 researchers
  - MERL Research Lab
    - Joe Marks, Director
    - Basic research in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

Spatially Augmented Reality (SAR)

HMD-VR ⟷ Spatially Immersive-VR
e.g. CAVE

AR using HMD ⟷ Spatially Augmented Reality
Video or Optical see-through
SAR, Shaderlamps

Classification of AR



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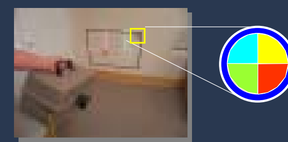
AR Issues



- 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

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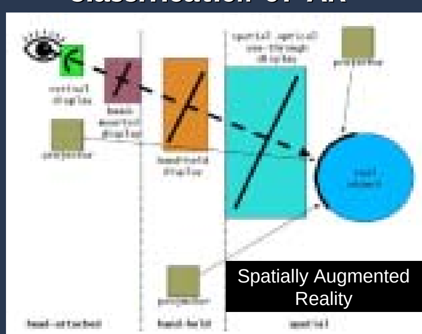
Classification of AR



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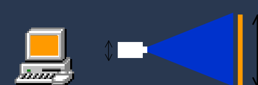
Advantages of Projectors

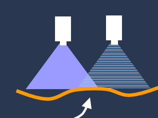
- Size of image

  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

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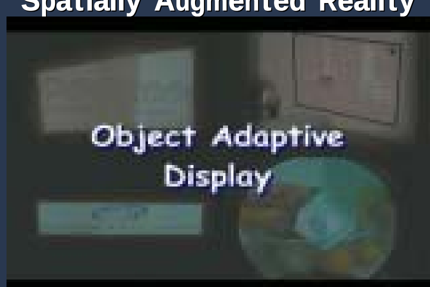
Spatially Augmented Reality



Raskar, vanBaar, Beardsley, Willwacher, Rao, Forlines
'iLamps: Geometrically Aware and Self-Configurable Projectors', SIGGRAPH 2003

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Disadvantages

- Projector limitations
  - Limited depth of field
  - Shadows
  - Affected by display surface reflectance
- Challenges
  - Calibration required
  - Rendering involves complex relationships

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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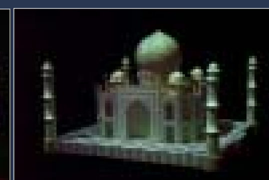
Shader Lamps Image based Illumination

- 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 Worksop (EGRW 2001)

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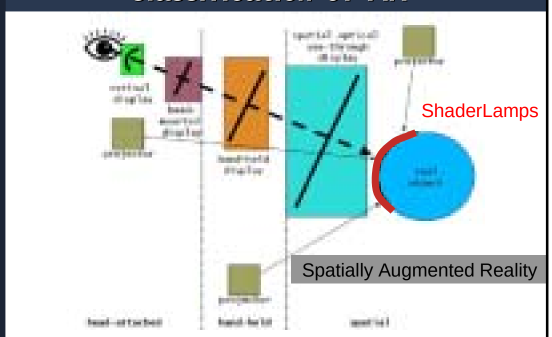
Classification of AR



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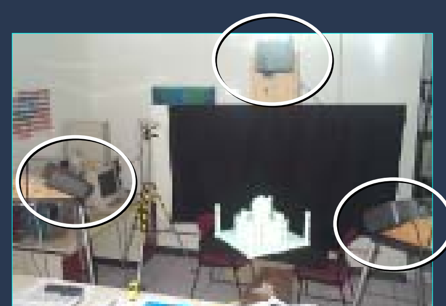

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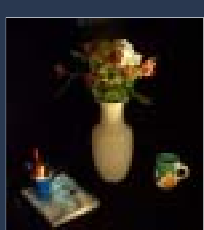
Shader Lamps Motivation

View-dependent Appearance

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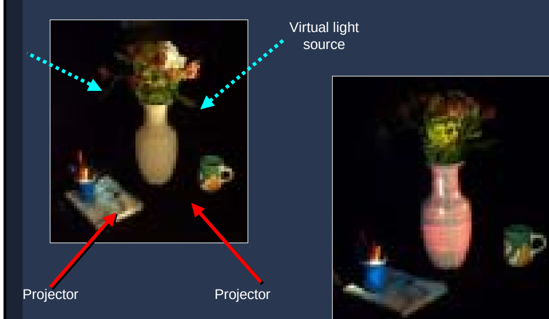
Changing Appearance



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Examples

- Son et Lumiere

Projecting slide of augmented photo

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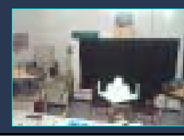
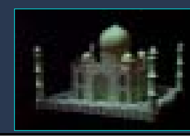
Challenges

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





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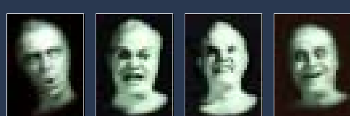
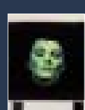
Examples

- 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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<u>Old</u>	<u>New</u>
– Large, rigid installations	– Easy setup, Non-trivial objects
– A 2D image or video projection	– Real time 3D animation
– Single projector	– Multiple projectors
– Texture	– BRDF

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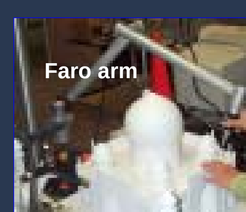
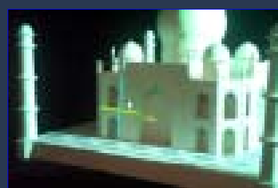
Steps

- Preprocessing
  - Scan 3D object and create virtual model, ***G***



Steps

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



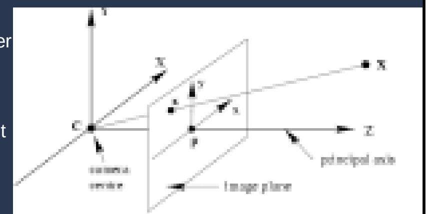
Camera (and Projector) anatomy

Camera center

Image plane

Principal point

Principal axis



Motivation

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

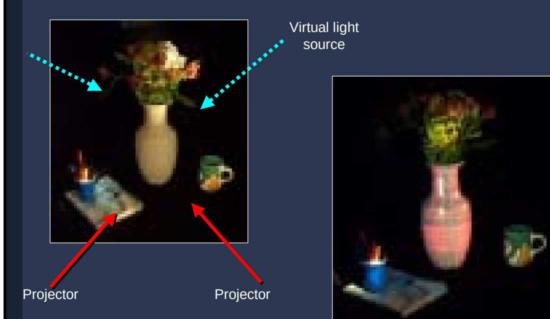
Steps

- 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

Projector Model

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

Changing Appearance



Steps

- Preprocessing
  - Scan 3D object and create model
  - Approximately position projector(s)
  - Compute pose, *P*
    - Find fiducials
    - Find pixels that illuminate them
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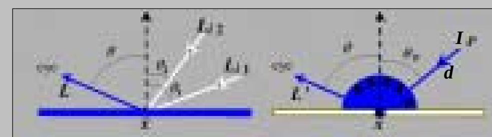
Radiance Adjustment

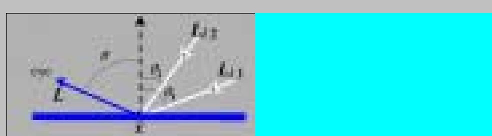


Virtual Real

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

Pixel intensity — *Intensity correction* — Desired radiance — Reflectance

Radiance Adjustment



Virtual

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

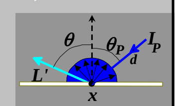
Desired radiance — BRDF — Incident radiance

