Rapidly increasing demands to display desired appearances on arbitrary surfaces correctly.
State-of-the-art-report in Eurographics 2007

- Survey of ProCams (projector-camera system) research in 2000s
- Various radiometric compensation technologies are summarized
  - Per-pixel color correction for textured projection surface

The Visual Computing of Projector-Camera Systems

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6. Overcoming Technical Limitations

Most of the image correction techniques that are described in this report are constrained by technical limitations of projector and camera hardware. An insufficient resolution or dynamic range of both devices leads to a significant loss of image quality. A too short focal depth results in regionally defocused image areas when projected onto surfaces with an essential depth variance. Slow projection frame-rates will cause the perception of temporally embedded codes. This section is dedicated to giving an overview of novel (at present mainly experimental) approaches that might lead to future improvements of projector-camera systems in terms of focal depth (Subsection 6.1), high resolution (Subsection 6.2), dynamic range (Subsection 6.3) and high speed (Subsection 6.4).
Overview

• Summarize what happened after the STAR report especially in the following topics
  – Focal length
  – High resolution
  – Dynamic range
  – High speed
• Introduce new topics and technical challenges
Focal length
Focal length: Coded aperture approach

Static code (broadband)  Dynamic code

Grosse et al., Coded aperture projection, ACM TOG 2010.
**Focal length: Coded aperture approach**

- $i_{\text{display}} = i_{\text{input}} \times i_{\text{aperture}}$
- $F\{i_{\text{deblur}}\} = F\{i_{\text{target}}\} / F\{i_{\text{aperture}}\}$

Grosse et al., Coded aperture projection, *ACM TOG* 2010.
Focal length: Coded aperture approach

Grosse et al., Coded aperture projection, ACM TOG 2010.
Focal length: Multiprojection approach

- Assumption
  - Multiple overlapping projections

Focal length: Multiprojection approach

- Measure the areas of projected pixel from each projector
- Decide weights based on the areas
  - Large pixel (=defocused) $\rightarrow$ small weight
  - Small pixel (=focused) $\rightarrow$ large weight

Focal length: Multiprojection approach

Focal length: Multiprojection approach

- Model-based projected pixel estimation
  - Works for dynamic object

**Focal length:** Focal sweep approach

**Focal length:** Focal sweep approach

**Focal sweep projection**

Focus tunable lens (FTL)

Periodical modulation at >60 Hz

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Focal length: Focal sweep approach

Focus tunable lens (FTL)

Perceived pixel

Focal plane

Iwai et al., Extended Depth-of-Field Projector by Fast Focal Sweep Projection, IEEE TVCG 2015.
**Focal length:** Focal sweep approach

Focal length: Focal sweep approach

Iwai et al., Extended Depth-of-Field Projector by Fast Focal Sweep Projection, IEEE TVCG 2015.
High resolution
High resolution: super resolution approach

- Optimize overlapping projections so that higher resolution image is displayed

Damera-Venkata et al., Display supersampling, ACM TOG 2009.
High resolution: super resolution approach

- Extend super-resolution approach to 3D surface
  - Issue: Resolution decrease due to the grazing angle

Aliaga et al., Fast High-Resolution Appearance Editing Using Superimposed Projections, ACM TOG 2012.
Optimal multiple projector placement is computed, which reproduces the target appearance the most accurately.

• Two spatial light modulators (LCDs) in a projector
  – One for low resolution and the other for high resolution

Sajadi et al., Edge-guided resolution enhancement in projectors via optical pixel sharing, ACM TOG 2012.
High resolution: Optimize projection colors for close-up view

- Radiometric compensation corrects projected result
  - Camera is used to measure surface reflectance
- **1-to-1 pixel correspondence** between camera and projector provides undesirable artifacts in close-up view
  - Averaged intensity in a camera pixel area is measured
  - When reflectance is steeply varied within the camera pixel, artifacts occur

High resolution:
Optimize projection colors for close-up view

- Measure reflections in a single projector pixel by multiple camera pixels
- Optimize projection color so that a projected result is as close to target as possible

Dynamic range
Dynamic range: Double modulation approach

- 1. low resolution LCoS panel (chrominance modulator)
- 2. high resolution LCoS panel (luminance modulator)

Kusakabe et al., A YC-separation-type projector: High dynamic range with double modulation, JSID 2012.
Dynamic range: Double modulation approach

- Final contrast ratio is the product of two modulation blocks
  - \( c_1 \times c_2 : 1 \)
    (Chrominance modulator = \( c_1 : 1 \), luminance modulator = \( c_2 : 1 \))
- Much lower resolution of chrominance modulator can be used
  - Human vision features high spatial frequency response with respect to luminance more than chrominance.

