ISMAR2015 Tutorial
Computational Imaging and Projection
Oct 3, 2015

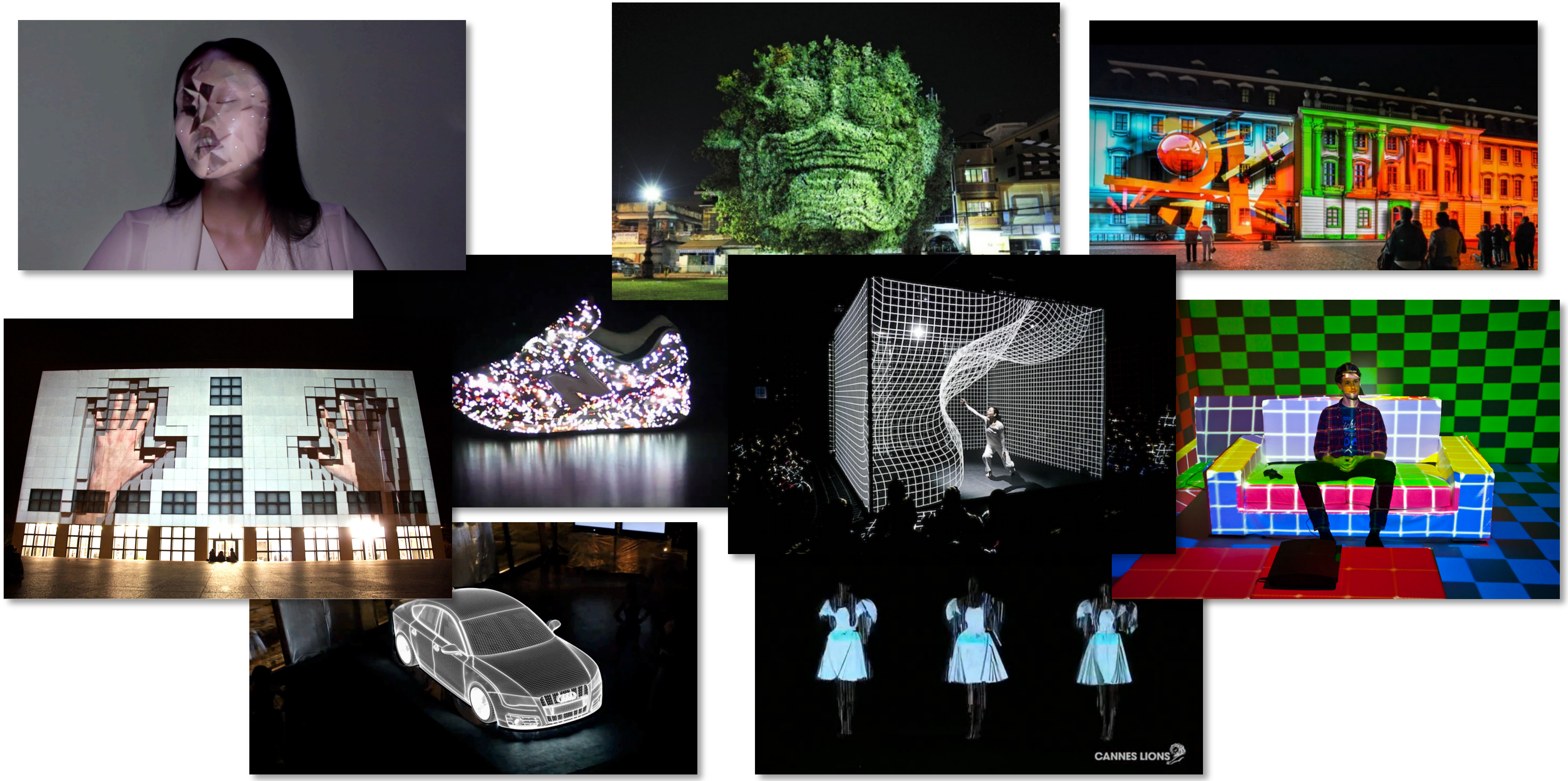
Computational Projection Display

Daisuke Iwai
Osaka University

OSAKA UNIVERSITY

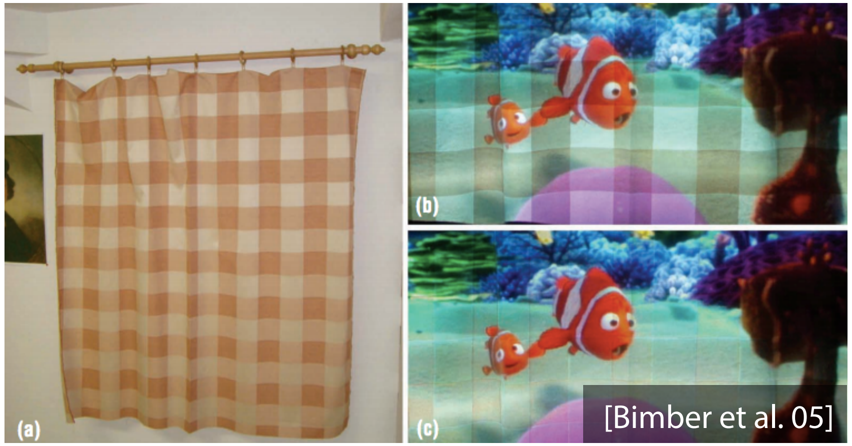
Projection mapping everywhere

- 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



DOI: 10.1111/j.1467-8659.2008.01175.x

COMPUTER GRAPHICS *forum*
Volume 27 (2008), number 8 pp. 2219–2245

The Visual Computing of Projector-Camera Systems

Oliver Bimber[1], Daisuke Iwai[1,2], Gordon Wetzstein[3] and Anselm Grundhöfer[1]

[1]Bauhaus-University Weimar, Germany
{bimber, iwai, grundhoefer}@uni-weimar.de
[2]Osaka University, Japan
iwai@sens.sys.es.osaka-u.ac.jp
[3]University of British Columbia, Canada

Technical limitations in 2007

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).

where each r_λ is a single colour channel λ of a camera image with resolution $m \times n$, i_λ is the projection pattern with a resolution of $p \times q$, and e_λ are direct and global illumination effects caused by the environment light and the projector's black level captured from the camera. Each light transport matrix $T_{\lambda_c}^{\lambda_p}$ (size: $mn \times pq$) describes the contribution of a single projector colour channel λ_p to an individual camera channel λ_c. The model can easily be extended for k projectors

light transport matrix (up to several hours), this approach will not be practical before accelerated scanning techniques have been developed.

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

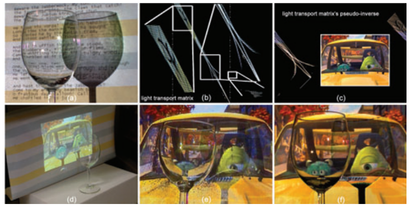


Figure 16: *Real-time radiometric compensation (f) of global illumination effects (a) with the light transport matrix's (b) approximated pseudo-inverse (c).*

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).

6.1. Increasing Focal Depth

Projections onto geometrically complex surfaces with a high-depth variance generally do not allow the displayed content to be in focus everywhere. Common DLP or LCD projectors usually maximize their brightness with large apertures. Thus, they suffer from narrow depths of field and can only generate focused imagery on a single fronto-parallel screen. Laser projectors, which are commonly used in planetaria, are an exception. These emit almost parallel light beams, which make very large depths of field possible. However, the cost of a single professional laser projector can exceed the cost of several hundred conventional projectors. In order to increase the depth of field of conventional projectors, several approaches for deblurring unfocused projections with a single or with multiple projectors have been proposed.

Zhang and Nayar [ZN06] presented an iterative, spatially-varying filtering algorithm that compensates for projector defocus. They employed a coaxial projector-camera system to measure the projection's spatially varying defocus. Therefore, dot patterns as depicted in Figure 17a are projected onto the screen and captured by the camera (b). The defocus kernels for each projector pixel can be recovered from the captured images and encoded in the rows of a matrix B. Given the environment light EM including the projector's

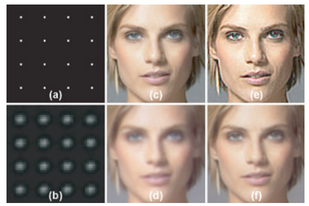


Figure 17: *Defocus compensation with a single projector: An input image (c) and its defocused projection onto a planar canvas (d). Solving Equation (10) results in a compensation image (e) that leads to a sharper projection (f). For this compensation, the spatially varying defocus kernels are acquired by projecting dot patterns (a) and capturing them with a camera (b). © 2006 ACM [ZN06].*

black level and a desired input image O, the compensation image I can be computed by minimizing the sum-of-squared pixel difference between O and the expected projection $BI + EM$ as

$$\underset{I,\, 0 \le I \le 255}{\arg\min} \; \|BI + EM - O\|^2, \qquad (10)$$

which can be solved with a constrained, iterative steepest gradient solver as described in [ZN06].

An alternative approach to defocus compensation for a single projector setup was presented by Brown *et al.* [BSC06]. Projector defocus is modelled as a convolution of a projected original image O and Gaussian PSFs as $R(x, y) = O(x, y) \otimes H(x, y)$, where the blurred image that can be cap-

Overview

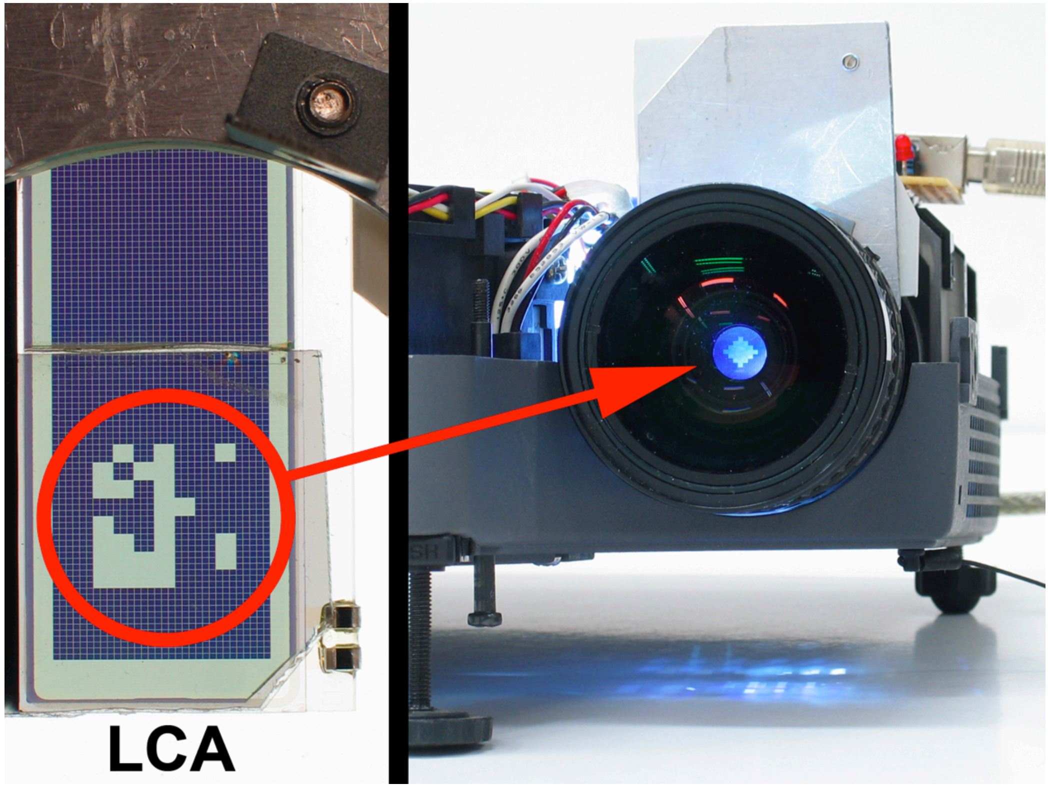
- Summarize what happened after the STAR report especially in the following topics
  - Focal length
  - High resolution
  - Dynamic range
  - High speed
- Introduce new topics and technical challenges

Focal length

OSAKA UNIVERSITY
Live Locally, Grow Globally

Focal length: Coded aperture approach

Static code (broadband)

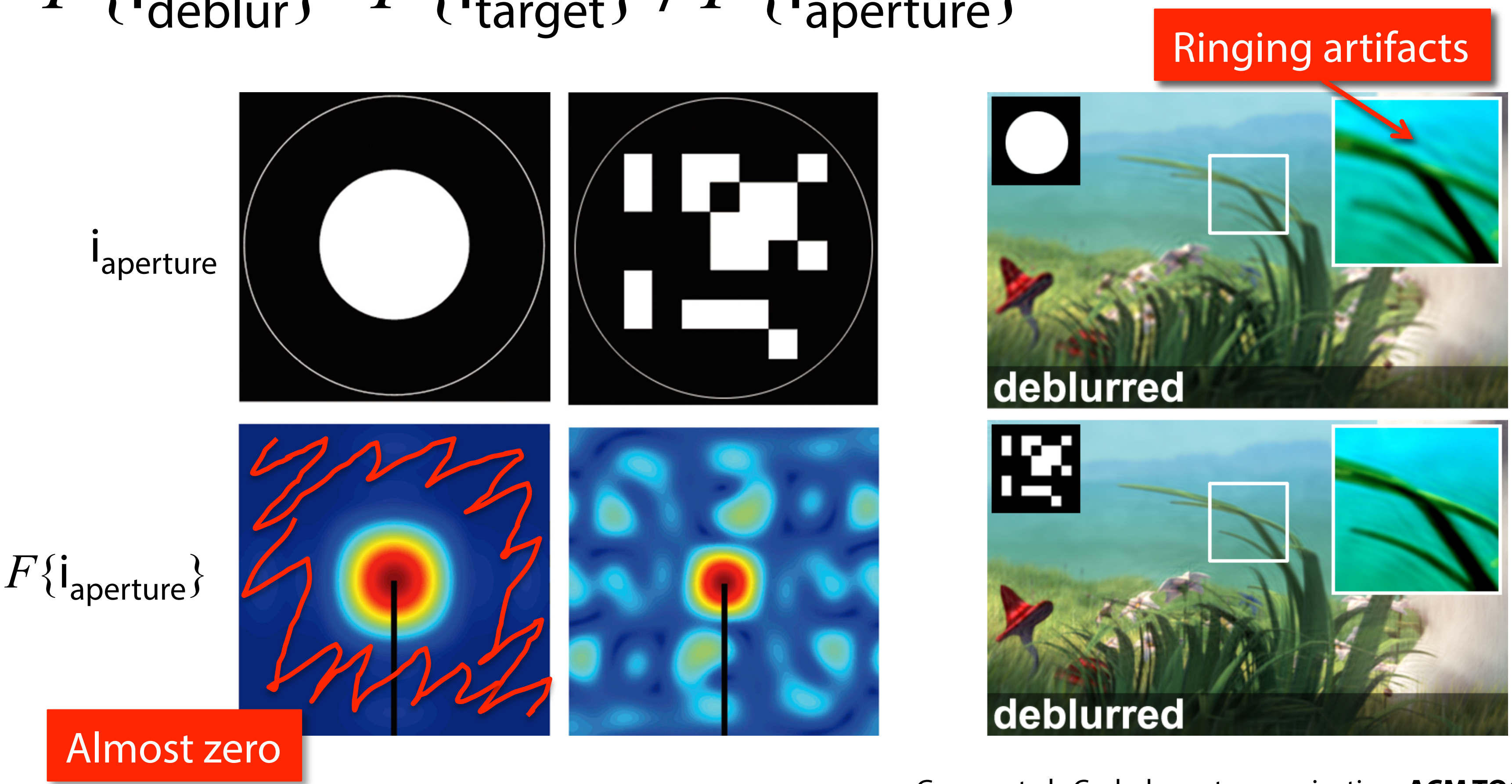


Dynamic code

Grosse et al., Coded aperture projection, **ACM TOG** 2010.