Intensity Correction

Per-pixel factor — Rendered Image

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

- Rendering with
  - Light at c.o.p. : $cos(\theta_p)$
  - Diffuse reflectance : k
  - Distance attenuation : $1/\ d(x)^2$
  - $\theta_p > 60^0$ cut off



Radiance Adjustment

Virtual Real

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

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

Resultant radiance — Pixel intensity

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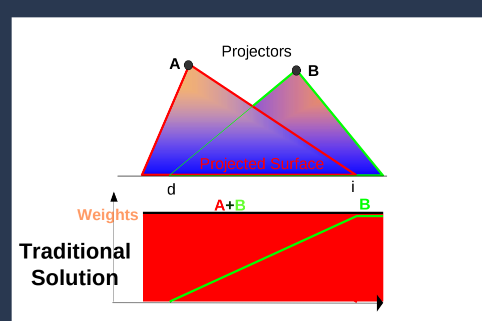
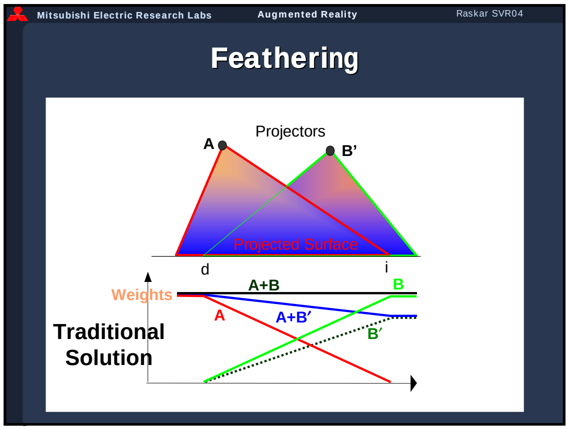
Feathering in Overlap

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Augmented Reality
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Feathering
Projectors
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B'
Projected Surface
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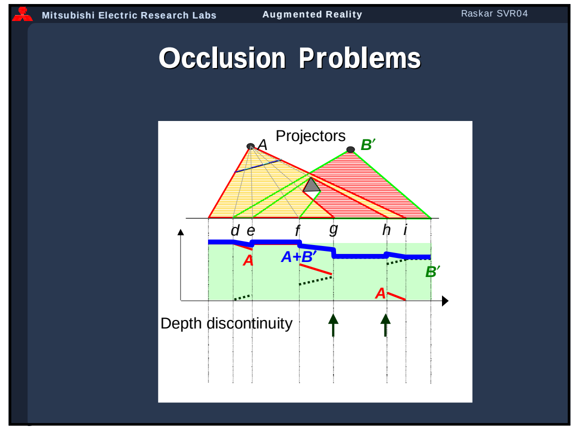
Weights
A+B
B
A
A+B'
B'
Traditional Solution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Occlusion Problems
Projectors
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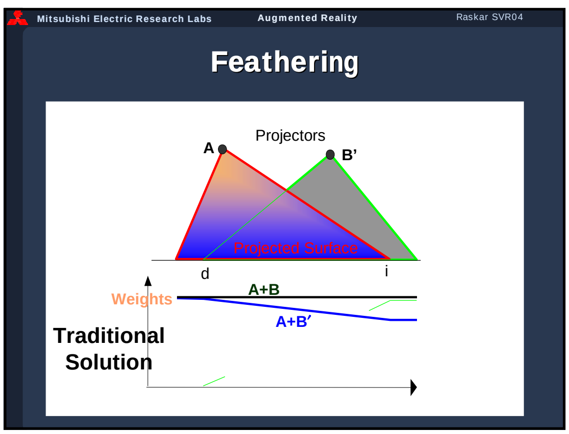
Depth discontinuity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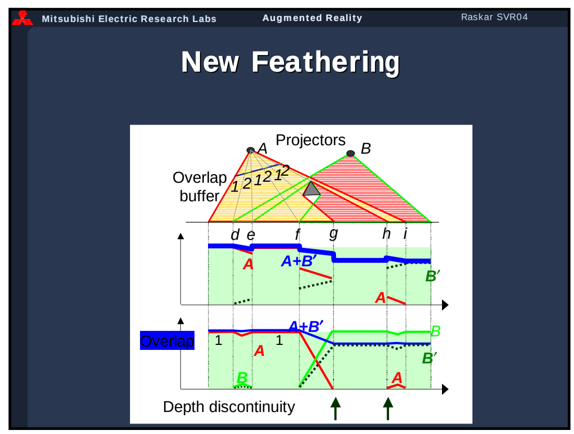
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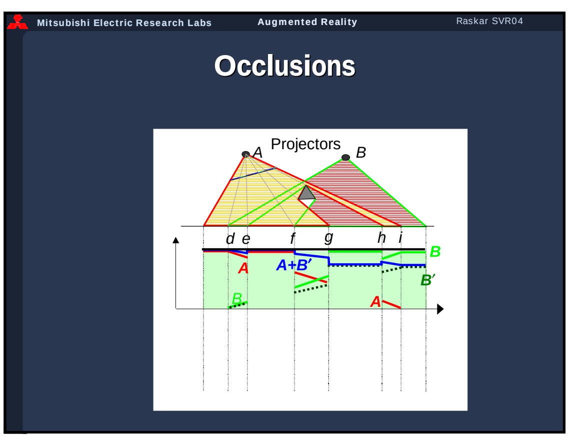
Depth discontinuity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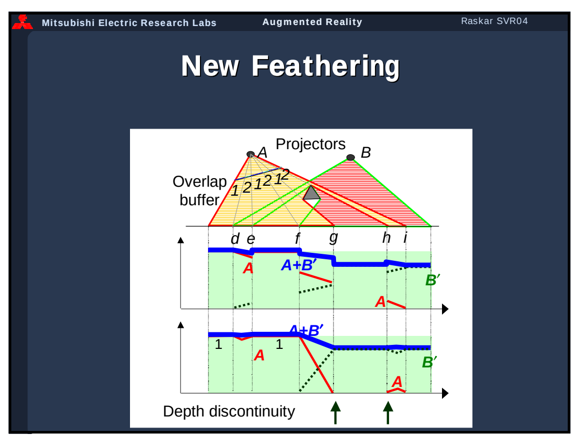
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Depth discontinuity

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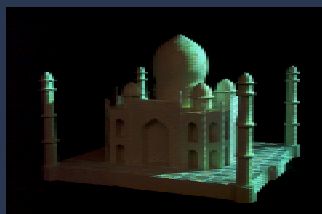
Virtual Illumination

Shadows, Shading and Blending



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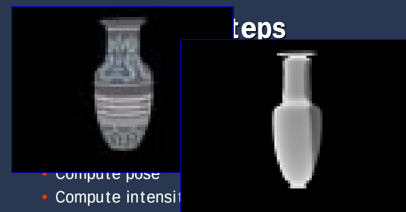
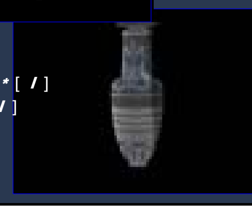


teps

- Compute pose
- Compute intensi

– Run time
- Render image [*I*]
- Intensity correction, [α] * [*I*]
- Feathering, [β] * [α] * [*I*]



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Steps

– Preprocessing
- Scan 3D object and create model, *G*
- Approximately position projector(s)
- Compute pose, *P*
- Compute intensity correction, α

– Run time
- Render image [*I*] using model *G* from pose *P*

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Steps

– Preprocessing
- Scan 3D object and create model, *G*
- Approximately position projector(s)
- Compute pose, *P*
  - Find fiducials
  - Find pixels that illuminate them
  - Find projector pose

