Computational Illumination
Active Light - Devices and Techniques

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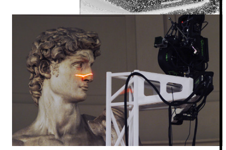
Outline

- Controlled Illumination in Remote Sensing
  - Range Scanners
  - BRDF measurement
- Display Systems
  - Projector Systems
    - single camera - single projector systems
    - single camera – multiple projector systems
  - 3D displays
    - integral photography
    - rotating diffuser 3D displays
    - holographic display systems / spatial light modulators

Acquisition Devices for Objects and Material Properties

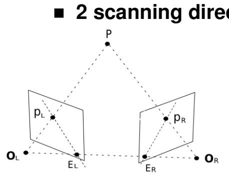
Remote Sensing – Range Scanners

- Laser Range Scanner
  - most commonly used range scanner
  - principle of triangulation
  - good accuracy for diffuse surfaces
  - bad for specular surfaces
  - overview in [Blais04]

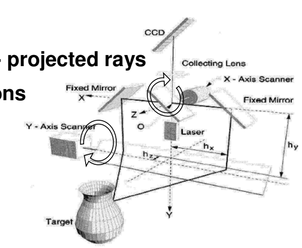


Remote Sensing – Range Scanners

- Principle of laser range scanner – single point laser scanning
- triangulation:
  - intersect two back- projected rays
  - 2 scanning directions



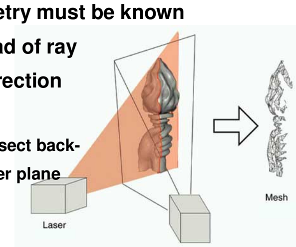
epipolar geometry



point scanner schematic

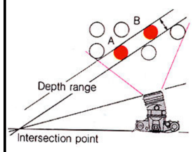
Remote Sensing – Range Scanners

- Laser range scanner – slit scanner
  - laser – camera geometry must be known
  - use laser plane instead of ray
  - only one scanning direction
  - triangulation:
    - for each lit pixel, intersect back-projected ray with laser plane

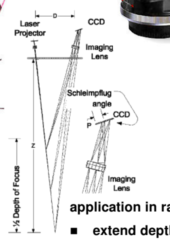


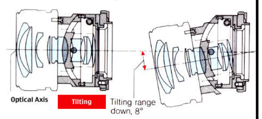
Remote Sensing – Range Scanners

- Laser Range Scanners – focal plane selection
- Scheimpflug principle
- tilt-shift lenses



Scheimpflug principle





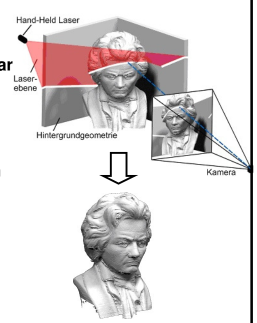
application in range scanning

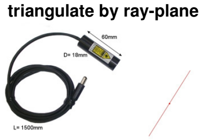
- extend depth of field

Tilt-Shift Lens Examples

Remote Sensing – Range Scanners

- Laser Range Scanning – Cheapo Version [Winkelbach06]
- hand-held line laser
- known background geometry
- need two planes that are not co-linear
- known camera calibration
- compute laser plane from lines on the background planes
- triangulate by ray-plane intersection





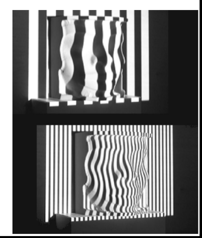
Remote Sensing – Range Scanners

- Structured Light Scanners
- variation on a theme: triangulation by ray-plane intersections
- sequential projection of patterns allows for simultaneous identification of several illumination plane intersections

example for 8 planes

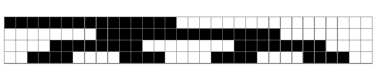
pass 1	0	0	0	0	1	1	1	1
pass 2	0	0	1	1	0	0	1	1
pass 3	0	1	0	1	0	1	0	1

need $\log_2(N)$ passes to identify N planes

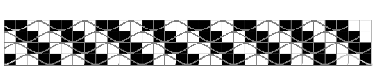


Remote Sensing – Range Scanners

- Structured Light Scanners with Phase-Shifting [Wolf03]
- combines binary encoding and shifted sine patterns