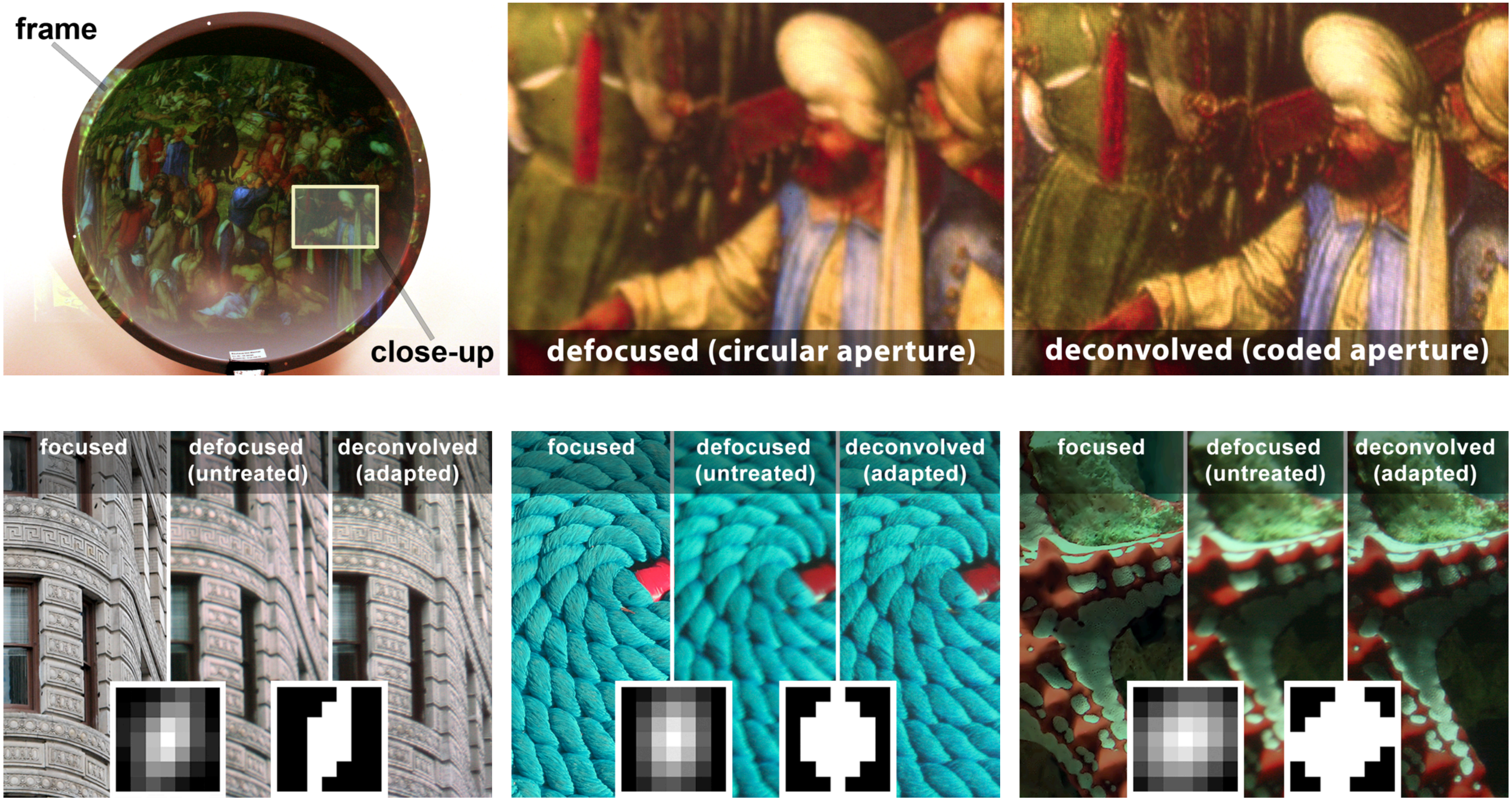
Focal length: Coded aperture approach

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



Grosse et al., Coded aperture projection, **ACM TOG** 2010.

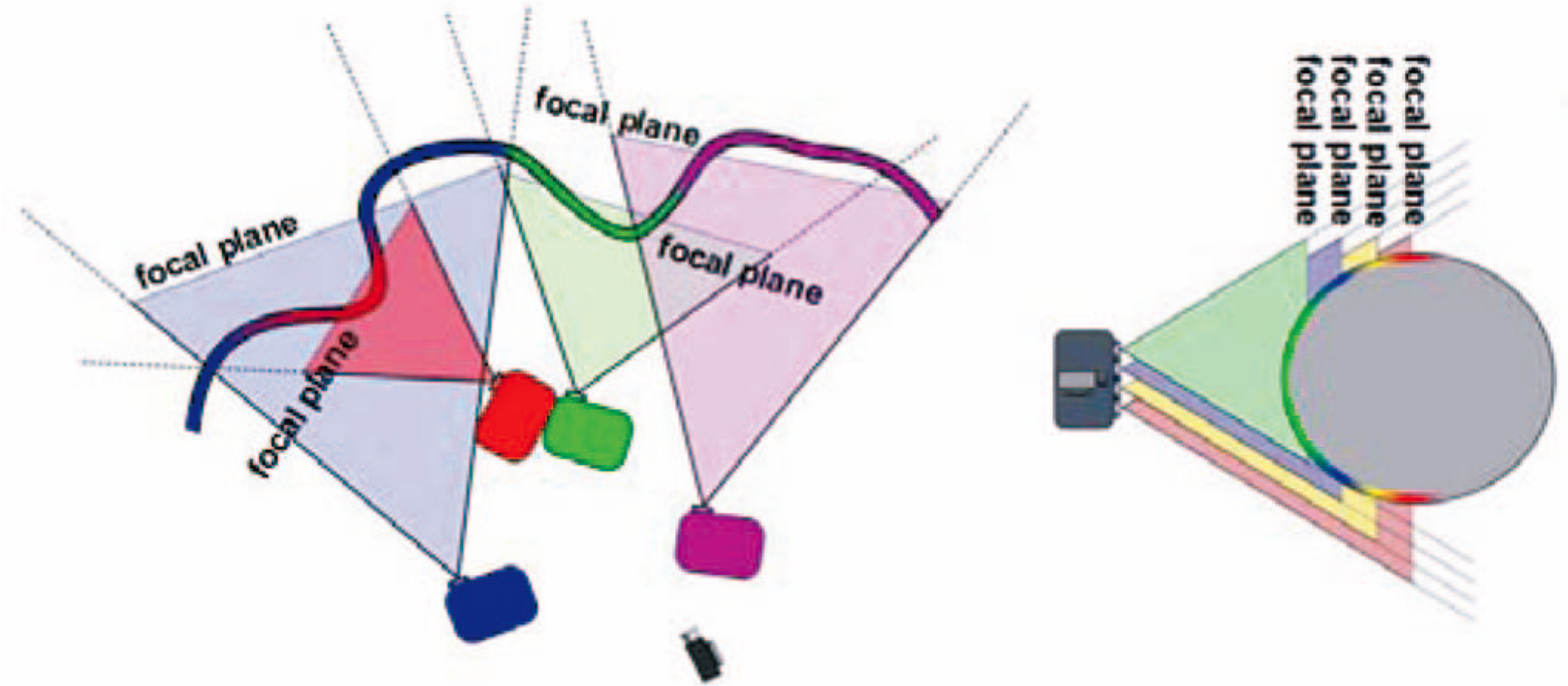
Focal length: Coded aperture approach



Grosse et al., Coded aperture projection, **ACM TOG** 2010.

Focal length: Multiprojection approach

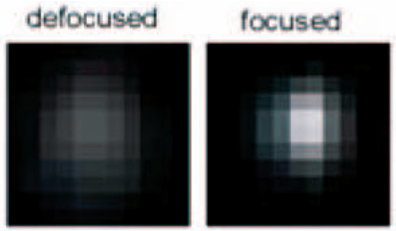
- Assumption
  - Multiple overlapping projections



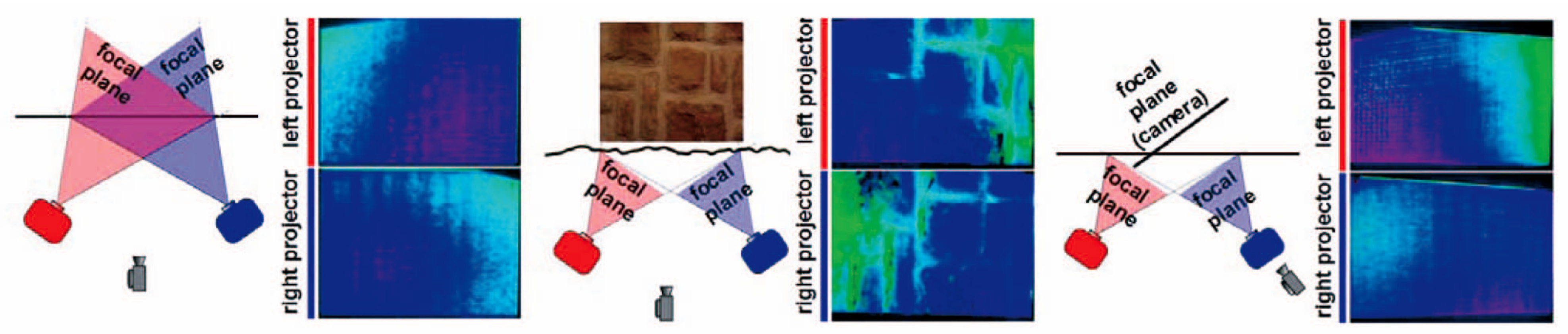
Bimber et al., Multifocal Projection: A Multiprojector Technique for Increasing Focal Depth, **IEEE TVCG** 2006.

Focal length: Multiprojection approach

- Measure the areas of projected pixel from each projector

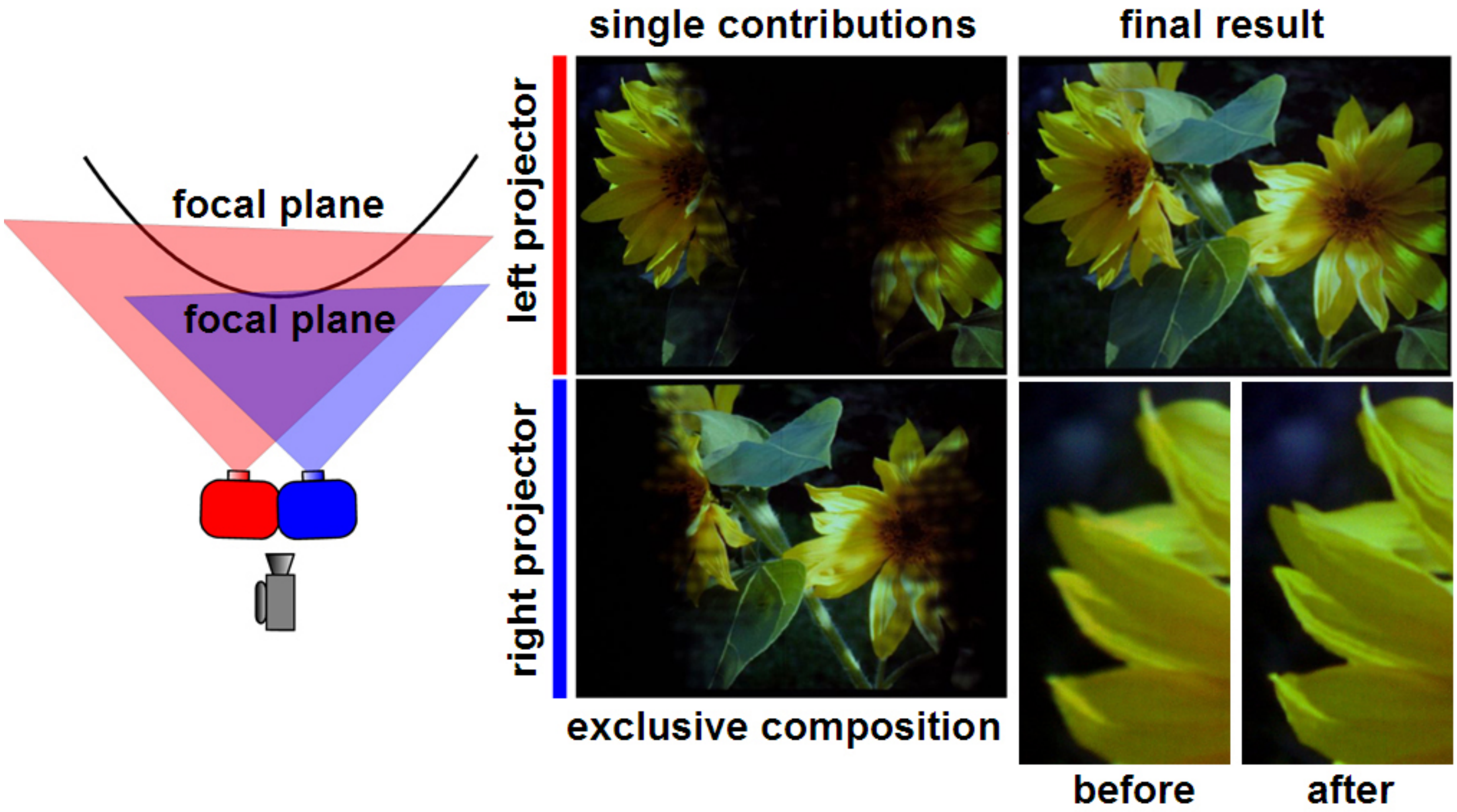


- Decide weights based on the areas
  - Large pixel (=defocused) → small weight
  - Small pixel (=focused) → large weight



Bimber et al., Multifocal Projection: A Multiprojector Technique for Increasing Focal Depth, **IEEE TVCG** 2006.

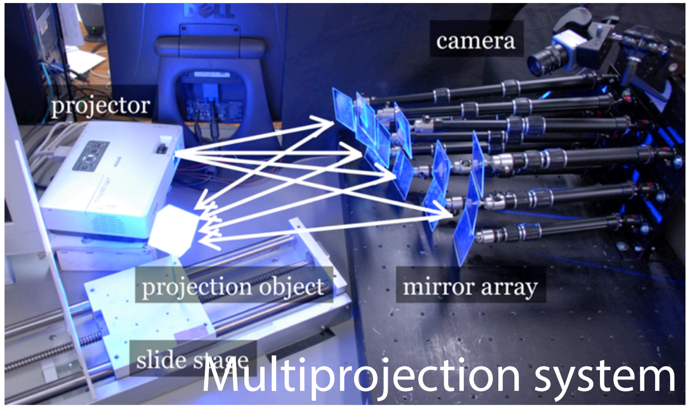
Focal length: Multiprojection approach

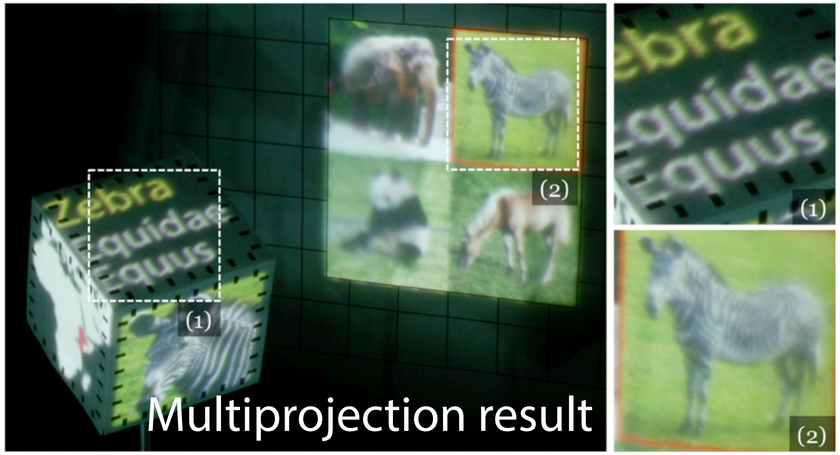


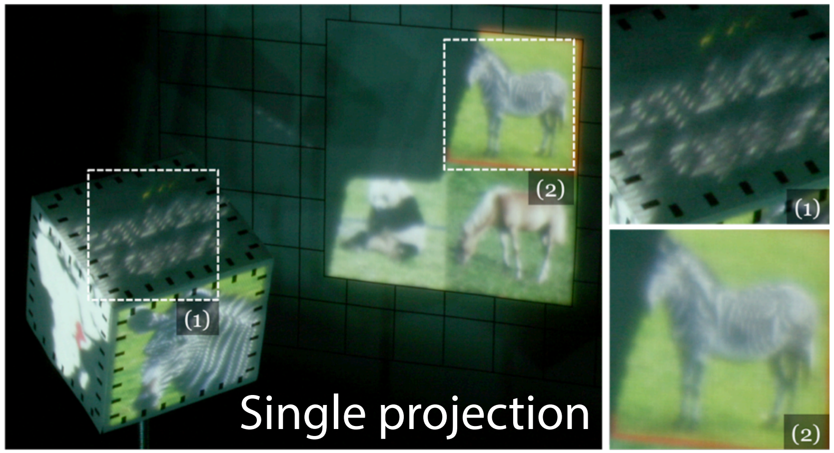
Bimber et al., Multifocal Projection: A Multiprojector Technique for Increasing Focal Depth, **IEEE TVCG** 2006.