– Run time
- Render 3D model *G* from *P*, [*I*]
- Intensity correction for object shape [α] * [*I*]
- Feathering for projector overlap [β] * [α] * [*I*]

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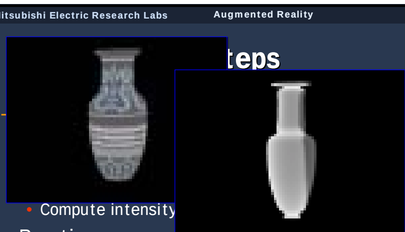

teps

- Compute intensity

– Run time
- Render image [*I*]
- Apply intensity correction for object shape [α]*[*I*]
- Apply feathering for projector overlap, [β]*[α]*[*I*]

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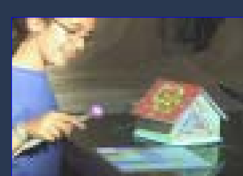
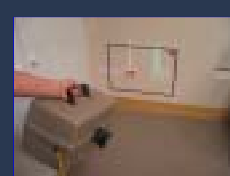
Moving Objects



Moving Surface



Moving Projector

Moving Viewer

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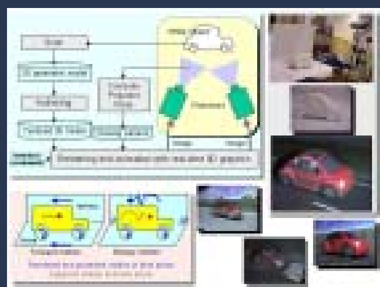
Apparent Motion



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

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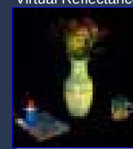
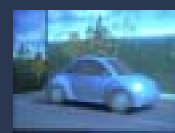
ShaderLamps

Virtual Reflectance

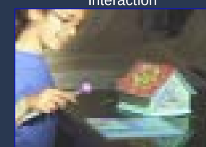


Virtual Illumination

Virtual Motion



Interaction



www.ShaderLamps.com

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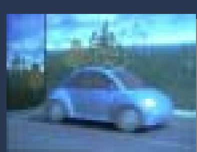
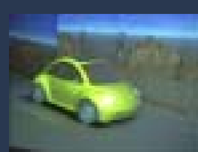
Virtual Motion

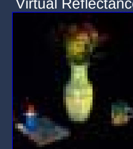




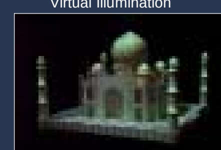
Mitsubishi Electric Research Labs Augmented Reality Raskar SVR04

Projector-based Augmentation

Virtual Reflectance

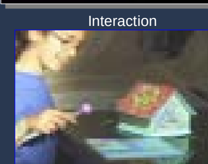


Virtual Illumination



Virtual Motion

Interaction



www.ShaderLamps.com

Mitsubishi Electric Research Labs Augmented Reality Raskar SVR04

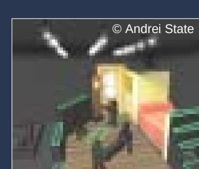
Applications

Indoors, under controlled lighting

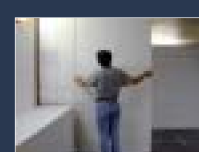
- Architectural models
  - Augment walk-around scaled model of buildings
  - Project and 'paint' surface colors, textures
  - Lighting, sunlight, seasons
  - Internal structure, pipes, wiring
- Assembly line
  - Instructional text, images and procedures
- Entertainment
  - Live shows, exhibits, demonstrations

Mitsubishi Electric Research Labs Augmented Reality Raskar SVR04

Desired Virtual Model



Projected Guidance for Placement

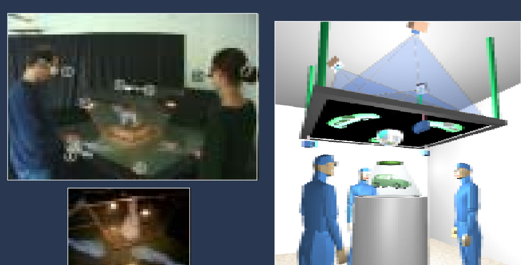


Projection Techniques

- Projection Screen Geometries
  - Planar
  - Rectilinear
  - Cylindrical
  - Spherical
  - Irregular

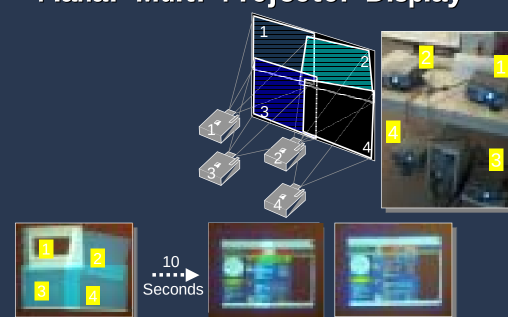
Geometry	Technique
Planar, Rectilinear	Planar Homography
Cylindrical, Spherical	Quadric image transfer
Irregular	Discretized Warping

Projector-based AR



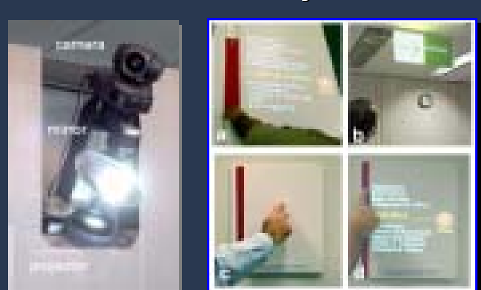
Bimber, O., Fröhlich, B., Schmalstieg, D., and Encarnação, L.M. 'The Virtual Showcase'. *IEEE Computer Graphics & Applications*, vol. 21, no.6, 2001.

Planar Multi-Projector Display



[Raskar, Jeroen van Baar]