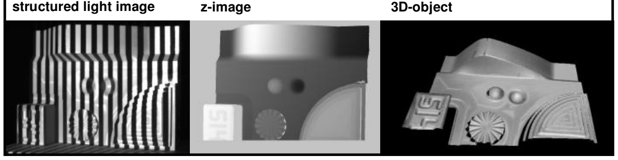
binary code (coarse depth)



sinusoidal patterns (fine depth) realized by

- defocusing
- optical filters
- gray values

structured light image z-image 3D-object

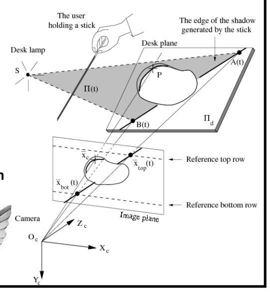


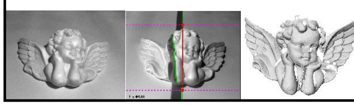
Remote Sensing – Range Scanners

- dynamic structured light scanner [Wolf03]
  - 3 binary patterns
  - 4 phase shifted sinusoidal patterns
  - 200 fps camera
  - → ~30 3D scans/second

Remote Sensing – Range Scanners

- Structured Light Scanner – Cheapo Version [Bouguet98]
- uses a web-cam, a desk lamp, a pen ~15 €
  - calibrated
    - light source position
    - ground plane
    - camera parameters
  - estimate shadow plane by computing line on the ground plane
  - ray-plane triangulation for 3D reconstruction



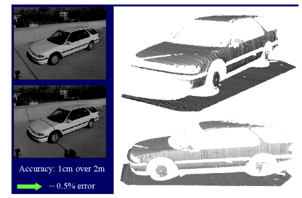


Remote Sensing – Range Scanners

- Stick Scanner in action

setup desktop

setup outdoor



- accuracy: 0.1 - 0.3 mm in a range of 10 cm

Remote Sensing – Range Scanners

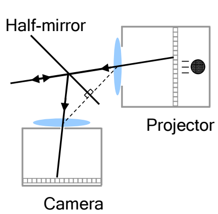
- time-of-flight scanners [Gvili03]
- NOT triangulation based
- short infrared laser pulse is sent from camera
- reflection is recorded in a very short time frame (picoseconds)
- results in depth profile (intensity image)

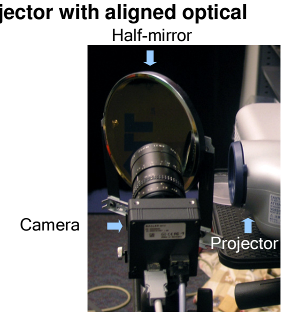
Remote Sensing – Range Scanners

- time-of-flight scanner – examples
- accuracy 1-2 cm in a range of 4 – 7 m
- applications:
  - "depth keying" replaces chroma keying
  - 3D interaction
  - large scale 3D scanning (LIDAR – light detection and ranging)

Remote Sensing – Range Scanners

- depth from projection defocus [Zhang06]
- setup: camera and projector with aligned optical axes

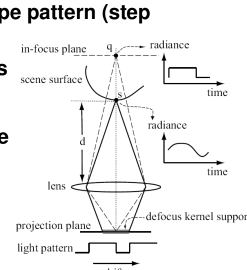




Remote Sensing – Range Scanners

principle of operation

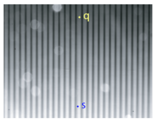
- focus projector behind scene element with the largest distance
- project a moving binary stripe pattern (step functions)
- pattern is blurred for objects not in the focal plane
- blur decreases with distance from projector



Remote Sensing – Range Scanners

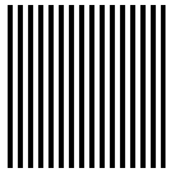
- record video sequence

  → allows for (temporal) per-pixel scanning of the blurred intensity profile

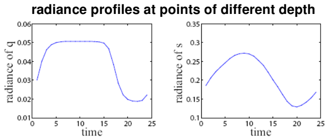


vertically slanted plane (gray values indicate depth)

projection pattern



radiance profiles at points of different depth

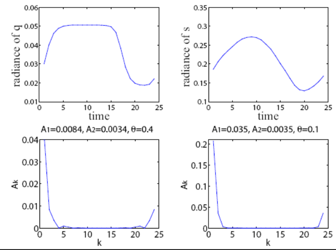


Remote Sensing – Range Scanners

- defocused patterns correspond to a low pass filtered version of the original pattern
- filter is depth dependent !
- analyze frequency spectrum:

scanned profile

frequency spectrum



Remote Sensing – Range Scanners

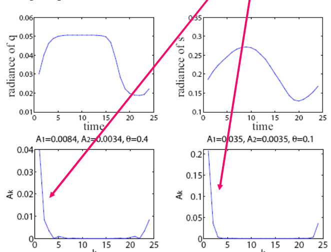
- defocused patterns correspond to a low pass filtered version of the original pattern
- filter is depth dependent !
- analyze frequency spectrum:

different slopes

(mind the different scale of the diagrams)

scanned profile

frequency spectrum

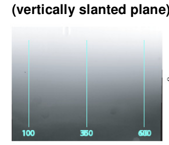


Remote Sensing – Range Scanners

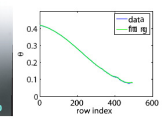
- use first two coefficients of discrete Fourier transform to compute parameter representative of slope

$$\theta = \frac{A_2}{A_1}$$

calibration depth map (vertically slanted plane)