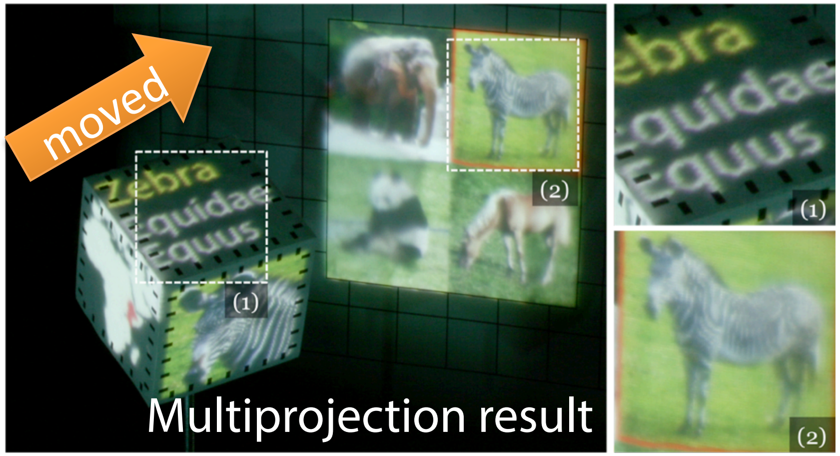
Focal length: Multiprojection approach

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





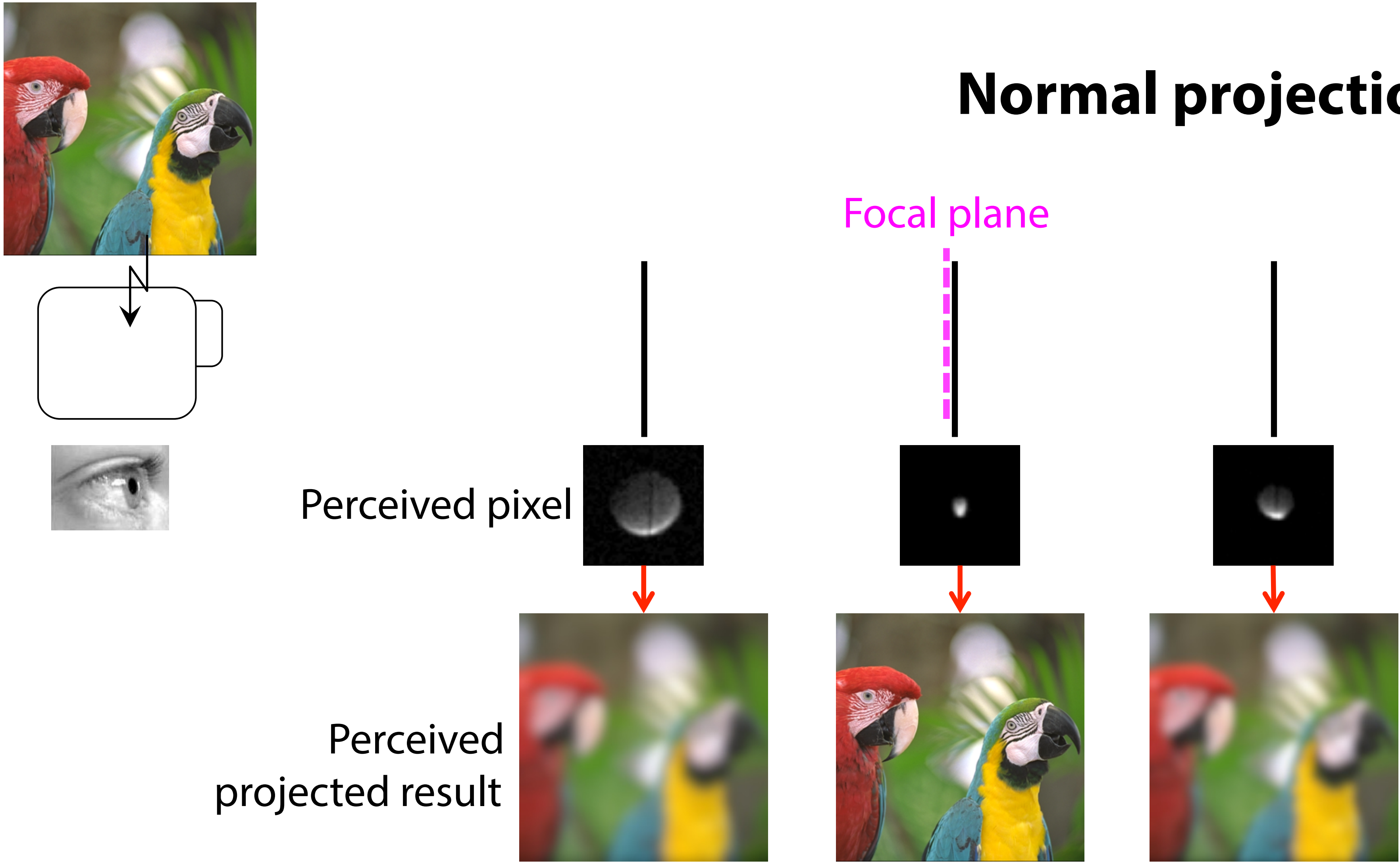




Nagase et al., Dynamic defocus and occlusion compensation of projected imagery by model-based optimal projector selection in multi-projection environment, **Virtual Reality** 2011.

Focal length: Focal sweep approach

Normal projection

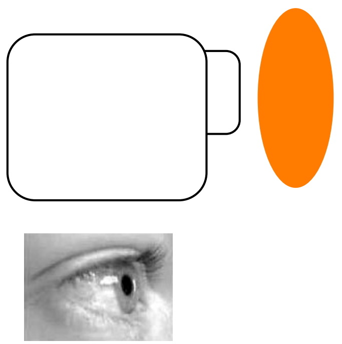


Iwai et al., Extended Depth-of-Field Projector by Fast Focal Sweep Projection, **IEEE TVCG** 2015.

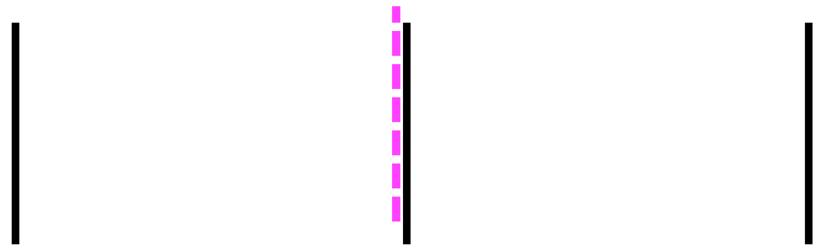
Focal length: Focal sweep approach

Focal sweep projection

Focus tunable lens
(FTL)



Focal plane

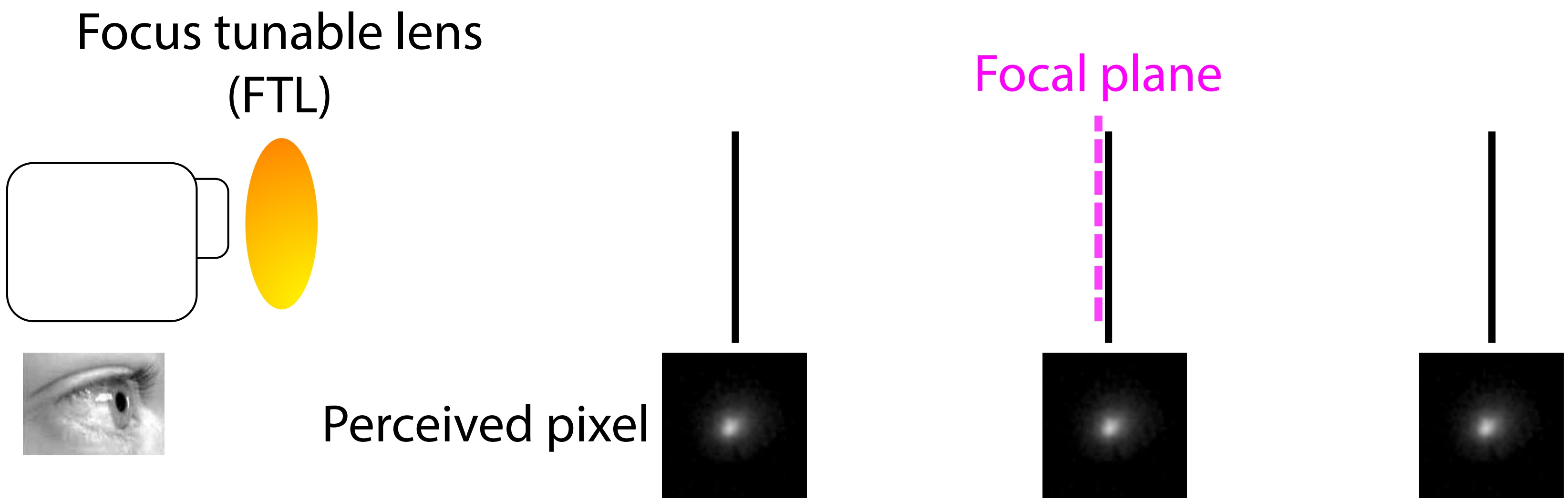


Periodical modulation at >60 Hz

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

Focal length: Focal sweep approach

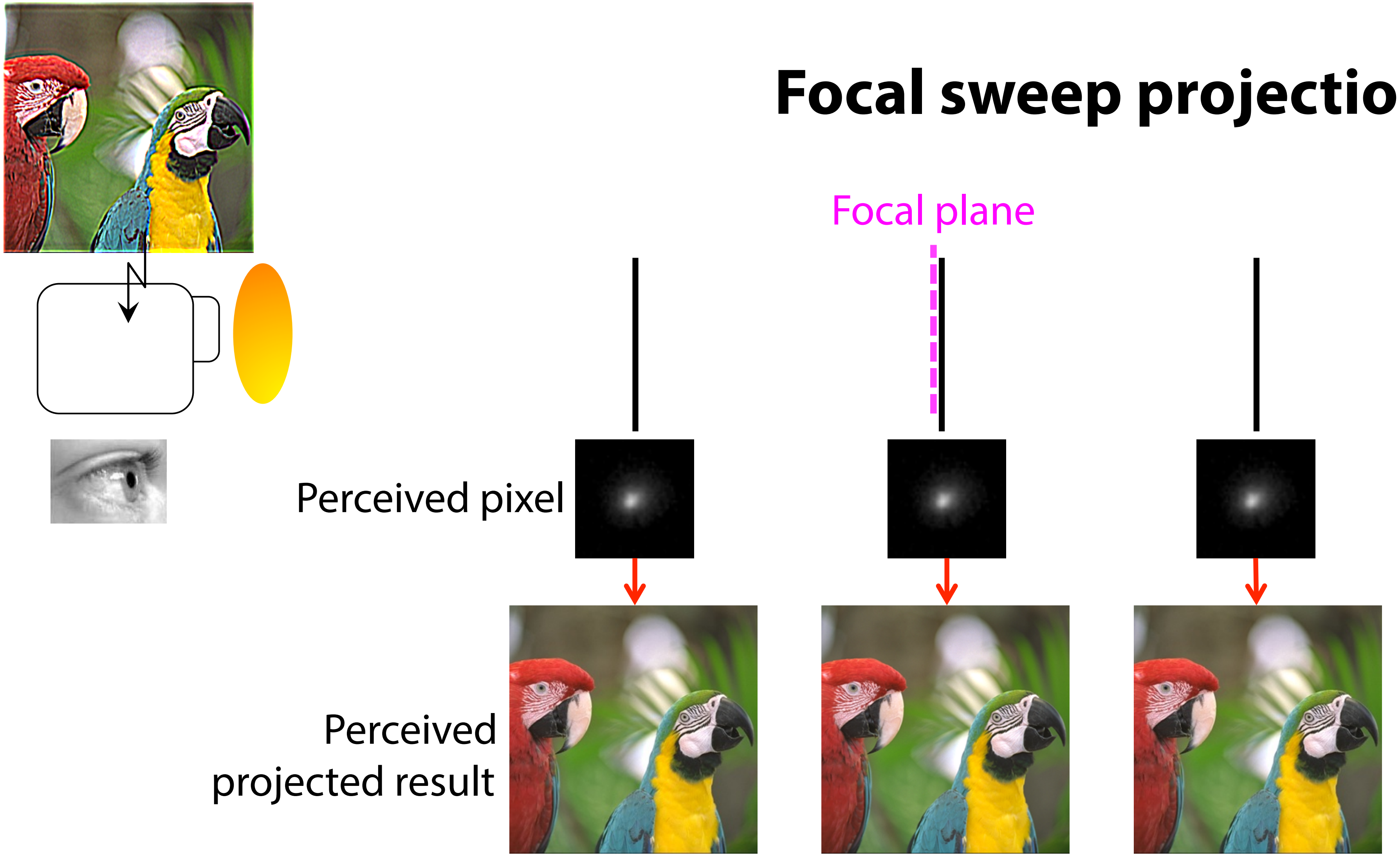
Focal sweep projection



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

Focal length: Focal sweep approach

Focal sweep projection



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

Focal length: Focal sweep approach

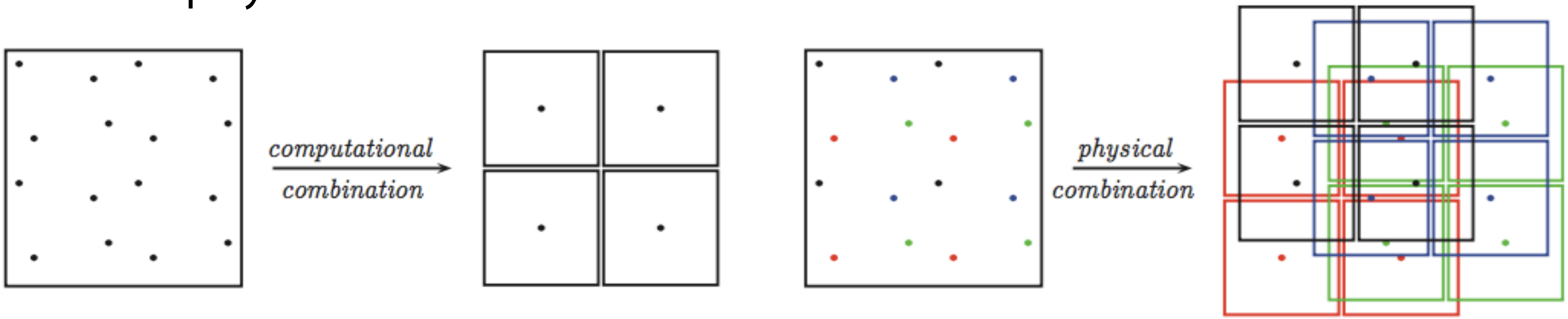
Iwai et al., Extended Depth-of-Field Projector by Fast Focal Sweep Projection, **IEEE TVCG** 2015.

High resolution

OSAKA UNIVERSITY
Live Locally, Grow Globally

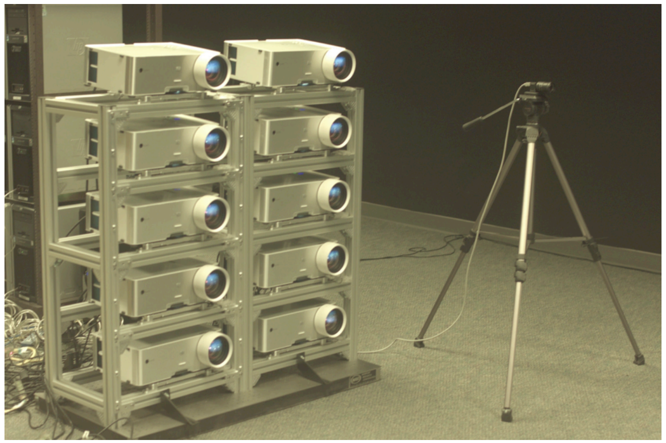
High resolution: super resolution approach

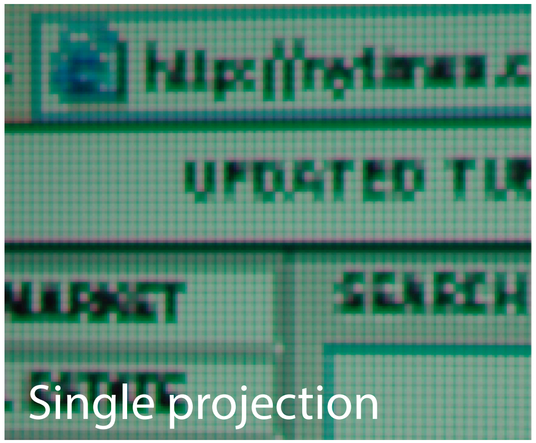
- Optimize overlapping projections so that higher resolution image is displayed

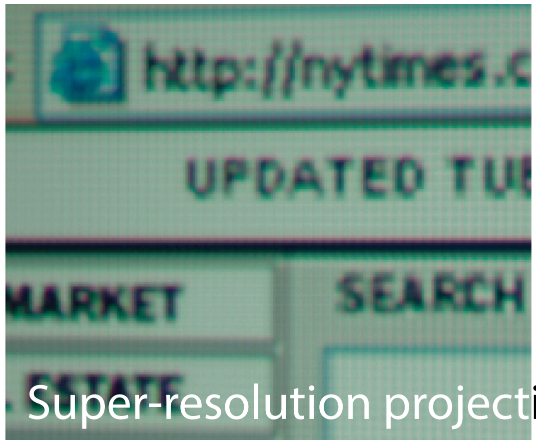


(a) conventional supersampling

(b) display supersampling



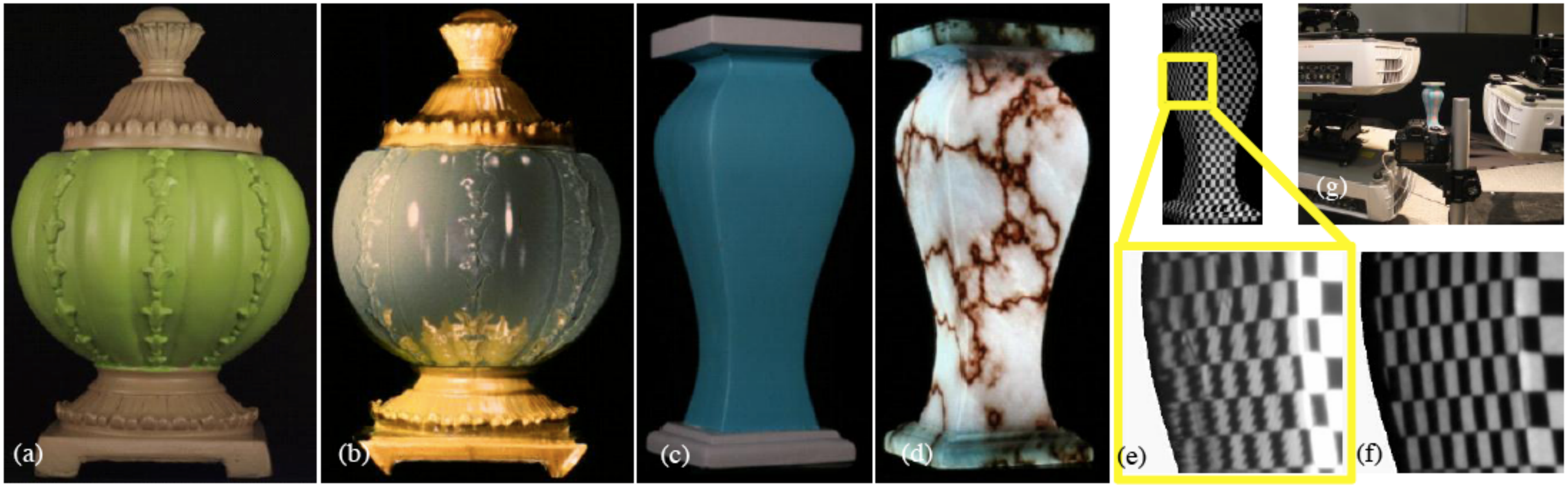




Damera-Venkata et al., Display supersampling, **ACM TOG** 2009.
Okatani et al., Study of Image Quality of Superimposed Projection Using Multiple Projectors, **IEEE TIP** 2009.