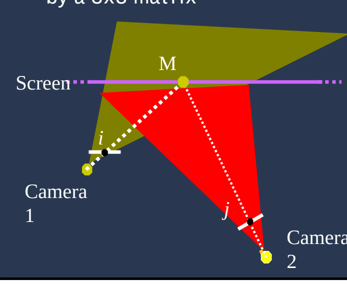
Steerable Projector

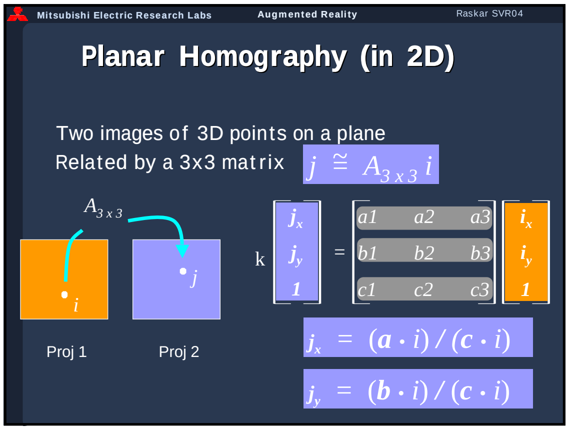


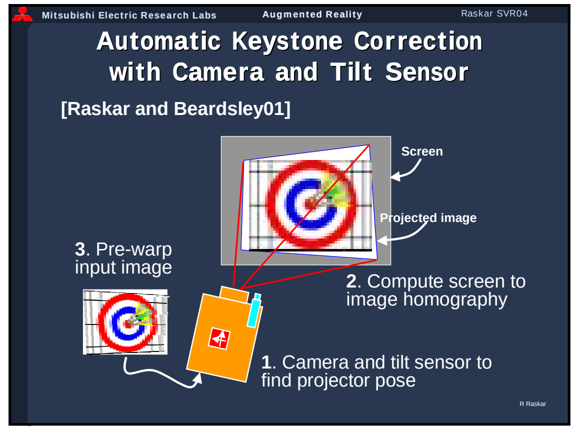
Pinhanez et al 2003

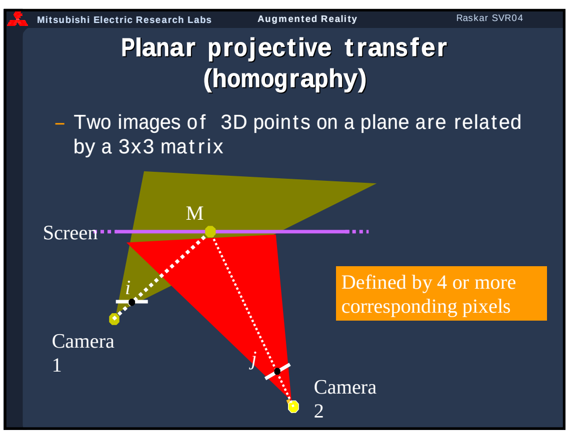
Planar projective transfer What is homography ?

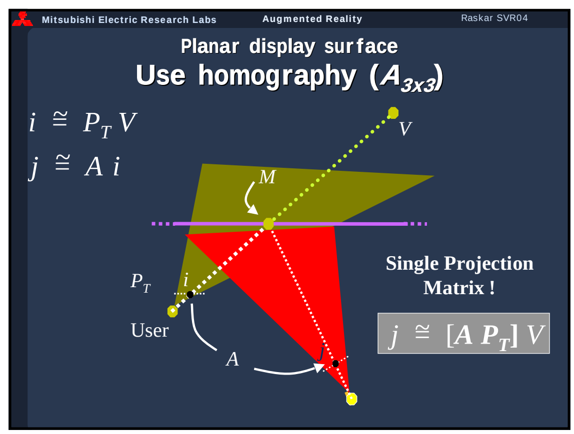
- Two images of 3D points on a plane are related by a 3x3 matrix

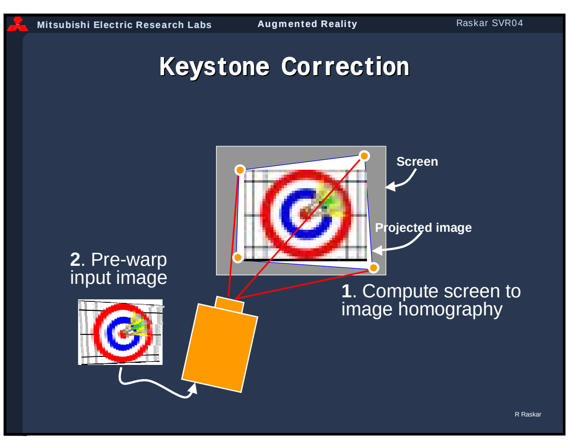


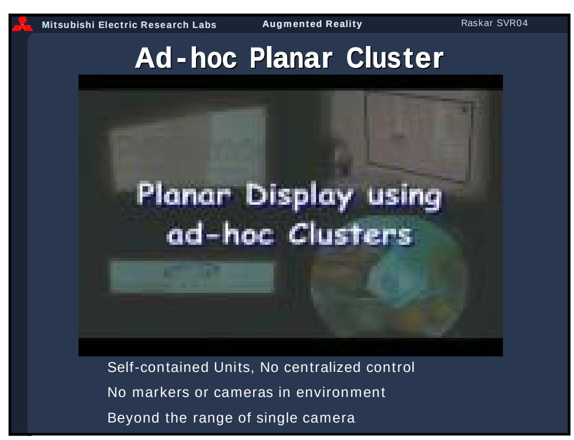

Mitsubishi Electric Research Labs
Augmented Reality
Raskar SVR04
Planar Homography (in 2D)
Two images of 3D points on a plane
Related by a 3x3 matrix
$j \cong A_{3\,x\,3}\, i$
$A_{3\,x\,3}$
i
j
Proj 1
Proj 2
k
j_x j_y 1
=
a1 a2 a3
b1 b2 b3
c1 c2 c3
i_x i_y 1
$j_x = (a \cdot i) / (c \cdot i)$
$j_y = (b \cdot i) / (c \cdot i)$

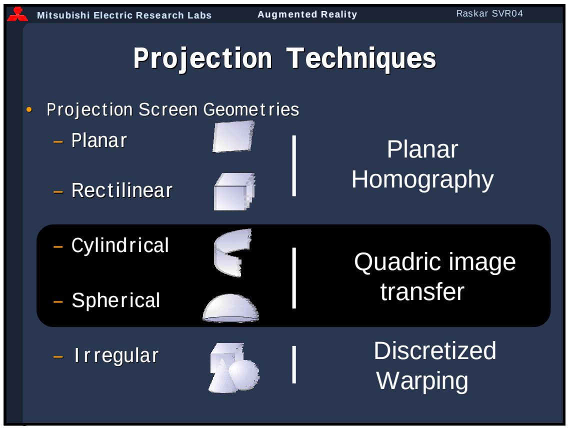

Mitsubishi Electric Research Labs
Augmented Reality
Raskar SVR04
Automatic Keystone Correction with Camera and Tilt Sensor
[Raskar and Beardsley01]
Screen
Projected image
3. Pre-warp input image
2. Compute screen to image homography
1. Camera and tilt sensor to find projector pose
R Raskar

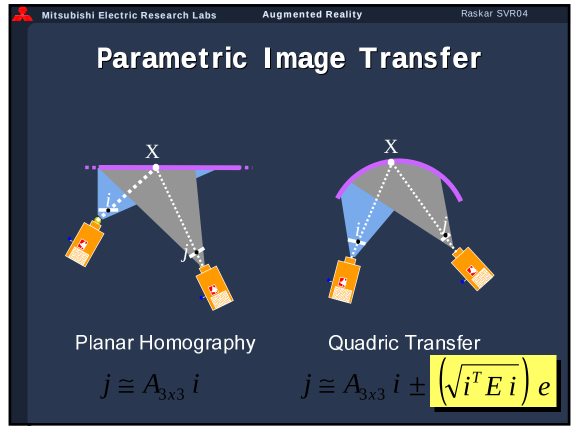

Mitsubishi Electric Research Labs
Augmented Reality
Raskar SVR04
Planar projective transfer (homography)
– Two images of 3D points on a plane are related by a 3x3 matrix
M
Screen
i
j
Defined by 4 or more corresponding pixels
Camera 1
Camera 2

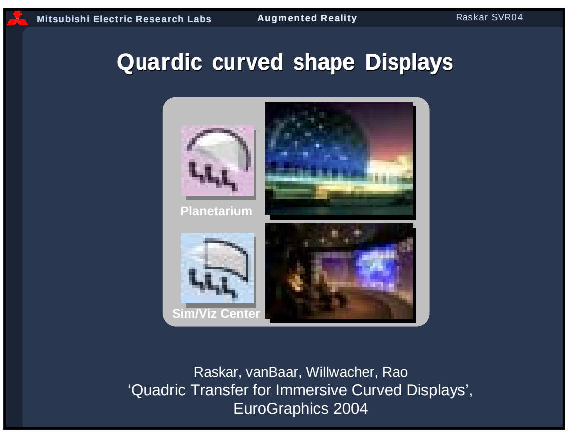

Mitsubishi Electric Research Labs
Augmented Reality
Raskar SVR04
Planar display surface
Use homography (A_{3x3})
$i \cong P_T V$
$j \cong A\, i$
V
M
P_T
i
User
A
j
Single Projection Matrix !
$j \cong [A\, P_T]\, V$