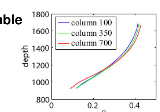


variation of theta w.r.t. vertical axis



- indicates how heavily low-pass filtered the signal is in a particular pixel → depth measure (look-up table computed by pre-calibration)

depth-theta look-up table for three different horizontal positions

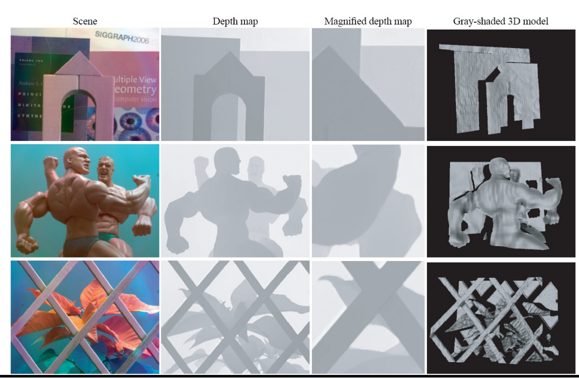


Remote Sensing – Range Scanners

- Depth from Projection Defocus
- advantages
  - per-pixel independent measurements
  - accurate at occlusion boundaries
  - works well for glossy surface properties
- Issues:
  - need small camera aperture (no defocus from lens)

    → need bright projector
  - projectors usually do not have high-frequency light sources (image not stable)

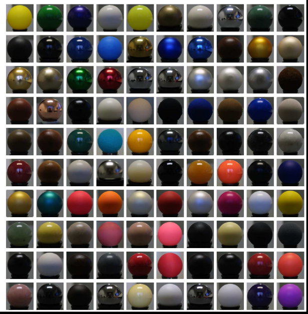
Remote Sensing – Range Scanners



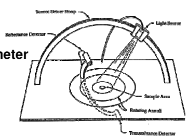
Remote Sensing – BRDF Measurements

- BRDF acquisition $L_o = \int_{\Omega_+} f_r(\theta_i,\phi_i,\theta_o,\phi_o) L_i(\theta_i,\phi_i) cos\theta_i d\omega$
- 4 degrees of freedom
- 2 for incoming light direction (θ_i,ϕ_i)
- 2 for viewing direction (θ_o,ϕ_o)

BRDF examples [Matusik03]

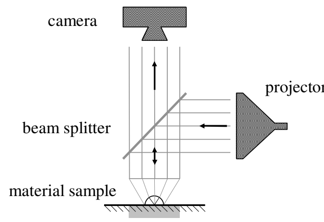


gonioreflectometer

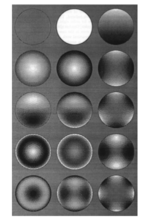


Remote Sensing – BRDF Measurements

- BRDF measurement with basis function illumination
- principle: project basis illumination and simultaneously measure response

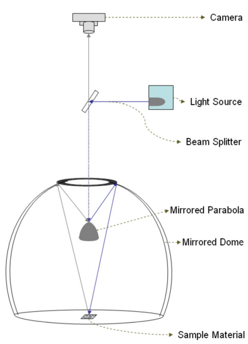


example basis functions [Koenderink96]



Remote Sensing – BRDF Measurements

- Measurement Apparatus [Ghosh07]
- mirrored dome and parabola allow for simultaneous projection of basis illumination and recording of the response
- basis function coefficients are directly measured
- type of basis functions: spherical harmonics [Cabral87, Kautz02]



Remote Sensing – BRDF Measurements

- approximate BRDF by linear combination of (orthonormal) basis functions

$$\hat{f}_r(\omega_i,\omega_r) = f_r(\omega_i,\omega_r)\cos\theta_i \approx \sum_k Z_k(\omega_i) z_k(\omega_r),$$

- insert into reflectance calculation

$$\begin{aligned} L_r(\omega_r) &= \int_{\mathbf{Z}} f_r(\omega_i,\omega_r) L_i(\omega_i)\cos\theta_i \, d\omega_i \\ &= \int_{\mathbf{Z}} \left(\sum_k Z_k(\omega_i) z_k(\omega_r)\right) L_i(\omega_i)\, d\omega_i \\ &= \sum_k z_k(\omega_r) \int_{\mathbf{Z}} Z_k(\omega_i) L_i(\omega_i)\, d\omega_i. \end{aligned}$$