High resolution: super resolution approach

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

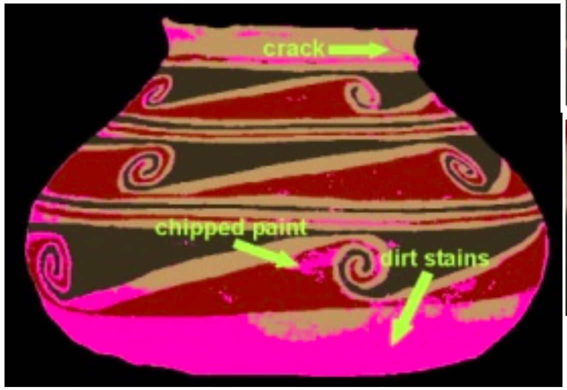


Aliaga et al., Fast High-Resolution Appearance Editing Using Superimposed Projections, **ACM TOG** 2012.

High resolution:
Projector placement optimization

- Optimal multiple projector placement is computed, which reproduces the target appearance the most accurately

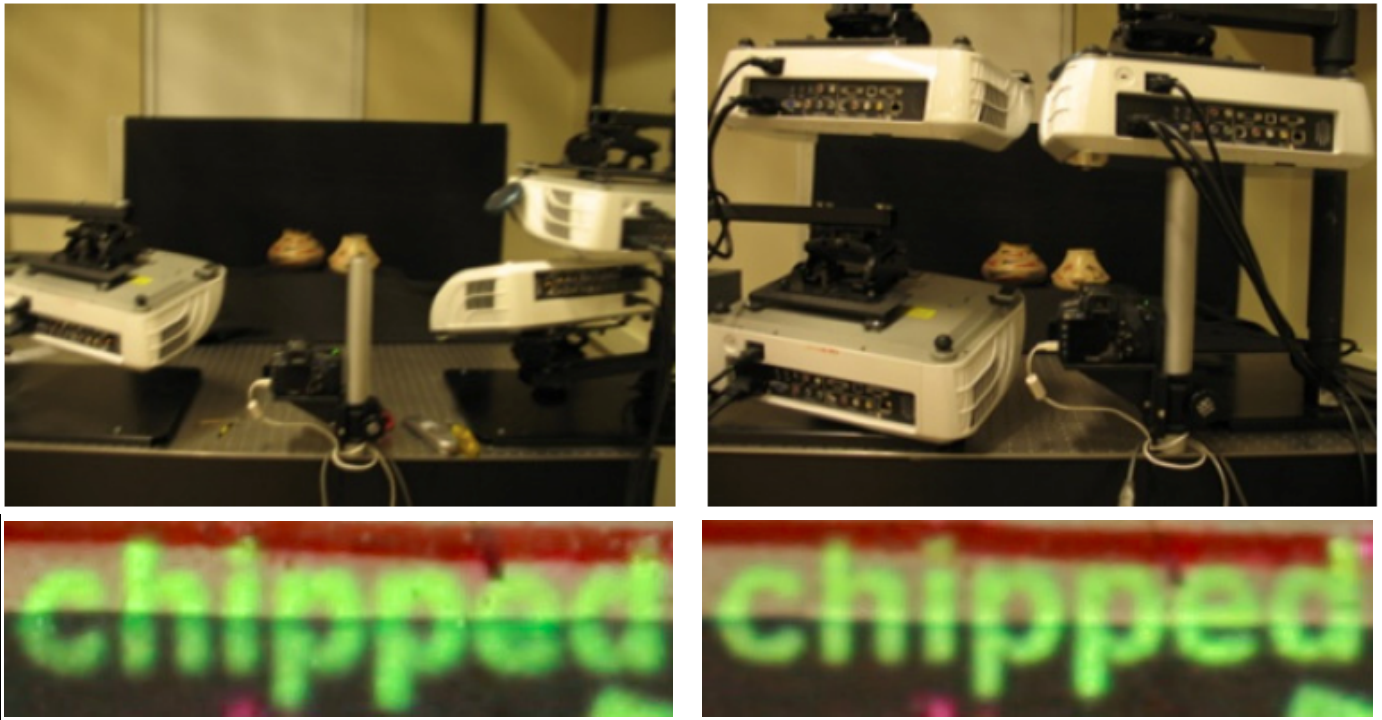
Projection object



Target appearance

ad hoc projectors

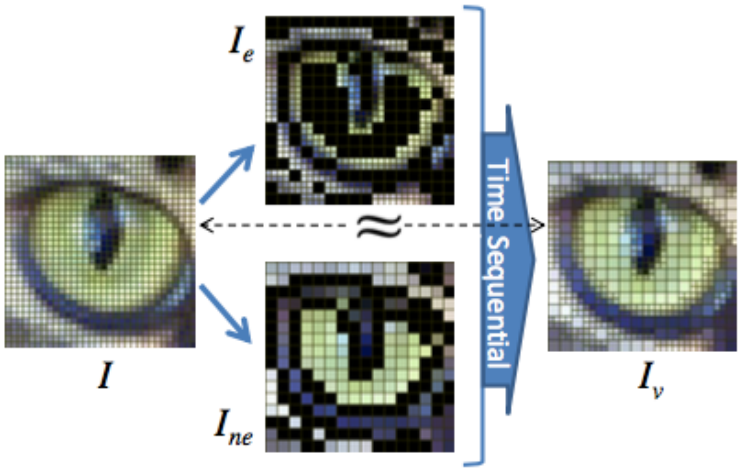
optimized projectors

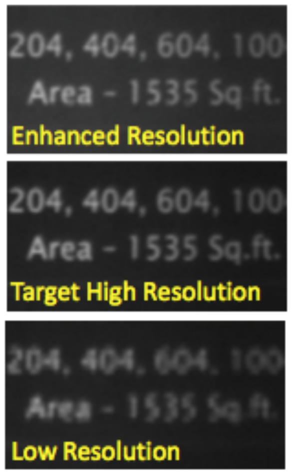


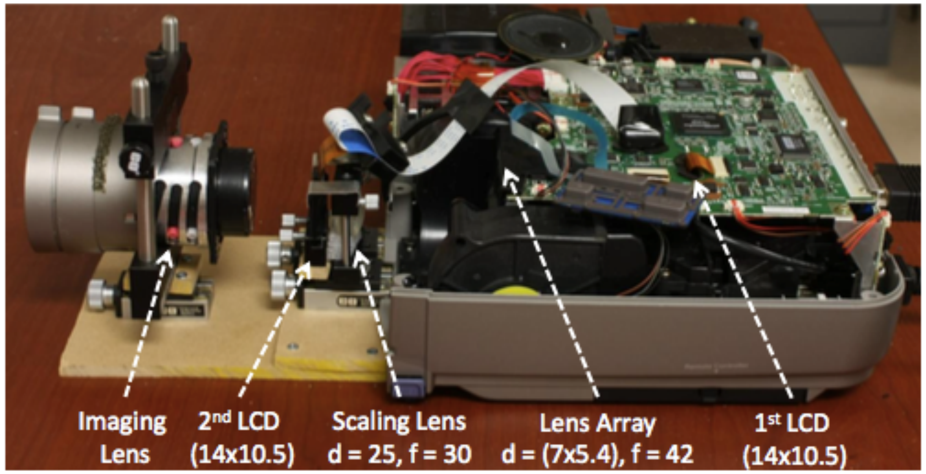
Law et al., Projector Placement Planning for High Quality Visualizations on Real-World Colored Objects, **IEEE TVCG** 2010.

High resolution: Pixel sharing approach

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



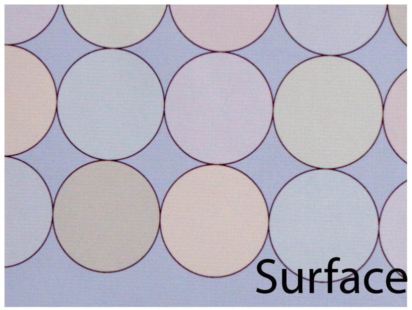


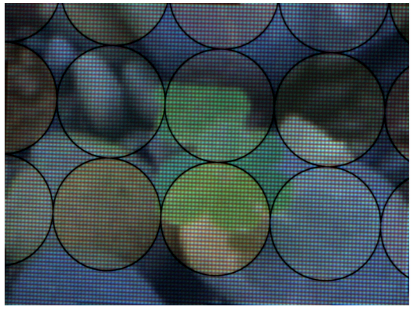


Sajadi et al., Edge-guided resolution enhancement in projectors via optical pixel sharing, **ACM TOG** 2012.

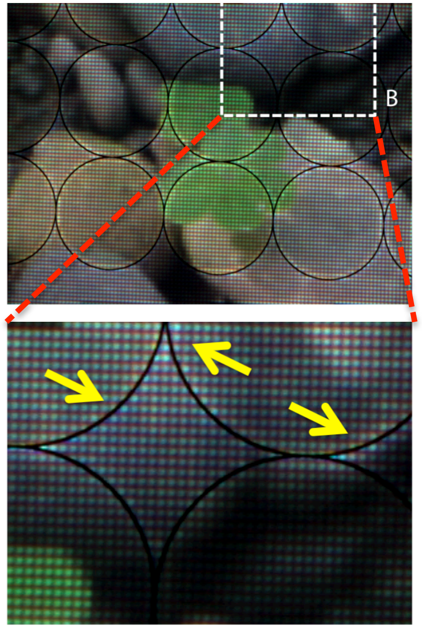
High resolution:
Optimize projection colors for close-up view

- 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





Projected result
w/o compensation

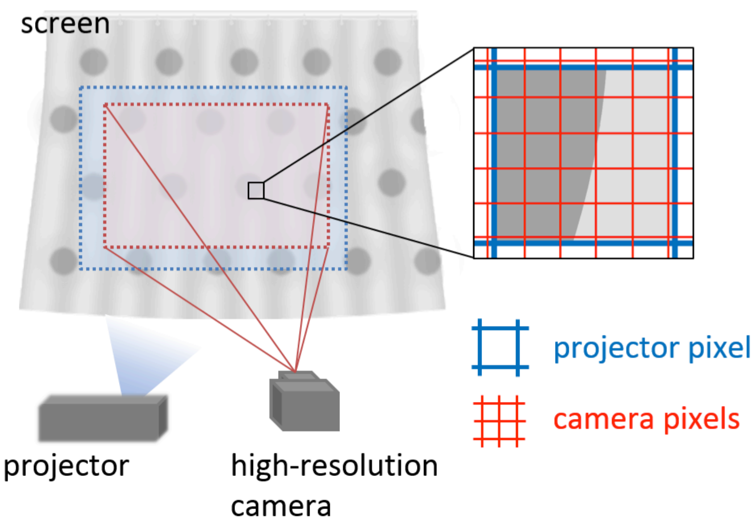


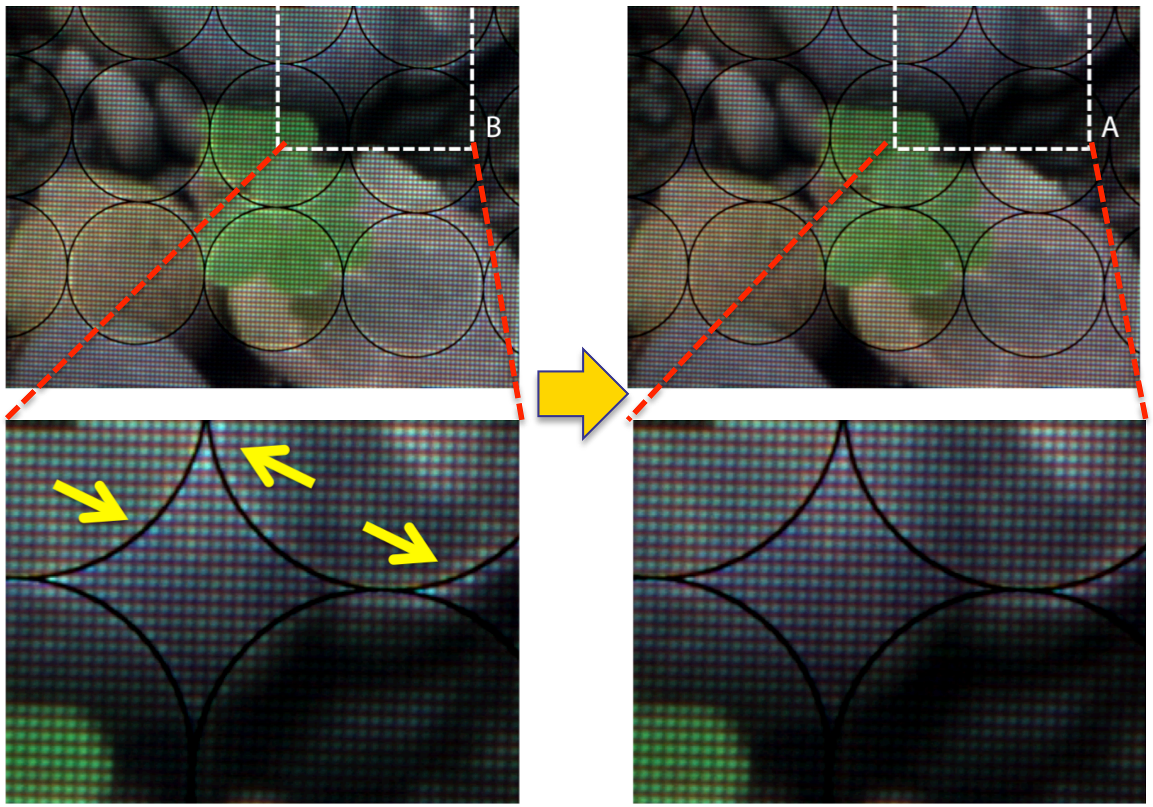
Projected result
w/ conventional
compensation

Mihara et al., Artifact Reduction in Radiometric Compensation of Projector-Camera Systems for Steep Reflectance Variations, **IEEE TCSVT** 2014.

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





Conventional compensation Proposed compensation

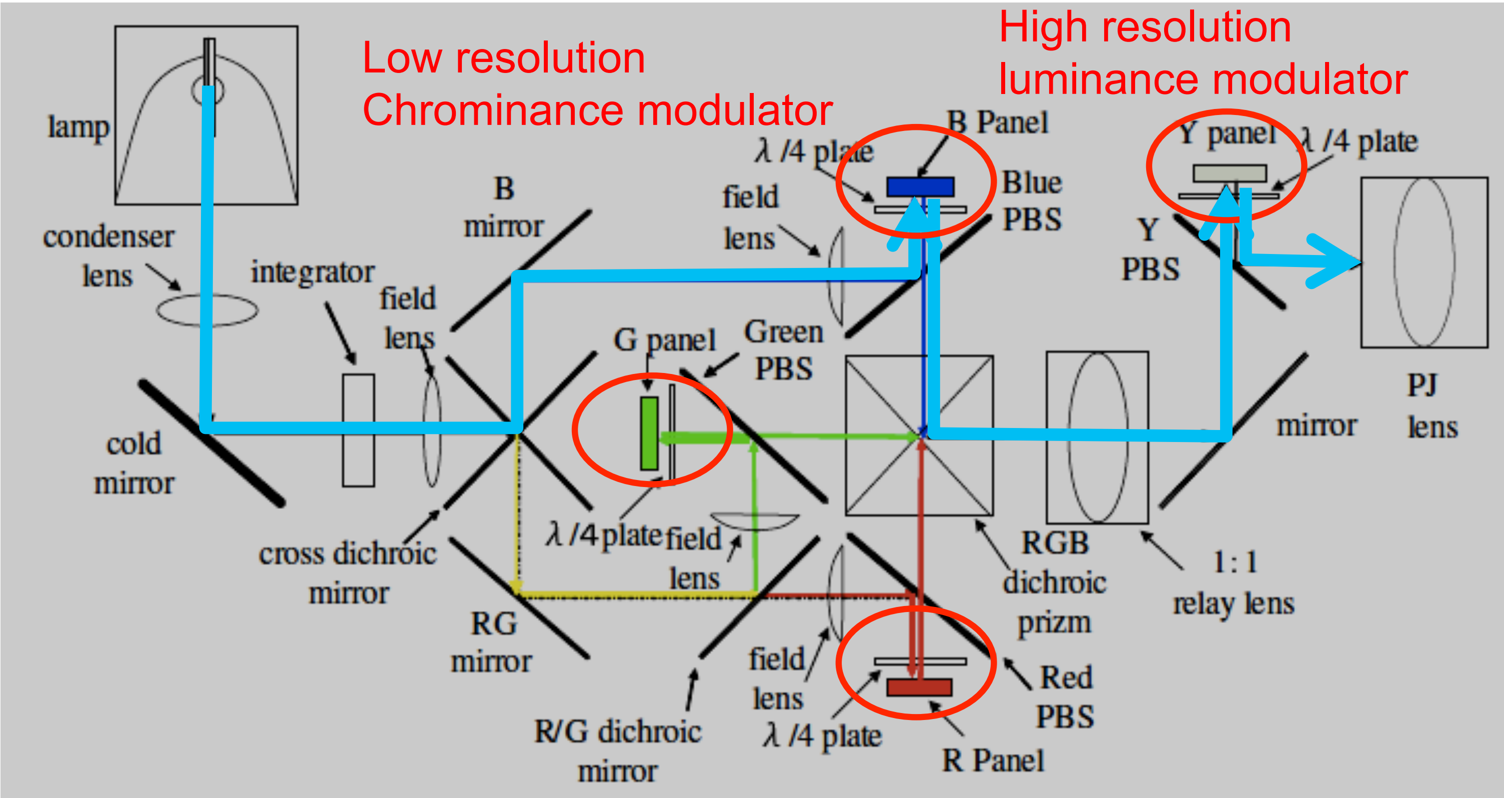
Mihara et al., Artifact Reduction in Radiometric Compensation of Projector-Camera Systems for Steep Reflectance Variations, **IEEE TCSVT** 2014.