Mitsubishi Electric Research Labs
Augmented Reality
Raskar SVR04
Keystone Correction
Screen
Projected image
2. Pre-warp input image
1. Compute screen to image homography
R Raskar

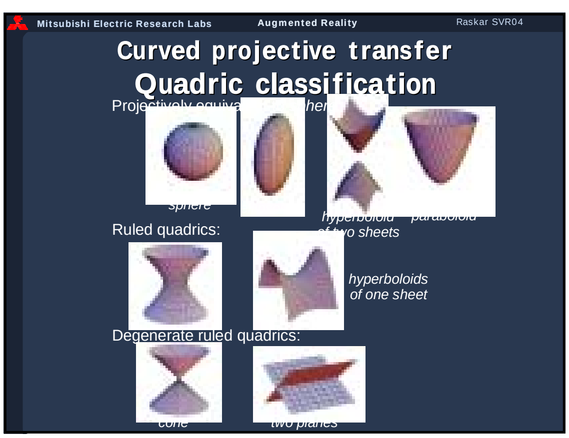

Mitsubishi Electric Research Labs
Augmented Reality
Raskar SVR04
Ad-hoc Planar Cluster
Planar Display using ad-hoc Clusters
Self-contained Units, No centralized control
No markers or cameras in environment
Beyond the range of single camera

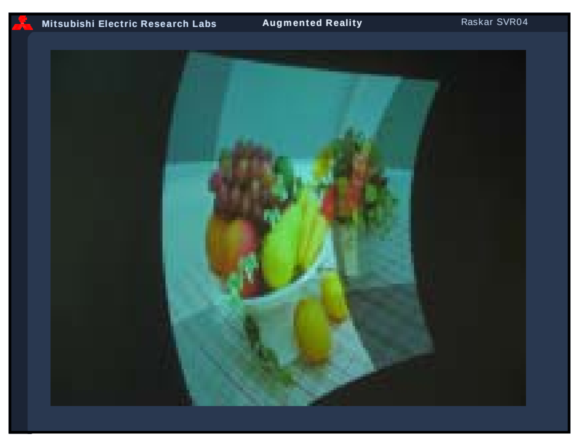

Mitsubishi Electric Research Labs
Augmented Reality
Raskar SVR04
Projection Techniques
Projection Screen Geometries
– Planar
– Rectilinear
Planar Homography
– Cylindrical
– Spherical
Quadric image transfer
– Irregular
Discretized Warping


Mitsubishi Electric Research Labs
Augmented Reality
Raskar SVR04
Parametric Image Transfer
X
X
Planar Homography
Quadric Transfer
$j \cong A_{3x3}\, i$
$j \cong A_{3x3}\, i \pm \left(\sqrt{i^T E\, i}\right) e$


Mitsubishi Electric Research Labs
Augmented Reality
Raskar SVR04
Quardic curved shape Displays
Planetarium
Sim/Viz Center
Raskar, vanBaar, Willwacher, Rao
'Quadric Transfer for Immersive Curved Displays',
EuroGraphics 2004


Mitsubishi Electric Research Labs
Augmented Reality
Raskar SVR04
Overlap on Quadric Screens


Mitsubishi Electric Research Labs
Augmented Reality
Raskar SVR04
Curved projective transfer
Quadric classification
of two sheets
Ruled quadrics:
hyperboloids
of one sheet
Degenerate ruled quadrics:


Mitsubishi Electric Research Labs
Augmented Reality
Raskar SVR04

Projection Techniques

- Projection Screen Geometries
  - Planar
  - Rectilinear
  - Cylindrical
  - Spherical
  - Irregular

Planar, Rectilinear: Planar Homography

Cylindrical, Spherical: Quadric image transfer

Irregular: Discretized Warping

Vertex Shader for Quadric Transfer in Cg

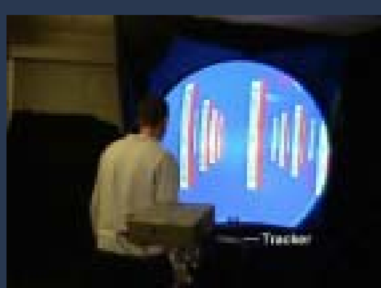
```
vertout main( appin IN, uniform float4x4 modelViewProj,
uniform float4 constColor, uniform float3x3 A, uniform float3x3 E,
uniform float3 e) {
    vertout OUT;
    float4 m1 = float4(IN.position.x, IN.position.y, IN.position.z, 1.0f );
    float4 m, mi ;      float3 m2,mp;      float scale;

    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;
}
```

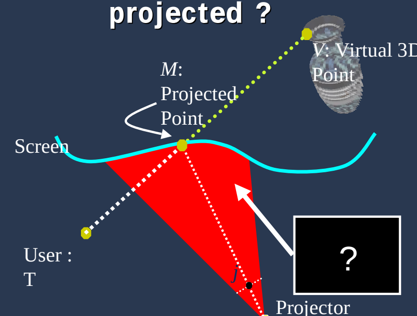
- **(Code in Course Notes)**

Non-planar Display Video

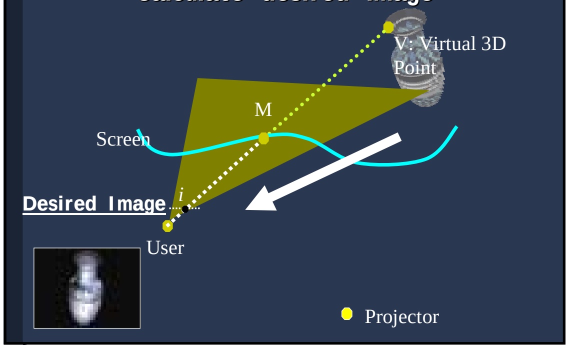
Head Tracked Single Pass Rendering



What image should be projected ?

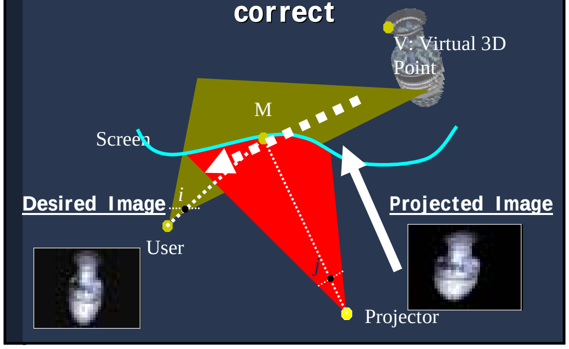


Step I :
Calculate 'desired' image



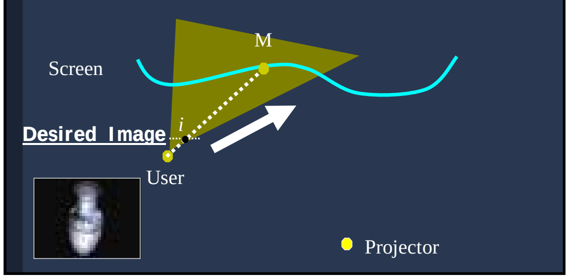
Mitsubishi Electric Research Labs Augmented Reality Raskar SVR04

