New Directions in Augmented Reality

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

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

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, CS, AI

Non-trivial AR

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

Spatially Augmented Reality (SAR)

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

Sparsely Augmented Reality (SAR)

HMD-VR Spatially Immersive-VR

e.g. CAVE

AR using HMD Spatially Augmented Reality

Video or Optical see-through

SAR, Shadertamps
Classification of AR

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

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

Disadvantages

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

Spatially Augmented Reality

Raskar, van Baar, Beardsley, Willenacher, Rao, Forlines
‘Lamps: Geometrically Aware and Self-Configurable Projectors’, SIGGRAPH 2003
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

Classification of AR

Shader Lamps

Image based Illumination

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

Shader Lamps

Motivation

Changing Appearance

View-dependent Appearance

Virtual light source

Projector
Examples

- Son et Lumiere
  Projecting slide of augmented photo

- Disney’s Haunted Mansion
  Pre-recorded video
  Singing busts
  Madame Leota

Challenges

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

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

• Old
  - Large, rigid installations
  - A 2D image or video projection
  - Single projector
  - Texture

• New
  - Easy setup, non-trivial objects
  - Real time 3D animation
  - Multiple projectors
  - BRDF
**Steps**

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

**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

**Projector Model**

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

**Steps**

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

**Changing Appearance**

- Virtual light source
### Steps

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

### Radiance Adjustment

$\text{Virtual} \rightarrow \text{Real}$

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

- **Virtual**
  - Desired radiance
  - BRDF
- **Real**
  - Pixel intensity
  - Intensity correction
  - Desired radiance
  - Reflectance

### Intensity Correction

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

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

### Feathering in Overlap

**Traditional Solution**

- $d$:
  - Projectors
  - Weights
- $A+B$:
  - Projected Surface
  - Weights
Feathering

Traditional Solution

Weights

Projected Surface

Feathering

New Feathering

Depth discontinuity

Overlap buffer

Occlusion Problems

Depth discontinuity

Occlusions

New Feathering
Virtual Illumination
Shadows, Shading and Blending

Steps
- Preprocessing
  - Scan 3D object and create model, \( G \)
  - Approximately position projector(s)
  - Compute pose, \( P \)
  - Compute intensity correction, \( \alpha \)
- Run time
  - Render image \([I]\)
  - Intensity correction, \([\alpha]\) * \([I]\)
  - Feathering, \([\beta]\) * \([\alpha]\) * \([I]\)

Moving Objects
- Moving Surface
- Moving Projector
- Moving Viewer
Apparent Motion


Virtual Motion

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

ShaderLamps

Projector-based Augmentation

Projected Guidance for Placement
**Projection Techniques**

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

**Projector-based AR**


**Planar Multi-Projector Display**

- Pinhanez et al 2003

**Steerable Projector**

- What is homography?
  - Two images of 3D points on a plane are related by a 3x3 matrix.
Planar Homography (in 2D)

Two images of 3D points on a plane Related by a 3x3 matrix

\[ j = A_{3x3} i \]

\[ j_x = (a \cdot i_x) / (c \cdot i_z) \]
\[ j_y = (b \cdot i_y) / (c \cdot i_z) \]

Planar Projective Transfer (homography)

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

\[ i \equiv P_T V \]
\[ j \equiv A i \]

Planar Display Surface

Use homography \((A_{3x3})\)

Keystone Correction

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

Ad-hoc Planar Cluster

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

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

Plane Warping

Quadric image transfer

Discretized Warping

Parametric Image Transfer

Planar Homography

Quadric Transfer

\( j \equiv A_{113} i \pm \sqrt{(i^T E i)} e \)

Quadratic curved shape Displays

Planetarium

Sim/Vis Center

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

Overlap on Quadric Screens

Curved projective transfer

Quadric classification

Ruled quadrics:
- Hyperboloids of two sheets
- Hyperboloids of one sheet

Degenerate ruled quadrics:
- Cones
- Planes

Mitsubishi Electric Research Labs
Augmented Reality
Raskar SVR04
Vertex Shader for Quadric Transfer in Cg

```c
vertout main( appin IN, uniform float4x4 modelViewProj, uniform float4x4 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)
Step I: Calculate 'desired' image

Step II: 'Project' the desired image from T

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

AR with location-aware RFID

RFIG 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
Radio Frequency Identification Tags (RFID)

- No batteries, Small size, Cost few cents

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?

Prototype Tag
- RF tag + photosensor
- Library
- Warehousing
- Baggage handling
- Currency
- Livestock tracking

Conventional Passive RFID

Conventional RF tag
- Memory
- Micro Controller
- Reader
- Computer

Photo-sensing RF tag
- Photosensor
- Light
RFID
(Radio Frequency Identification)

RFIG
(Radio Frequency Id and Geometry)

Interactive stabilized projection
Many geometric ops

Photosensing Wireless Tags
Find tag location using handheld Projector

Projected Sequential Frames
- Handheld Projector beams binary coded stripes
- Tags decode temporal code

AR with Photosensing RFID and Handheld Projector

Projected Sequential Frames
- Handheld Projector beams binary coded stripes
- Tags decode temporal code
Projected Sequential Frames:

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

For each tag:

a. From light sequence, decode $x$ and $y$ coordinate
b. Transmit back to RF reader (Id, $x$, $y$)

Visual feedback of 2D position:

a. Receive via RF $\{(x_1,y_1), (x_2,y_2), \ldots\}$ 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
Selecting tags

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

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

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]

Robot ‘Laser’ Guidance
Picking and Sorting Tagged Objects

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

Virtual Motion

Virtual Reflectance

Virtual Illumination

Interaction

www.ShaderLamps.com

Prototype Handheld Projector