Dynamic range

OSAKA UNIVERSITY
Live Locally, Grow Globally

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.

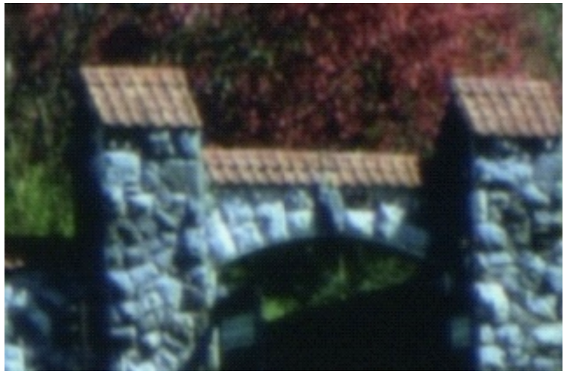
Dynamic range:
Double modulation approach

- Final contrast ratio is the product of two modulation blocks
  - c1 * c2 : 1
    (Chrominance modulator = c1 : 1, luminance modulator = c2 : 1)
- Much lower resolution of chrominance modulator can be used
  - Human vision features high spatial frequency response with respect to luminance more than chrominance.

Image modulated in chrominance (low resolution)

Image modulated in luminance (high resolution)

→

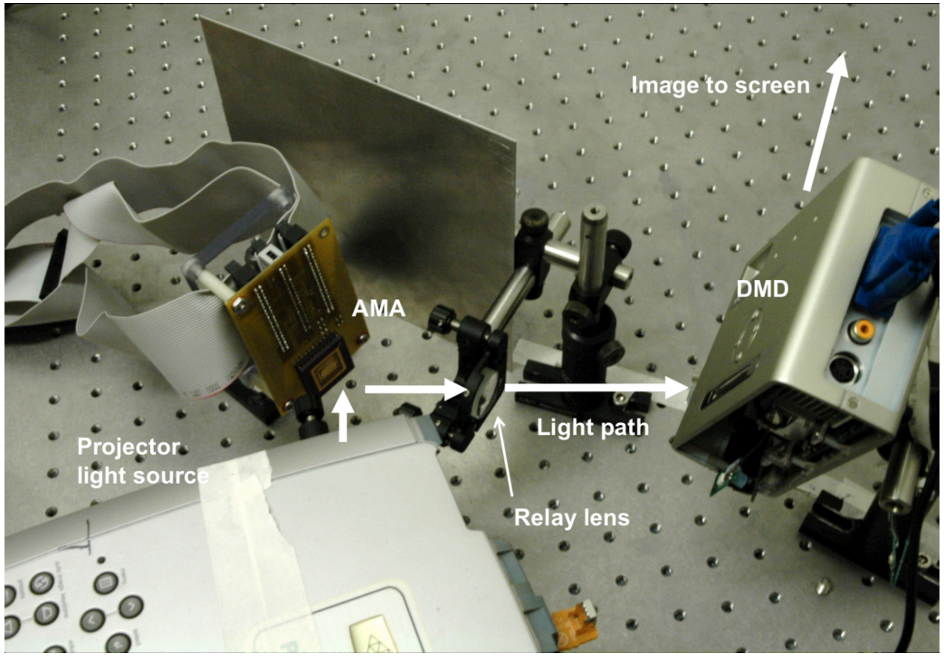


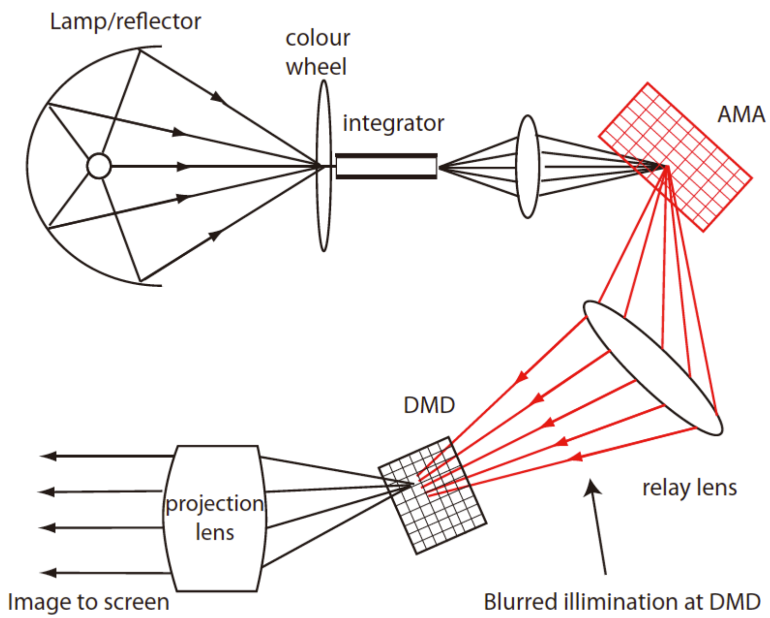
Output image

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

Target image

Projected result captured with a short exposure

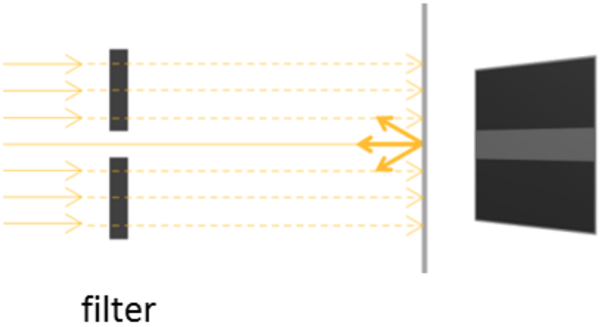
Allocation of light from light spot

Projected result captured with a longexposure

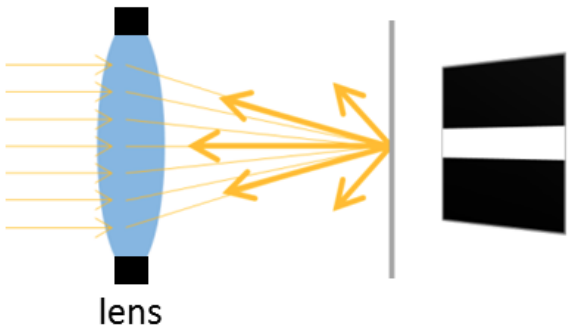
Hoskinson et al., Light reallocation for high contrast projection using an analog micromirror array, **ACM TOG** 2010.

Dynamic range:
Light reallocation approach

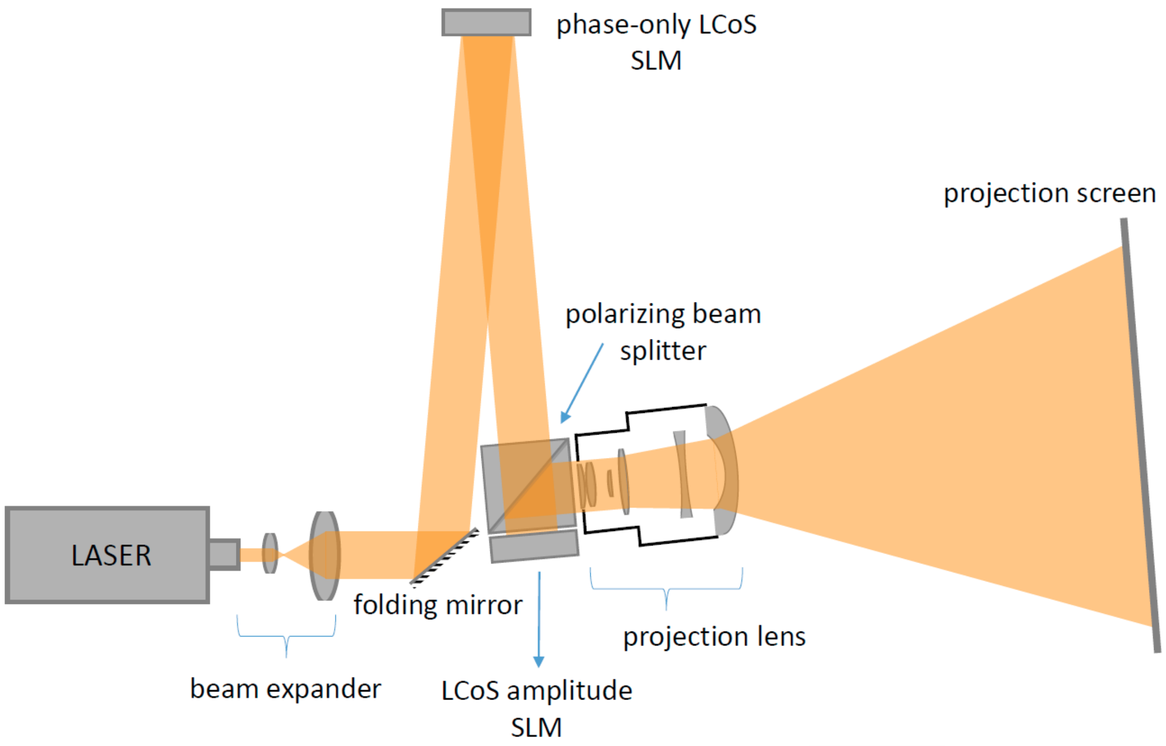
- Phase-based light reallocation



(a) *10% efficient image formation*

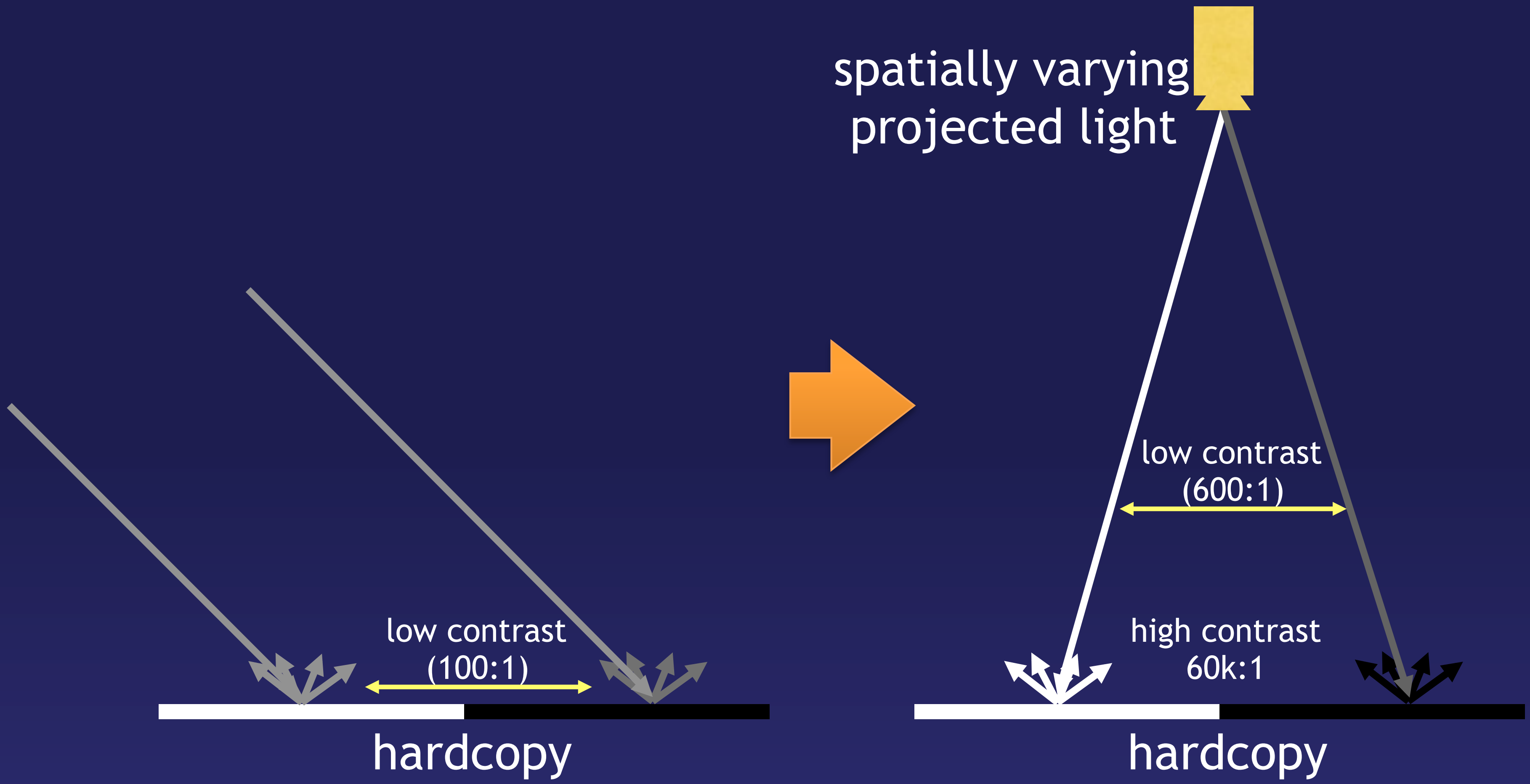


(b) *95% efficient image formation*



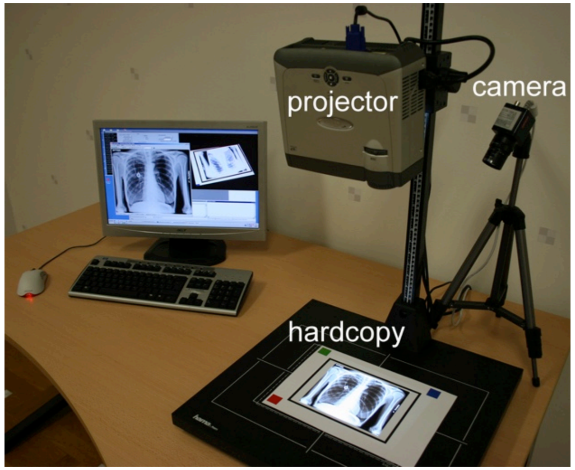
Damberg et al., High Brightness HDR Projection Using Dynamic Phase Modulation , **Proc ACM SIGGRAPH Etech** 2015.

Dynamic range:
Reflectance modulation approach

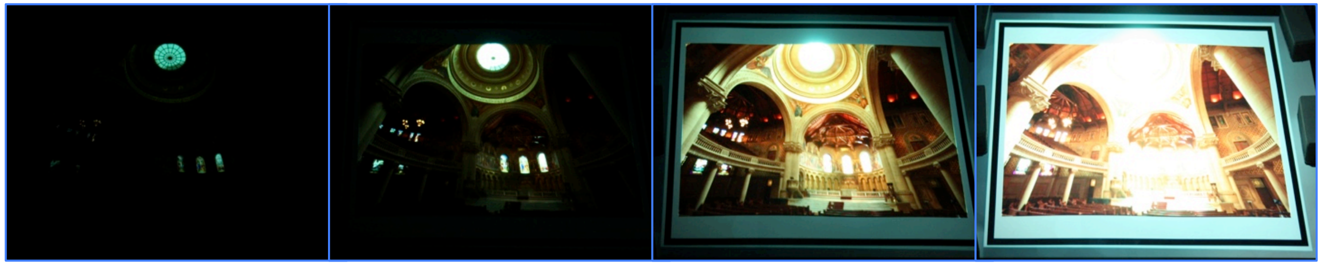


Bimber and Iwai, Superimposing Dynamic Range, **ACM TOG** 2008.