Result: Projecting a pre-warped image, so it looks correct



Mitsubishi Electric Research Labs Augmented Reality Raskar SVR04

Step II :
'Project' the desired image from T

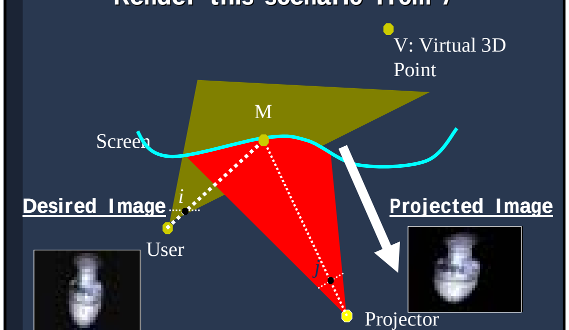


Mitsubishi Electric Research Labs Augmented Reality Raskar SVR04

AR with location-aware RFID

Mitsubishi Electric Research Labs Augmented Reality Raskar SVR04

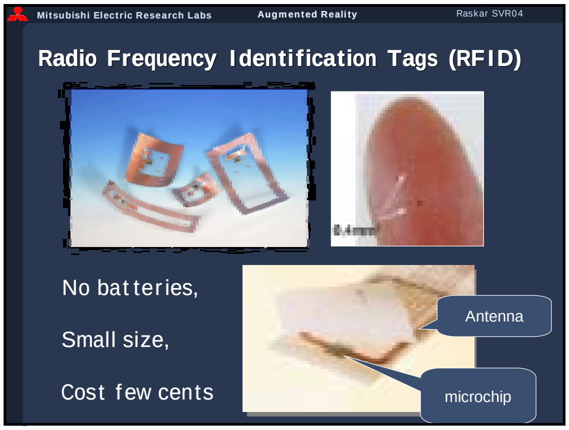
Step II :
Render this scenario from *P*

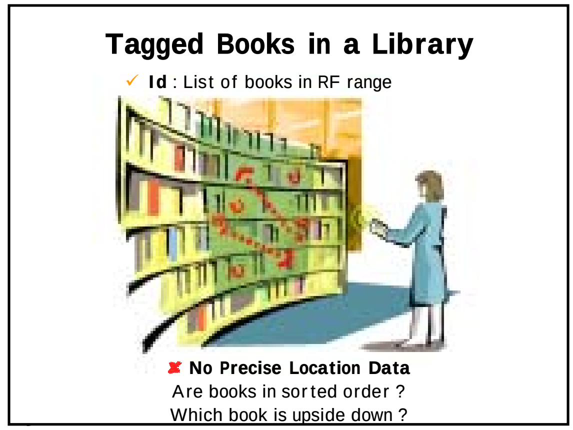


R F I G Lamps :
Interacting with a Self-describing World via Photosensing Wireless Tags and Projectors

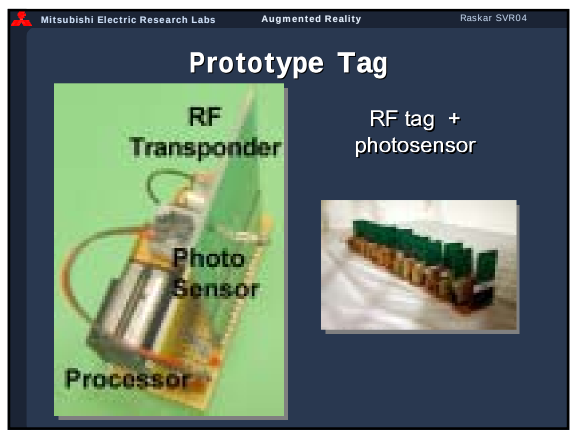
Ramesh Raskar, Paul Beardsley, Jeroen van Baar, Yao Wang, Paul Dietz, Johnny Lee, Darren Leigh, Thomas Willwacher

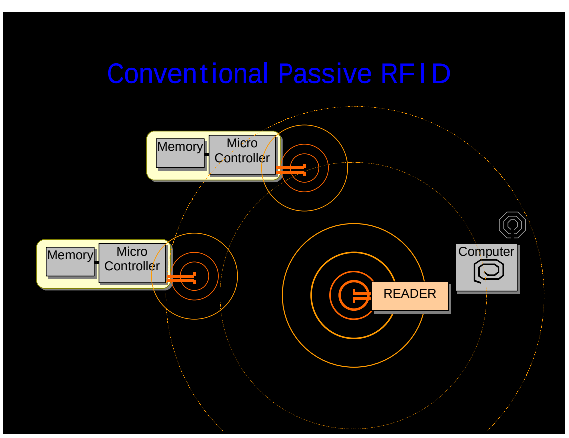
Mitsubishi Electric Research Labs (MERL), Cambridge, MA

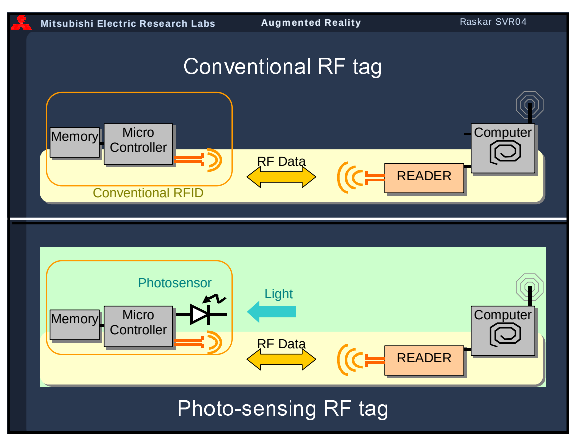

Mitsubishi Electric Research Labs
Augmented Reality
Raskar SVR04
Radio Frequency Identification Tags (RFID)
No batteries,
Small size,
Cost few cents
Antenna
microchip

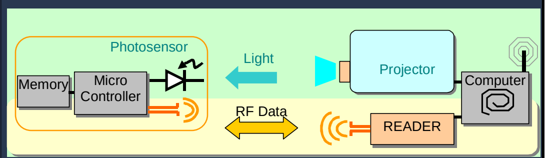

Tagged Books in a Library
Id : List of books in RF range
No Precise Location Data
Are books in sorted order ?
Which book is upside down ?


Mitsubishi Electric Research Labs
Augmented Reality
Raskar SVR04
Warehousing
Routing
Livestock tracking
Library
Baggage handling
Currency


Mitsubishi Electric Research Labs
Augmented Reality
Raskar SVR04
Prototype Tag
RF Transponder
Photo Sensor
Processor
RF tag + photosensor


Conventional Passive RFID
Memory
Micro Controller
Memory
Micro Controller
READER
Computer


Mitsubishi Electric Research Labs
Augmented Reality
Raskar SVR04
Conventional RF tag
Memory
Micro Controller
RF Data
READER
Computer
Conventional RFID
Photosensor
Light
Memory
Micro Controller
RF Data
READER
Computer
Photo-sensing RF tag



Mitsubishi Electric Research Labs Augmented Reality Raskar SVR04

RFID

(Radio Frequency Identification)

RFIG

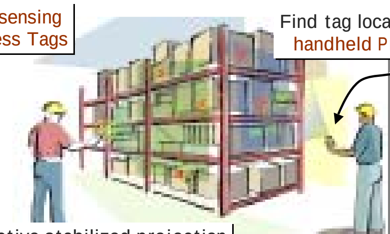
(Radio Frequency Id and Geometry)

RFID RFIG

(Radio Frequency Id & Geometry)