Kusakabe et al., A YC-separation-type projector: High dynamic range with double modulation, *JSID* 2012.
Dynamic range: Light reallocation approach

- Light energy from light source is reallocated
  - More light energy to bright image area
  - Less light energy to dark area
- AMA (analog micromirror array) is used for the light reallocation

Hoskinson et al., Light reallocation for high contrast projection using an analog micromirror array, ACM TOG 2010.
Dynamic range:
Light reallocation approach

Hoskinson et al., Light reallocation for high contrast projection using an analog micromirror array, ACM TOG 2010.
Dynamic range: Light reallocation approach

- Phase-based light reallocation

(a) 10% efficient image formation

(b) 95% efficient image formation

Dynamic range:
Reflectance modulation approach

Dynamic range:
Reflectance modulation approach

<table>
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<th>Shutter speed</th>
<th>×1</th>
<th>×16</th>
<th>×256</th>
<th>×2,048</th>
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</thead>
</table>

Proposed method

Projecting onto white surface

Photographic print under uniform illumination

Dynamic range: Reflectance modulation approach

- Projecting textures onto full color 3D printer output

Dynamic range: Reflectance modulation approach

- Projecting textures onto full color 3D printer output

Dynamic range: Reflectance modulation approach

- Dynamic reflectance pattern modulation using photochromic compounds (PhC) and UV lights
  - PhC: UV checker that changes its color when exposed under UV light

Iwai et al., Projection Screen Reflectance Control for High Contrast Display using Photochromic Compounds and UV LEDs, Opt Express 2014.
Dynamic range: Reflectance modulation approach

- Dynamic reflectance pattern modulation using photochromic compounds (PhC) and UV lights
  - PhC: UV checker that changes its color when exposed to UV light

Iwai et al., Projection Screen Reflectance Control for High Contrast Display using Photochromic Compounds and UV LEDs, *Opt Express* 2014.
High speed
High speed: Galvanometer mirrors approach

- Projected light is redirected using galvanometer mirrors
- Movement of projection target is measured by a coaxial high-speed camera

High speed: DLP approach

- 8bit image projection at 1000 Hz
- High speed procams

http://www.k2.t.u-tokyo.ac.jp/vision/dynaflash/
High speed: DLP approach

• Smart headlight

New topics
Light field projection

Light field projection

216 projectors

Anisotropic light shaping diffuser
- Horizontally 1 deg
- Vertically 60 deg

Light field projection

• Prof. Amano will have a talk on this topic as the next speaker!

Spectrum optimization

- For a good spectral reproduction, multi-primaries are selected by considering complete coverage of the range of visible wavelength.

Spectrum optimization

• Content-adaptive primary selection to optimize color gamut for projection images

Dynamic projection target

- Frame-by-frame tracking based on features detected in projected results

Dynamic projection target

- Projection object tracking using RGB-D camera

Dynamic projection target

- Diminishing projection marker embedded by full color 3D printer
  - Can track symmetrically-shaped object

Diminishable Visual Markers on Fabricated Projection Object for Dynamic Spatial Augmented Reality

Hirotaka Asayama, Daisuke Iwai, and Kosuke Sato
Osaka University, Japan

Asayama et al.,
Non-rigid projection target

- IR ink and IR camera

“DeforMe”
Projection-based Visualization of Deformable Surfaces using Invisible Textures

Parinya Punpongsanoh, Daisuke Iwai, Kosuke Sato
Graduate School of Engineering Science, Osaka University, Japan

Punpongsanoh et al.,
Non-rigid projection target

- Retro-reflective marker and IR camera

Fujimoto et al., Geometrically-Correct Projection-Based Texture Mapping onto a Deformable Object, IEEE TVCG 2014.
Distributed optimization

• More and more projectors will be available for each end user

• Managing many projectors is crucial, but increases
  – Computational cost
  – Communication traffic

• Solution
  – Distributed optimization
  → Please come to our talk on Oct 1 at Closed-Loop Visual Computing session!!!

Tsukamoto et al., Radiometric Compensation for Cooperative Distributed Multi-Projection System through 2-DOF Distributed Control, IEEE TVCG 2015.
Projecting onto human body

- Change tactile **thermal** perception by projecting warm/cool colors onto human hand

Ho et al., Combining color and temperature: A blue object is more likely to be judged as warm than a red object, *Scientific Reports* 2014.
Projecting onto human body

• Change tactile **shape** perception by projecting shifted hand image
• Please come to our poster!!! (#1109 on Sep 30)

Projecting onto human body

- Change tactile **softness** perception by enhancing the feel of pushing
- Please come to our talk on **Oct 2 at Perception** session!!!

“SoftAR”
Visually Manipulating Tactile Softness Perception in Spatial Augmented Reality

Parinya Punponsanon, Daisuke Iwai, and Kosuke Sato
Osaka University, Japan

Conclusion

• Summarized recent technologies of computational projection display
  – Focal length
  – High resolution
  – Dynamic range
  – High speed

• Introduce new topics and technical challenges

• Ultimate technical challenge
  – Projection under daylight