Dynamic range:
Reflectance modulation approach



Shutter speed: ×1 ×16 ×256 ×2,048



Proposed method

Projecting onto white surface

Photographic print under uniform illumination

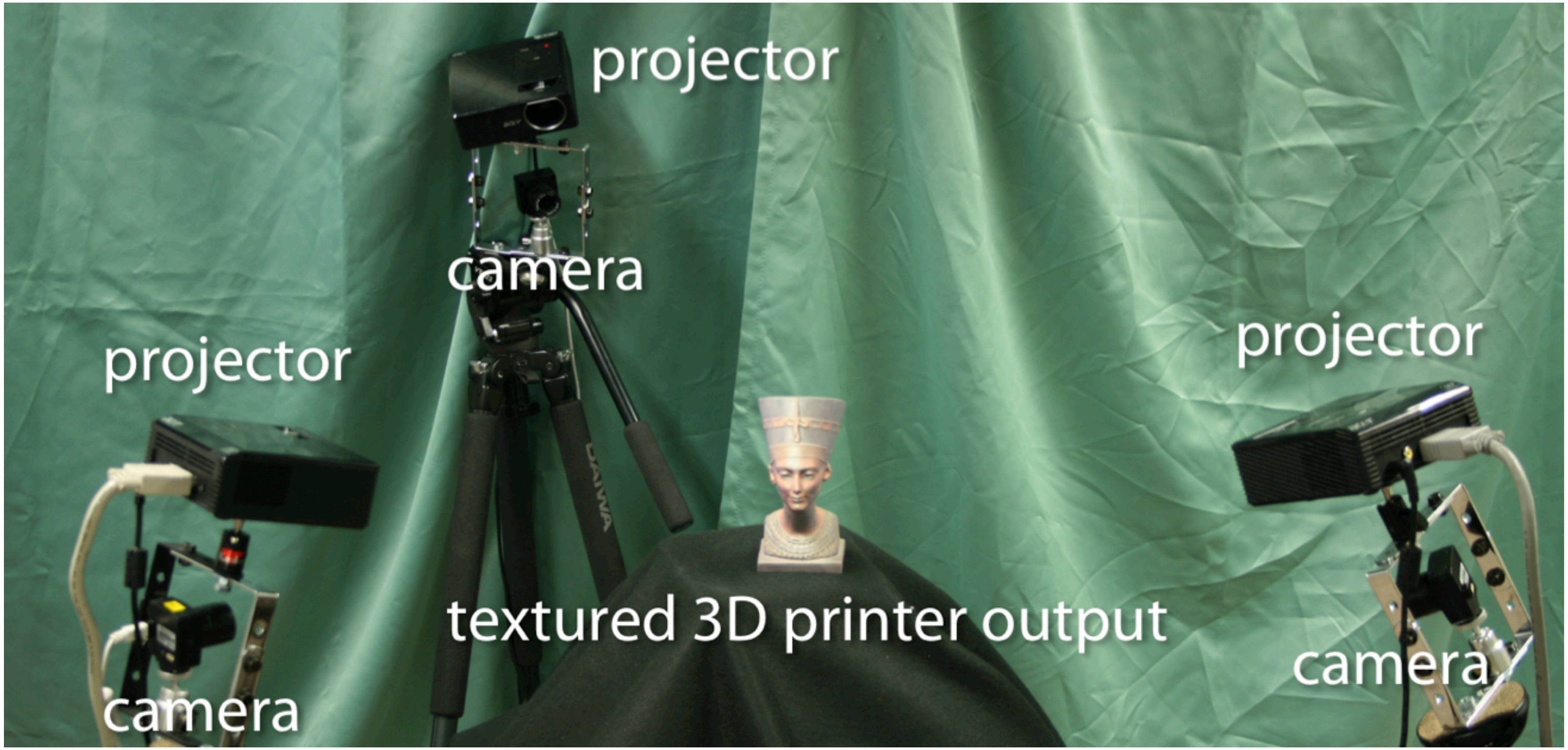
Local

Youtube

Bimber and Iwai, Superimposing Dynamic Range, **ACM TOG** 2008.

Dynamic range:
Reflectance modulation approach

- Projecting textures onto full color 3D printer output



Shimazu et al., 3D High Dynamic Range Display System, **Proc ISMAR** 2011.

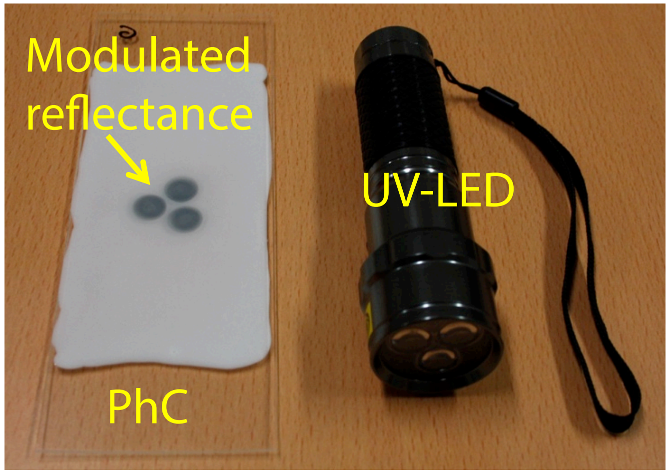
Dynamic range: Reflectance modulation approach

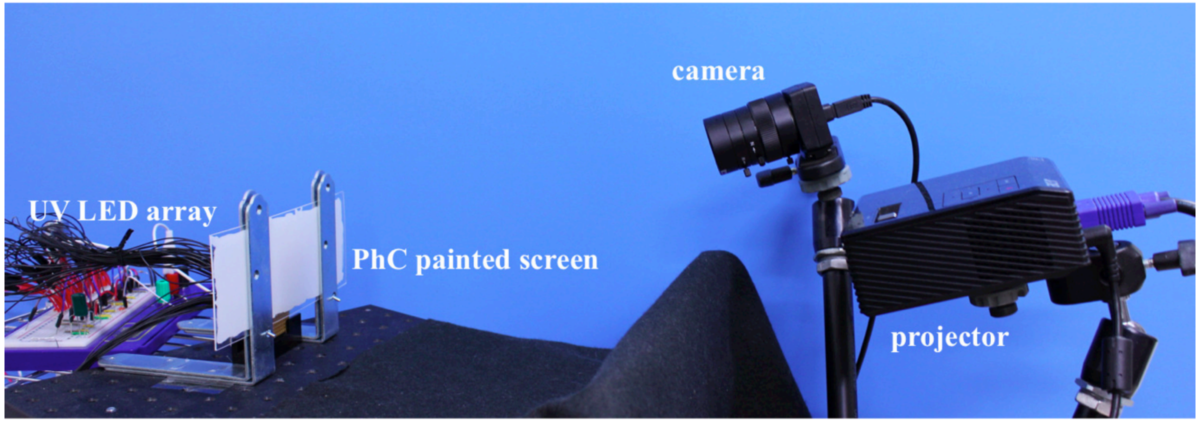
- Projecting textures onto full color 3D printer output

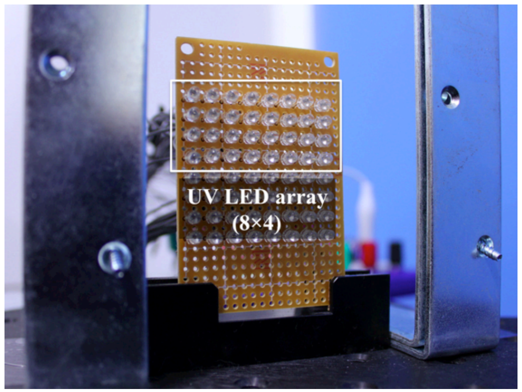
Shimazu et al., 3D High Dynamic Range Display System, **Proc ISMAR** 2011.

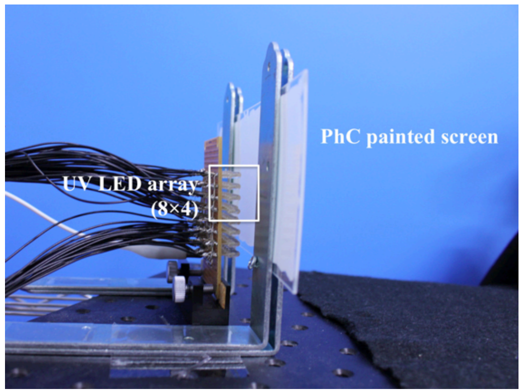
Dynamic range:
Reflectance modulation approach

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





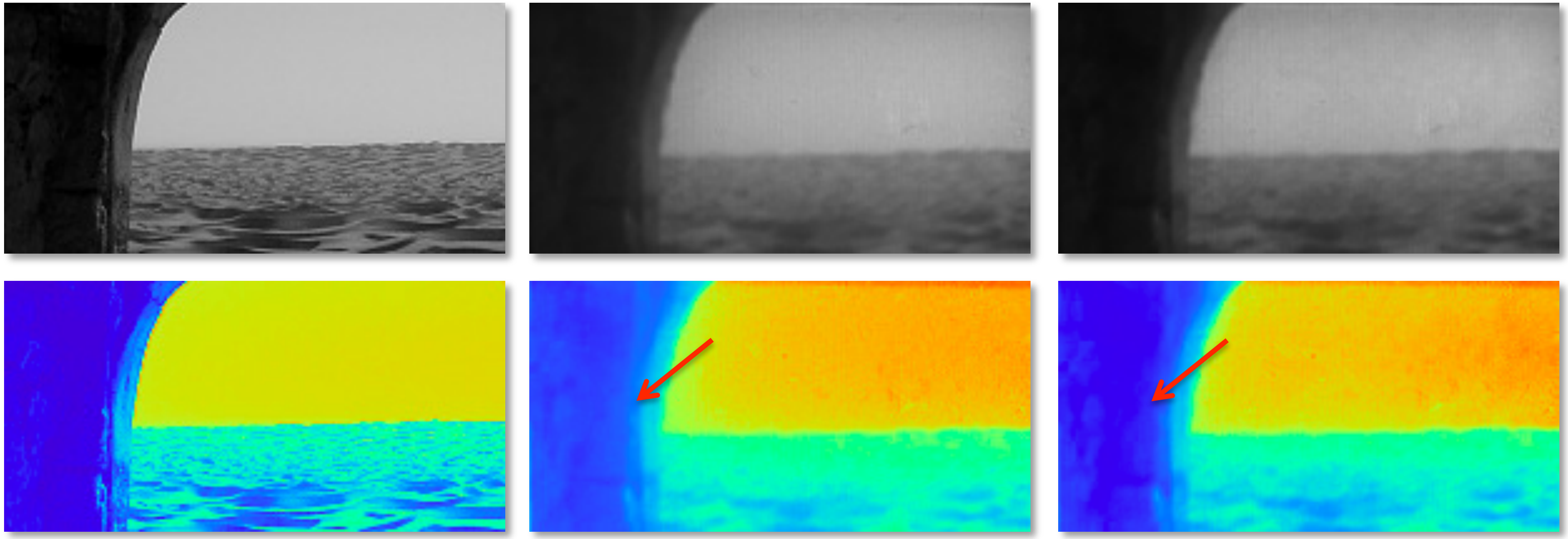




Iwai et al., Projection Screen Reflectance Control for High Contrast Display using Photochromic Compounds and UV LEDs, **Opt Express** 2014.

Dynamic range:
Reflectance modulation approach

- Dynamic reflectance pattern modulation u compounds (PhC) and UV lights
  - PhC: UV checker that changes its color whe nt



Target | w/o reflectance modulation | Proposed method

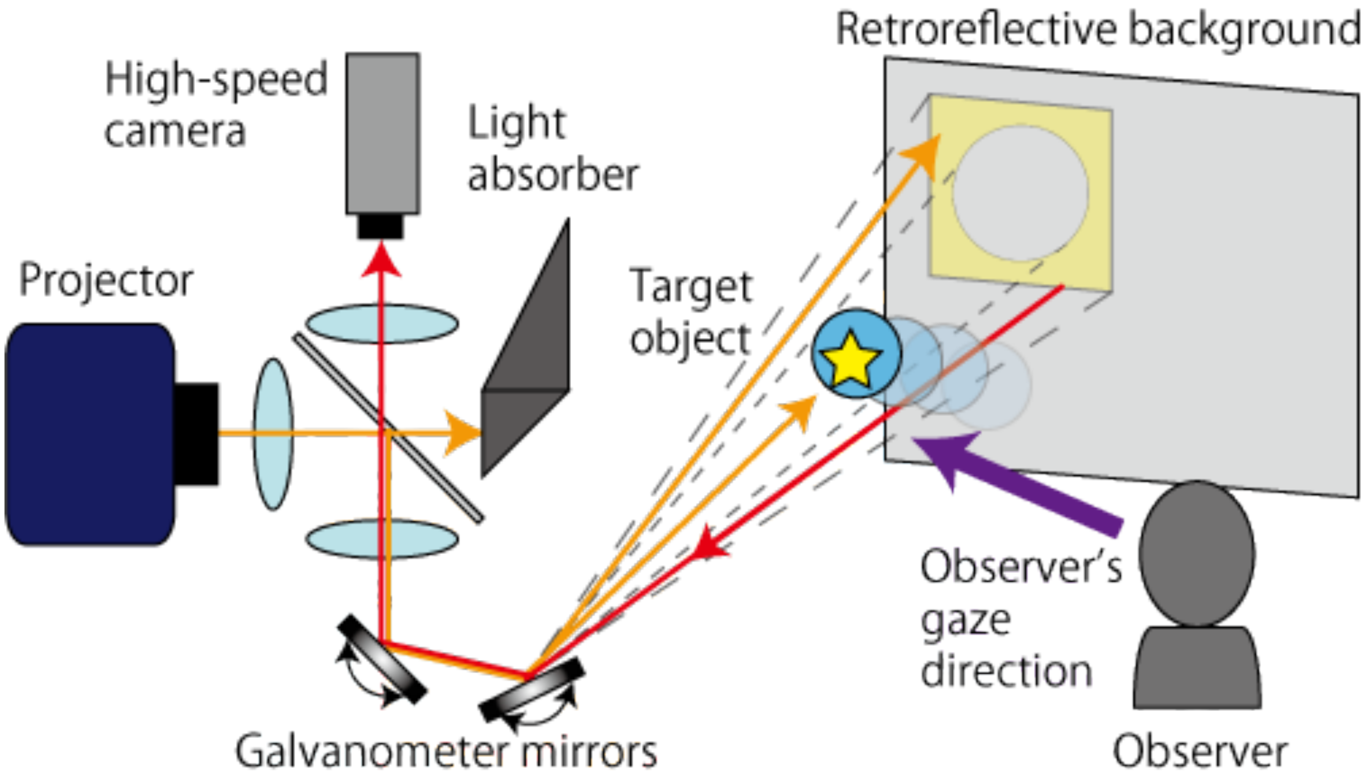
Iwai et al., Projection Screen Reflectance Control for High Contrast Display using Photochromic Compounds and UV LEDs, **Opt Express** 2014.

High speed

OSAKA UNIVERSITY
Live Locally, Grow Globally

High speed: Galvanometer mirrors approach

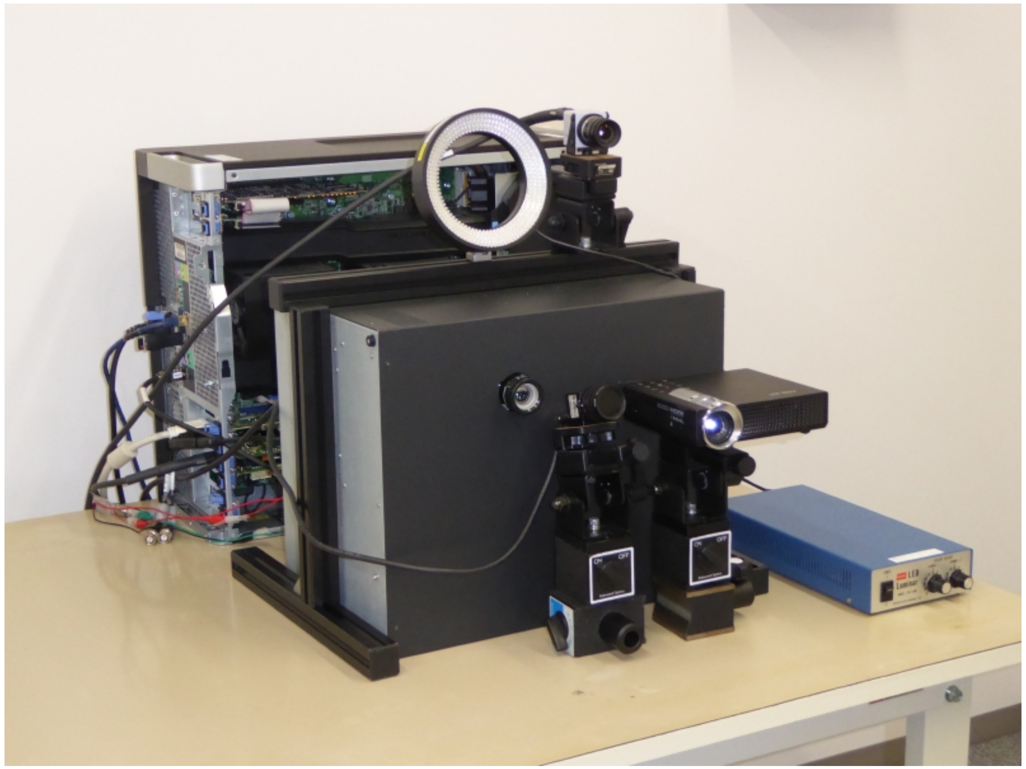
- Projected light is redirected using galvanometer mirrors
- Movement of projection target is measured by a coaxial high-speed camera



Sueishi et al., Robust High-speed Tracking against Illumination Changes for Dynamic Projection Mapping, **Proc IEE VR** 2015.