Photosensing Wireless Tags

Find tag location using handheld Projector



Interactive stabilized projection

Many geometric ops

Siggraph 2004

Mitsubishi Electric Research Labs Augmented Reality Raskar SVR04

Projected Sequential Frames

Pattern MSB | Pattern MSB-1 | – – – – | Pattern LSB

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

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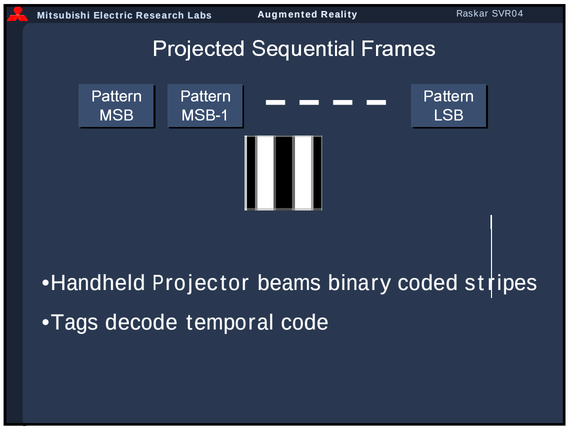
AR with Photosensing RFID and Handheld Projector

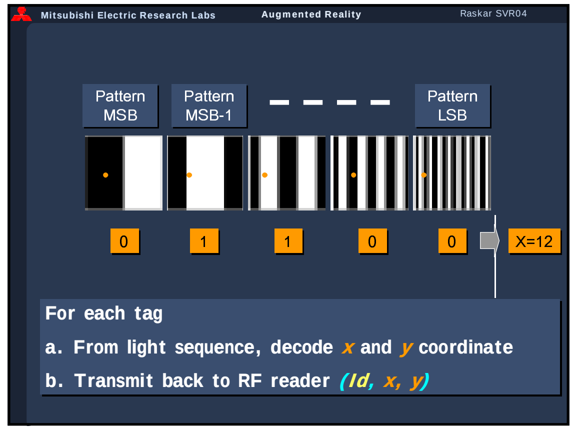
Mitsubishi Electric Research Labs Augmented Reality Raskar SVR04

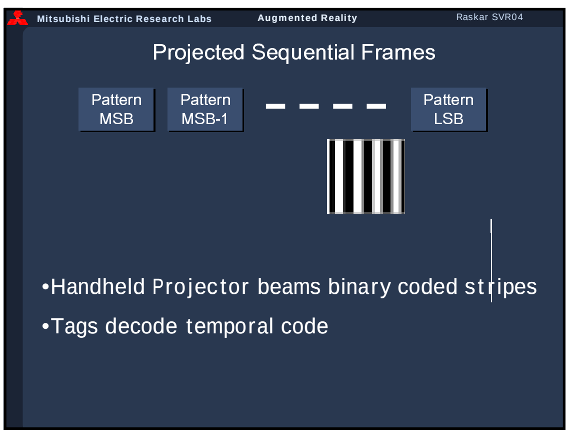
Projected Sequential Frames

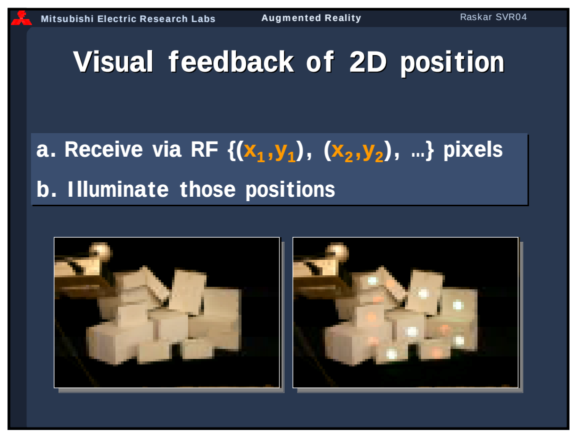
Pattern MSB | Pattern MSB-1 | – – – – | Pattern LSB

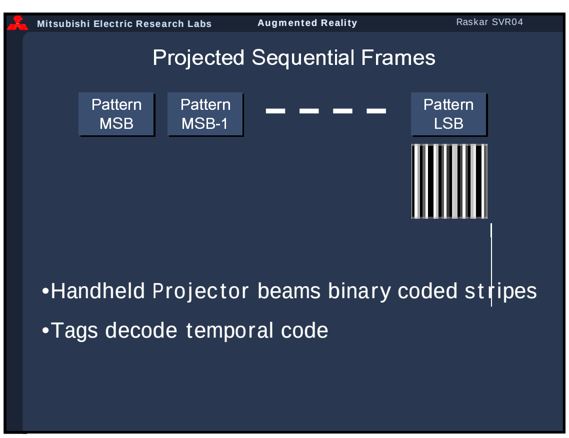
- Handheld Projector beams binary coded stripes
- Tags decode temporal code

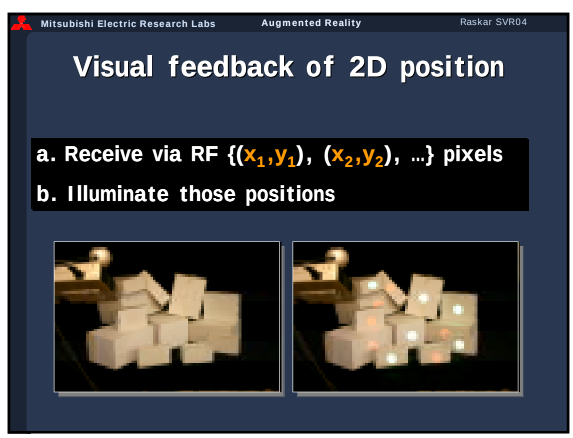

Mitsubishi Electric Research Labs
Augmented Reality
Raskar SVR04
Projected Sequential Frames
Pattern MSB
Pattern MSB-1
Pattern LSB
•Handheld Projector beams binary coded stripes
•Tags decode temporal code


Mitsubishi Electric Research Labs
Augmented Reality
Raskar SVR04
Pattern MSB
Pattern MSB-1
Pattern LSB
0
1
1
0
0
X=12
For each tag
a. From light sequence, decode *x* and *y* coordinate
b. Transmit back to RF reader *(Id, x, y)*


Mitsubishi Electric Research Labs
Augmented Reality
Raskar SVR04
Projected Sequential Frames
Pattern MSB
Pattern MSB-1
Pattern LSB
•Handheld Projector beams binary coded stripes
•Tags decode temporal code

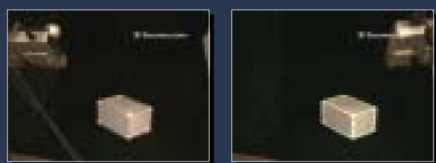

Mitsubishi Electric Research Labs
Augmented Reality
Raskar SVR04
Visual feedback of 2D position
a. Receive via RF {(x_1,y_1), (x_2,y_2), …} pixels
b. Illuminate those positions


Mitsubishi Electric Research Labs
Augmented Reality
Raskar SVR04
Projected Sequential Frames
Pattern MSB
Pattern MSB-1
Pattern LSB
•Handheld Projector beams binary coded stripes
•Tags decode temporal code

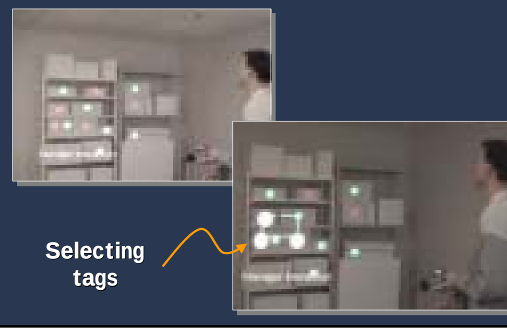

Mitsubishi Electric Research Labs
Augmented Reality
Raskar SVR04
Visual feedback of 2D position
a. Receive via RF {(x_1,y_1), (x_2,y_2), …} pixels
b. Illuminate those positions