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

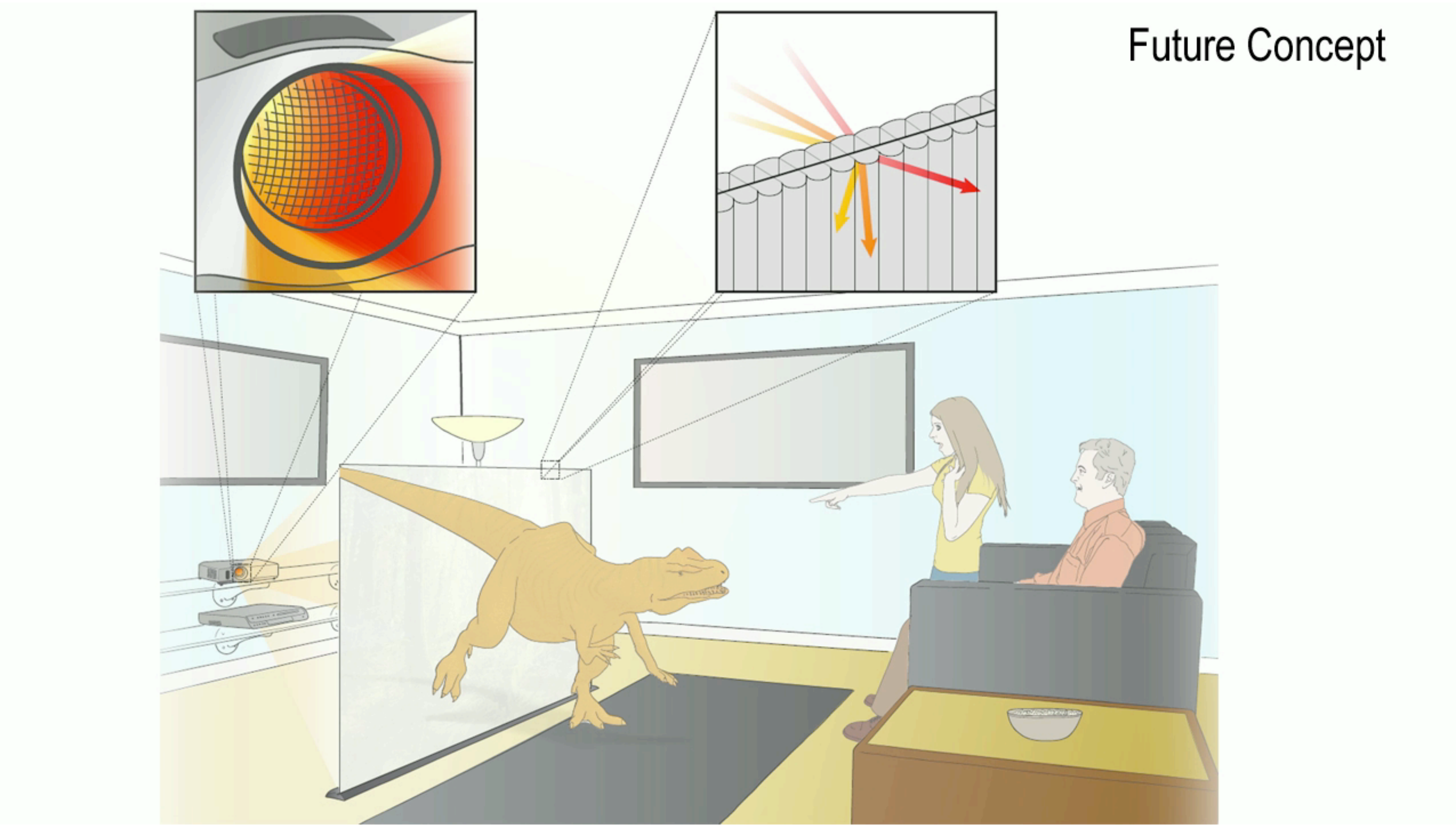
- Smart headlight

Tamburo et al., Programmable automotive headlights, **Proc ECCV** 2014.

New topics

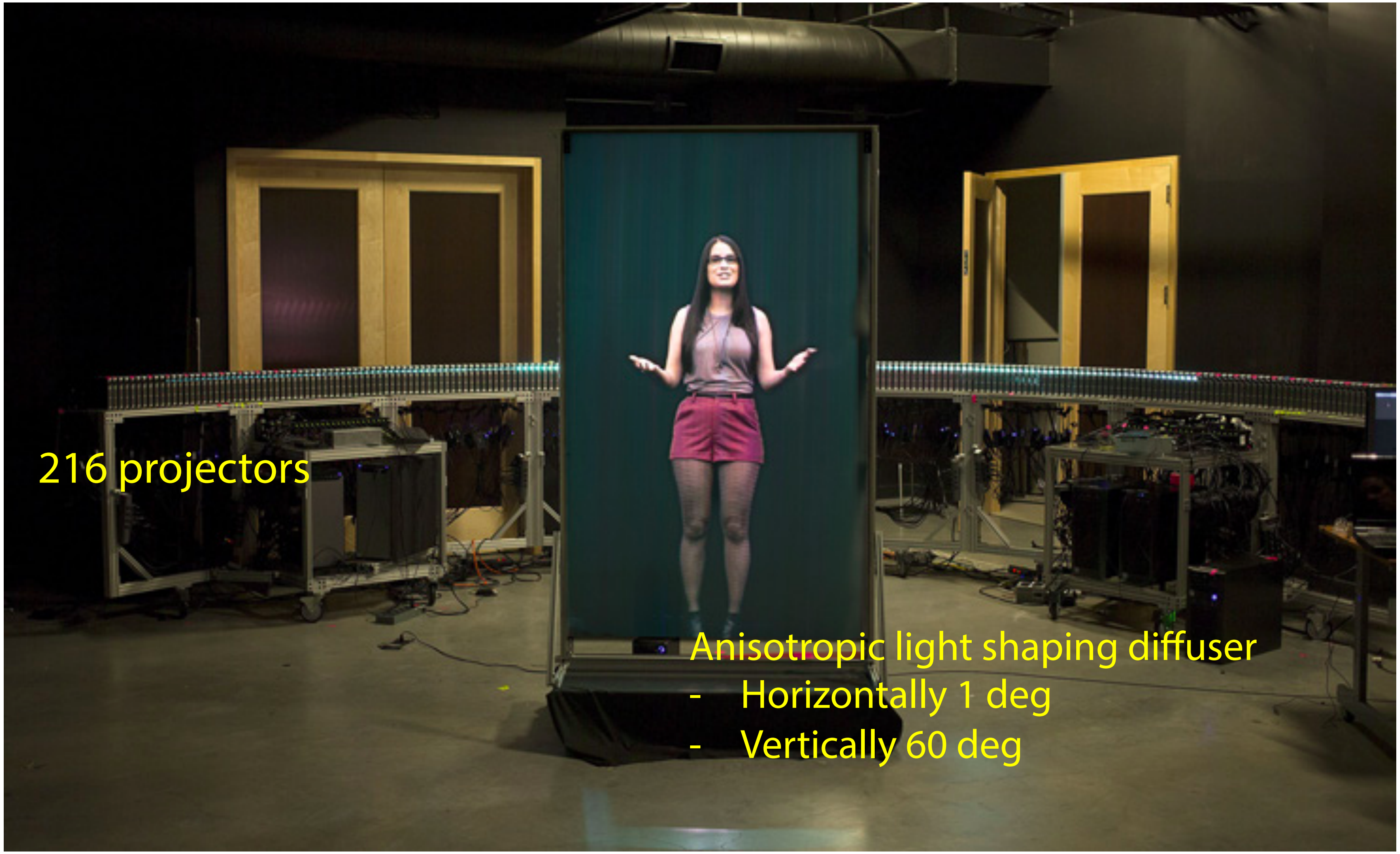
OSAKA UNIVERSITY
Live Locally, Grow Globally

Light field projection



Hirsch et al., A Compressive Light Field Projection System, **ACM TOG** 2014.

Light field projection



Jones et al., An Automultiscopic Projector Array for Interactive Digital Humans, **Proc SIGGRAPH Etech** 2015.

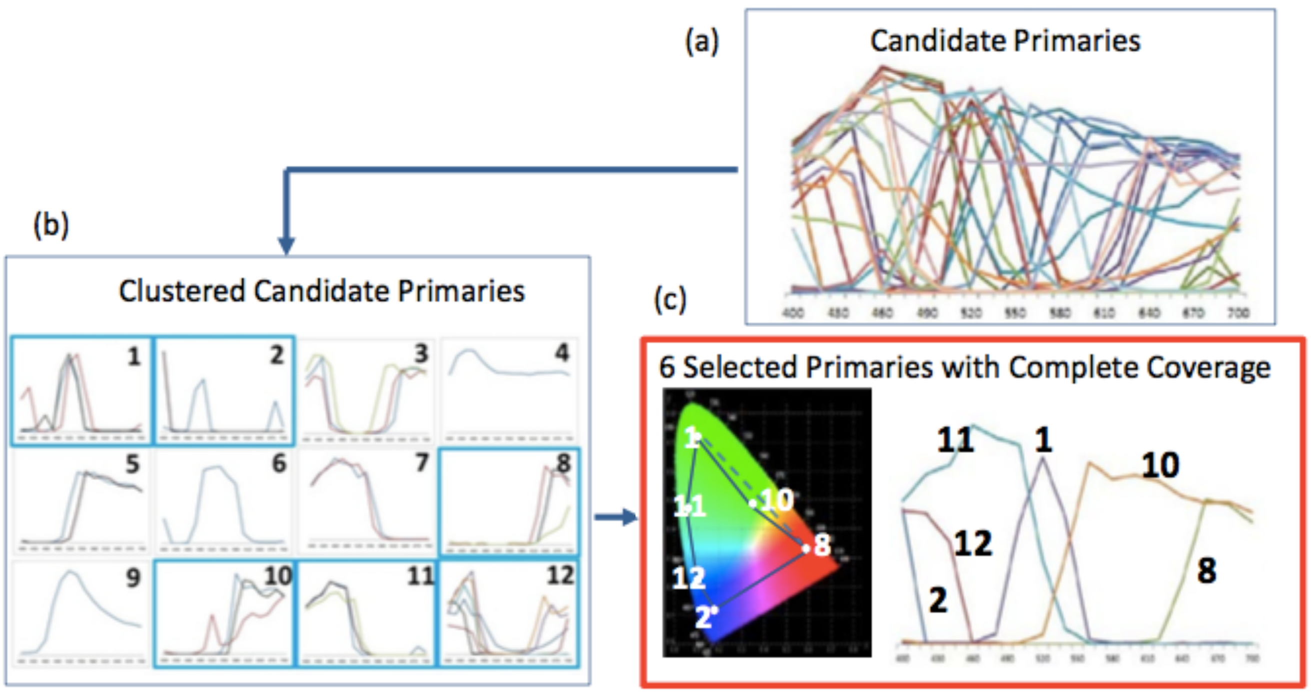
Light field projection

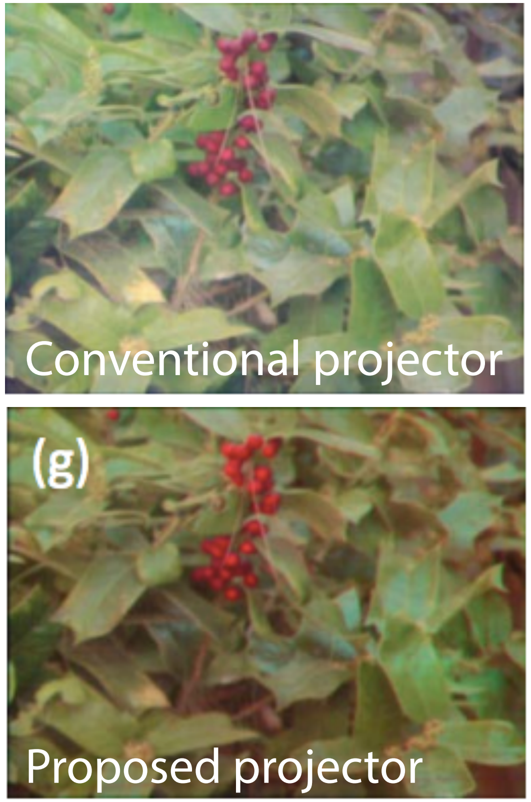
- Prof. Amano will have a talk on this topic as the next speaker!

Amano et al., Structural Color Display on Retro-reflective Objects, **Proc ICAT** 2015.

Spectrum optimization

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

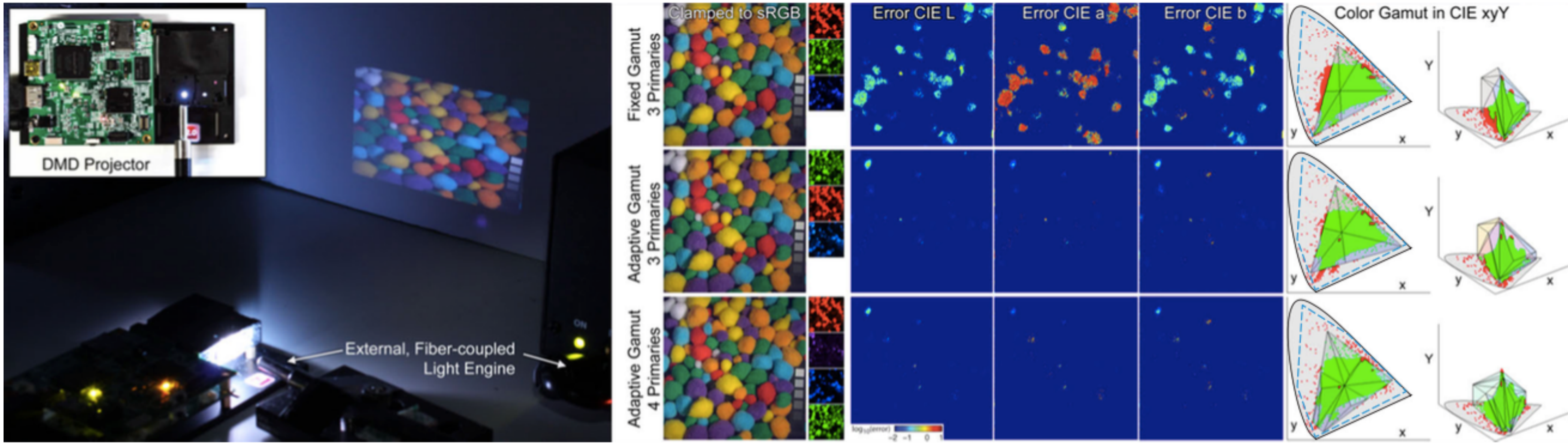




Li et al., Content-Independent Multi-Spectral Display Using Superimposed Projections, **Computer Graphics Forum** 2015.

Spectrum optimization

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



Kauvar et al., Adaptive Color Display via Perceptually-driven Factored Spectral Projection, **ACM TOG** 2015.

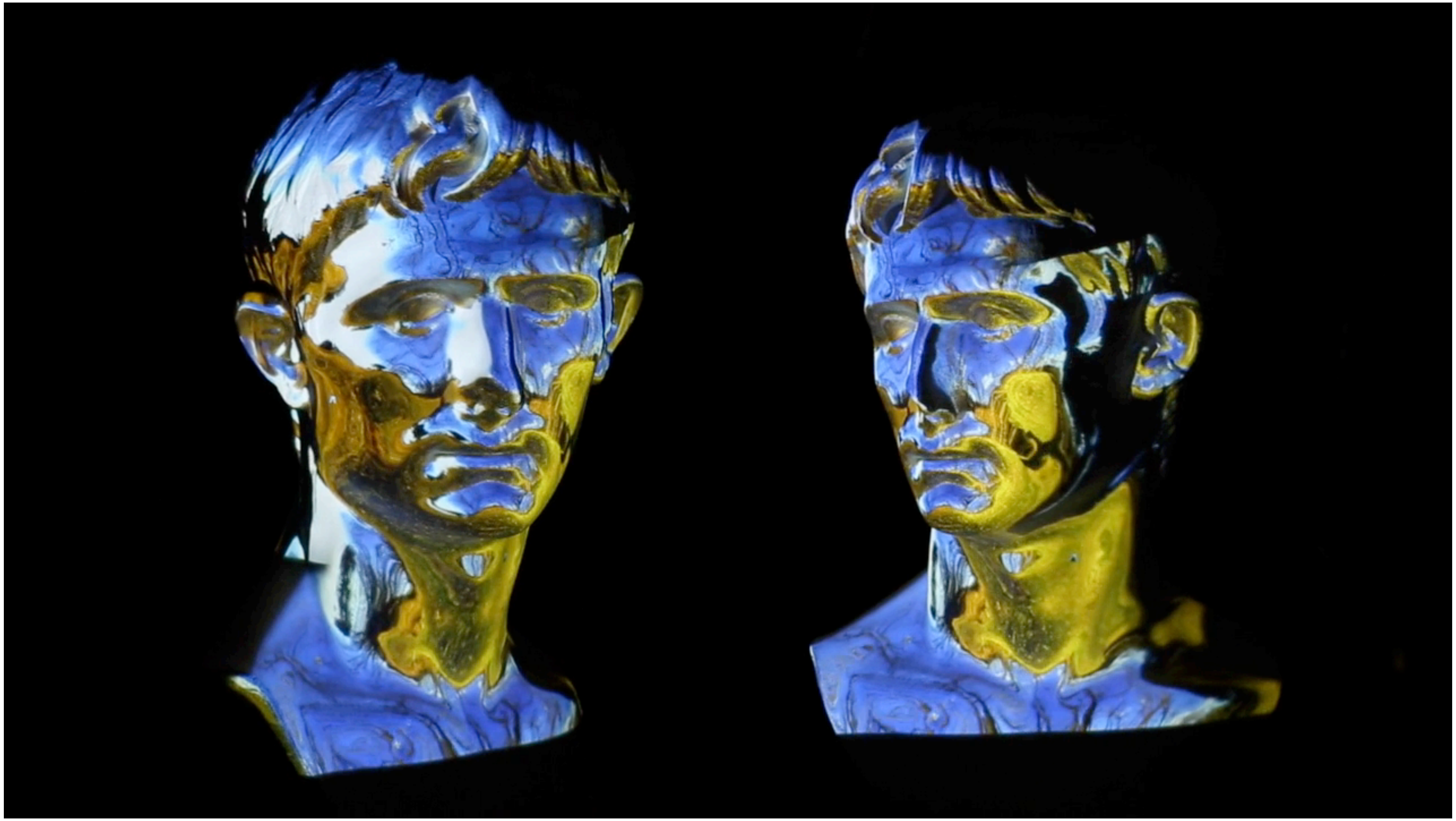
Dynamic projection target

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

Resch et al., Sticky Projections - A New Approach to Interactive Shader Lamp Tracking, **Proc ISMAR** 2014.

Dynamic projection target

- Projection object tracking using RGB-D camera



Siegl et al., Real-Time Pixel Luminance Optimization for Dynamic Multi-Projection Mapping, **ACM TOG** 2015.