3D from 2 Projector Views
(Structure from Motion)

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

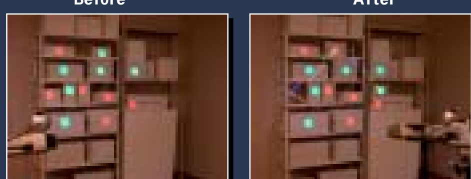


Desktop-like Interaction



Change Detection
without fixed camera, in any lighting condition

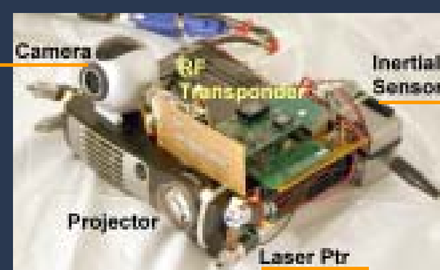
Before **After**



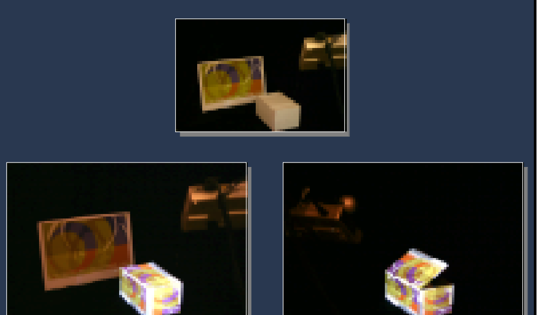
Record coordinates of tags from one view

Compare with new coordinates from a different view

Support for handheld projection



Texture Adaptation



Mouse Simulation

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

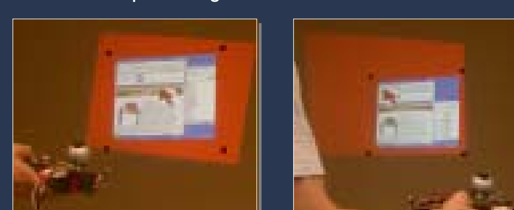
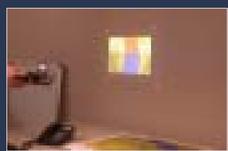
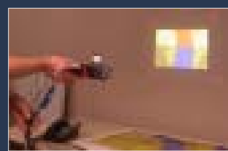


Image Quasi-Stabilization

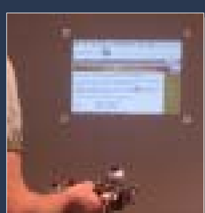




Eliminate hand jitter using inertial sensors+camera

Interactive Projection

Absolute Stabilization



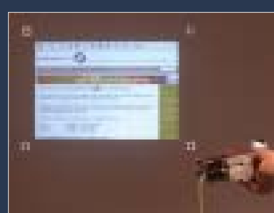
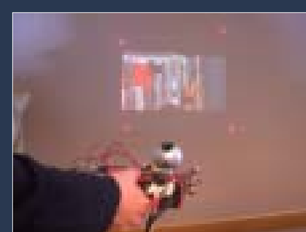


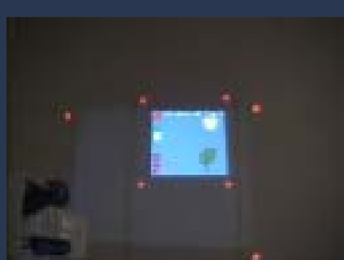
Image stays registered with world features

Adaptive Projection



'Copy and Paste'
Geometric and Photometric compensation

Image Stabilization



Prototype Handheld Projector

Machine AR

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

•Projector-Camera Workshop

June 2005

www.PROCAMS.org

•Web Page :

http://raskar.com/Projector/

•Projector mailing list

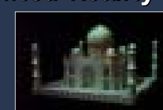
majordomo@cs.unc.edu

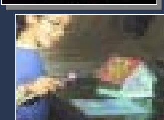
“subscribe projector”

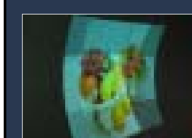
Robot ‘Laser’ Guidance
Picking and Sorting Tagged Objects

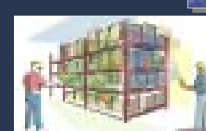
New Directions in Augmented Reality

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







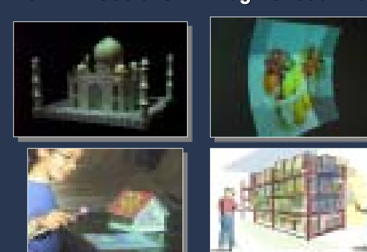


www.raskar.com

Acknowledgements

- MERL
  - Jeroen van Baar, Paul Beardsley, Remo Ziegler, Thomas Willwacher, Srinivas Rao, Cliff Forlines, Paul Dietz, Johnny Lee
- Office of the Future group at UNC Chapel Hill
  - Greg Welch, Kok-lim Low, Deepak B'padhyay
  - Henry Fuchs, Herman Towles
  - Wei-chao Chen
- Mitsubishi Electric, Japan
  - Yoshihiro Ashizaki, Masatoshi Kameyama, Masato Ogata, Keiichi Shiotani
- Images
  - Oliver Bimber, Claudio Pinhanez
  - Ed Lantz (Spitz Inc.), Marc Pollefeys (UNC Chapel Hill)
  - Aditi Majumder, Rahul Sukthankar,, Chris Jaynes, Shree Nayar
- SVR, Absolut, Luciano Pereira Soares

New Directions in Augmented Reality



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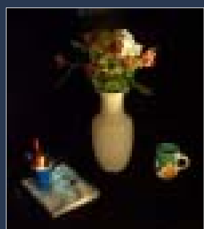
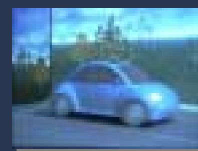
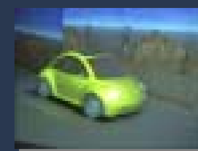
Shader Lamps Motivation



View-dependent Appearance

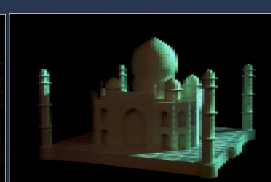
Virtual Motion





Shader Lamps Image based Illumination

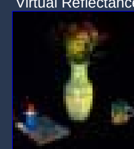
- Basic Idea
  - Render images and project on objects
  - Multiple projectors
  - View and object dependent color



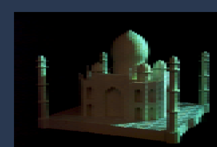
Raskar, Welch, Low, Bandyopadhyay, "Shader Lamps: Animating Real Objects with Image Based Illumination," Eurographics Rendering Worksop (EGRW 2001)

ShaderLamps

Virtual Reflectance

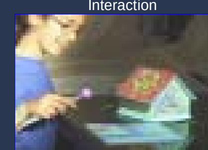


Virtual Illumination

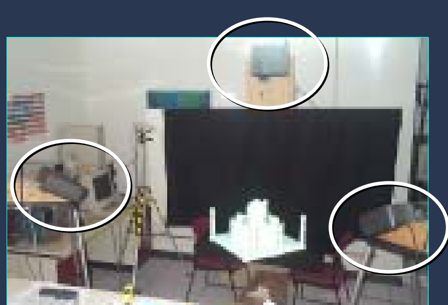


Virtual Motion

Interaction



www.ShaderLamps.com



Prototype Handheld Projector