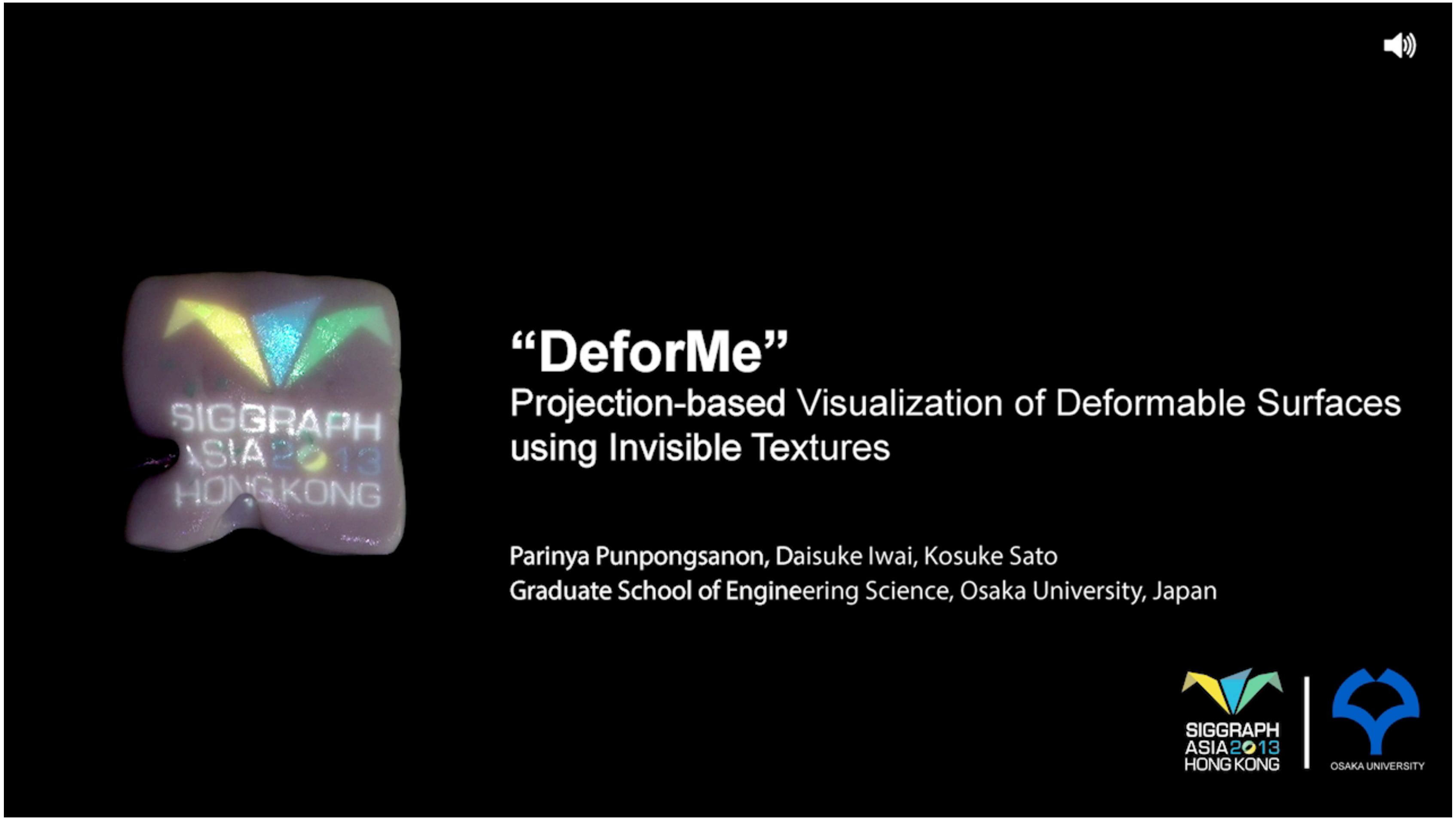
Dynamic projection target

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

Asayama et al.,
Diminishable Visual Markers on Fabricated Projection Object for Dynamic Spatial Augmented Reality, **Proc SIGGRAPH ASIA Etech** 2015.

Non-rigid projection target

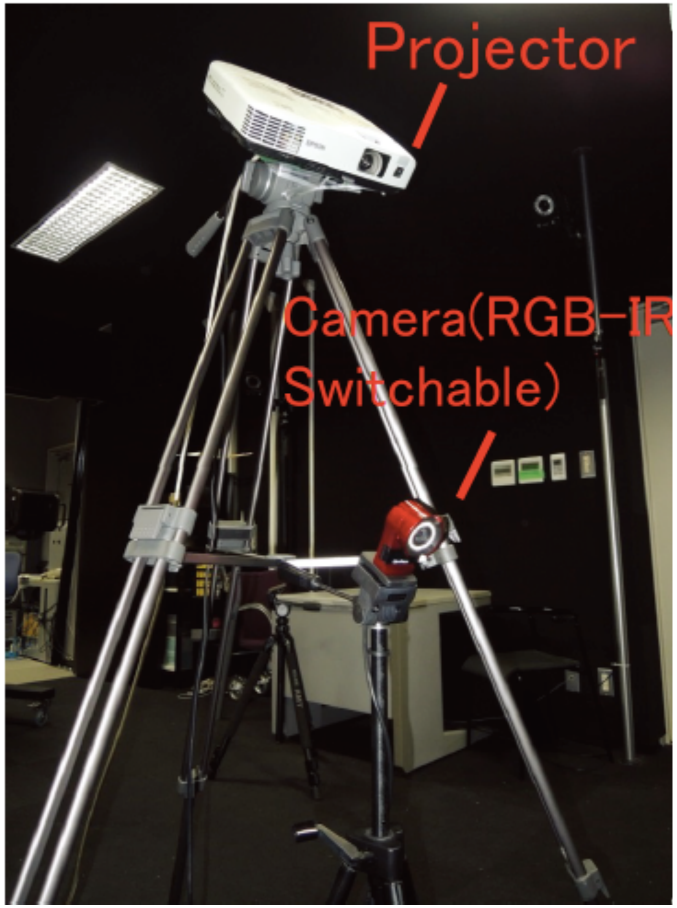
- IR ink and IR camera

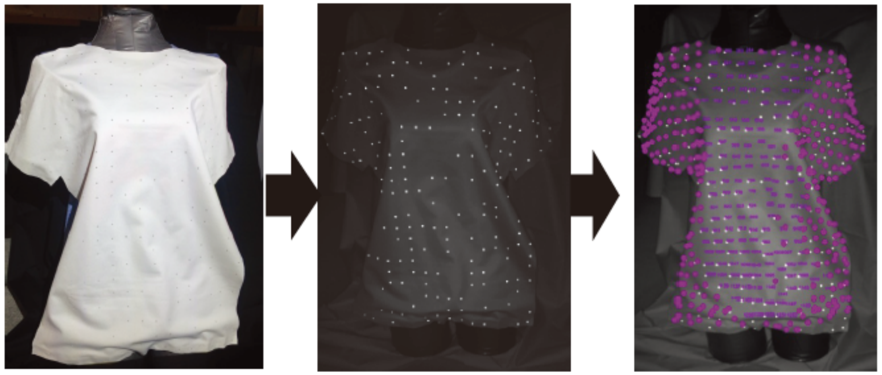


Punpongsanon et al.,
DeforMe: projection-based visualization of deformable surfaces using invisible textures, **Proc SIGGRAPH ASIA Etech** 2013.

Non-rigid projection target

- Retro-reflective marker and IR camera





Target object: T-shirt shaped cloth

Image by IR-camera

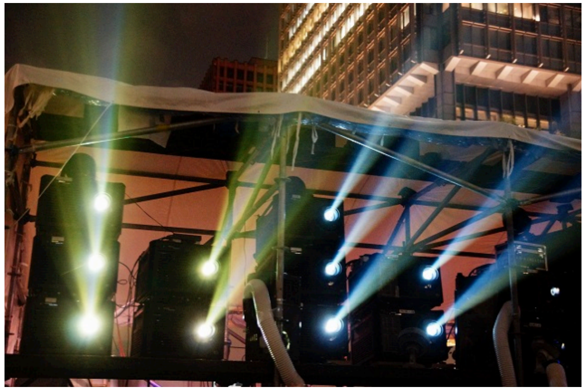
Result of marker recognition

Projection results

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!!!

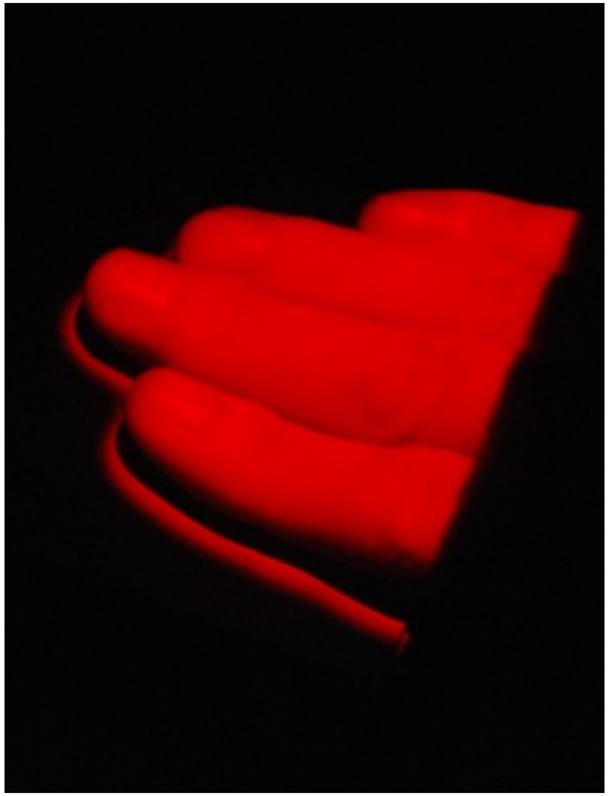


Tsukamoto et al.,
Radiometric Compensation for Cooperative Distributed Multi-Projection System through 2-DOF Distributed Control, **IEEE TVCG** 2015.

Projecting onto human body

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

Touched object becomes cooler

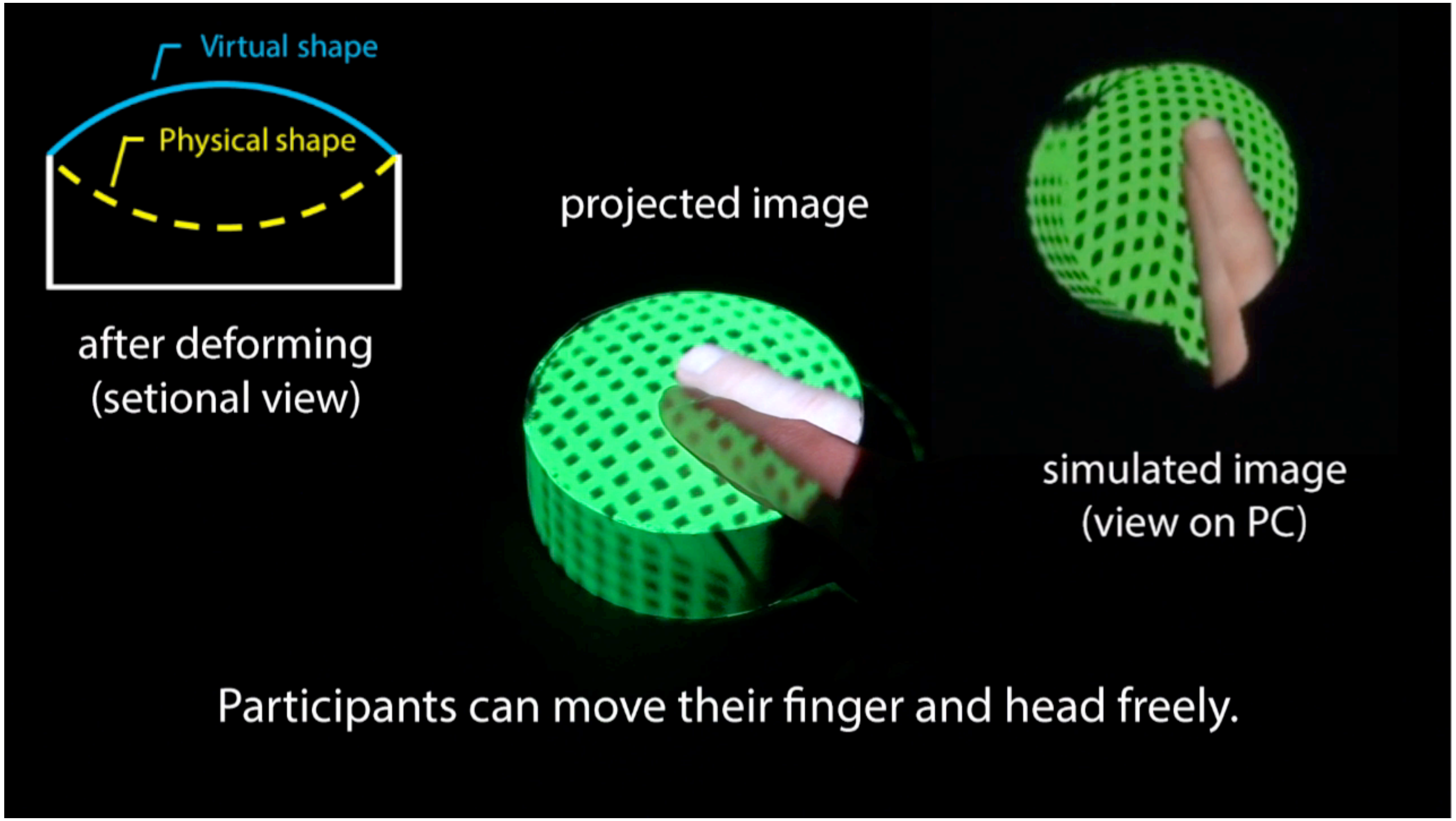


Touched object becomes warmer

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

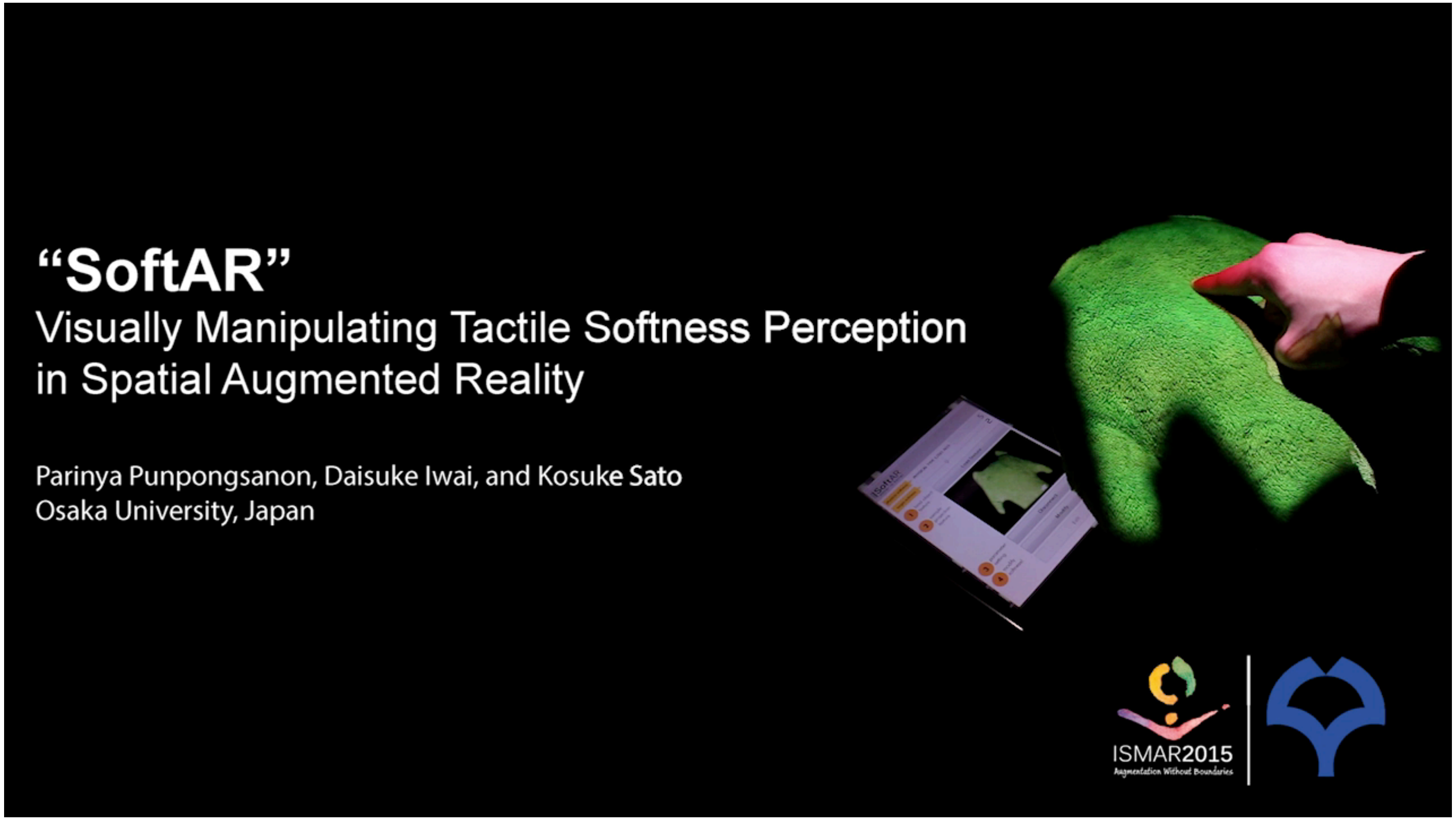
- Change tactile **shape** perception by projecting shifted hand image
- Please come to our poster!!! (**#1109 on Sep 30**)



Kanamori et al., [POSTER] Manipulating Haptic Shape Perception by Visual Surface Deformation and Finger Displacement in Spatial Augmented Reality, **Proc ISMAR** 2015.

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!!!



Punpongsanon et al., SoftAR: Visually Manipulating Haptic Softness Perception in Spatial Augmented Reality, **IEEE TVCG** 2015.

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