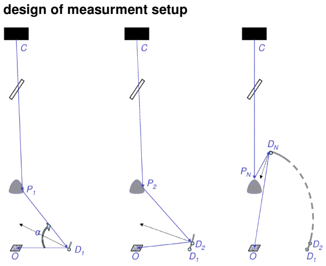
→ coefficients are given by

$$z_k(\omega_r) = \int_{\mathbf{Z}} Z_k(\omega_i) f_r(\omega_i,\omega_r)\cos\theta_i \, d\omega_i.$$

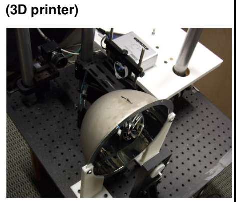
Remote Sensing – BRDF Measurements

- design of the dome
- fix camera and parabola
- ray-trace to determine dome and hole geometry

design of measurment setup



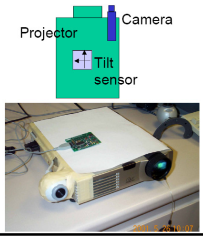
physical realization using rapid prototyping equipment (3D printer)



Display Technologies

Display Technologies – Single Camera – Projector Systems

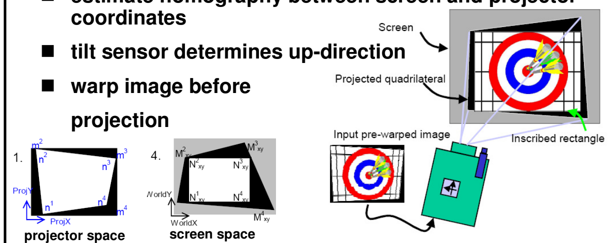
- single camera – projector systems
- applications
  - keystone – removal
  - projection onto curved or arbitrarily shaped surfaces
  - human-computer interaction



[Raskar01]

Display Technologies – Single Camera – Projector Systems

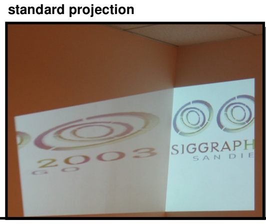
- automatic key-stone correction [Raskar01]
- calibrate projector – camera pair (similar to stereo camera calibration)
- estimate homography between screen and projector coordinates
- tilt sensor determines up-direction
- warp image before projection



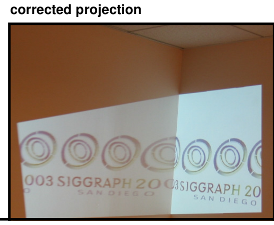
Display Technologies – Single Camera – Projector Systems

- projection onto multiple planar surfaces [Raskar03]
- use structured light to determine scene geometry
- compute conformal mapping (i.e. a mapping that keeps angular distortions and non-uniform scaling minimal between 2D image coordinates and 3D world coordinates)
- project pre-warped image

standard projection

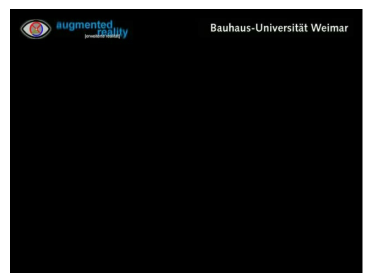


corrected projection



Display Technologies – Single Camera – Projector Systems

- projection onto arbitrary surfaces [Zollmann06]
- rectified from "sweet spot" where the camera is located

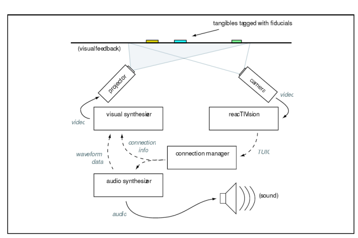


Display Technologies – Single Camera – Projector Systems

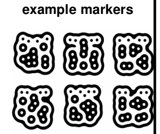
- Human-Computer Interaction
- example: ReacTable, tangible synthesizer [Jordà05]
- <movie>

Display Technologies – Single Camera – Projector Systems

- markers are placed on semi-transparent screen
- detection by camera
- projector augments interface

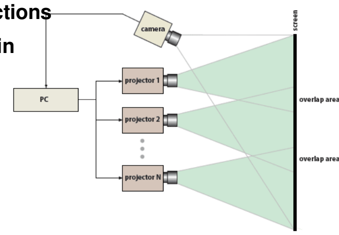


example markers



Display Technologies – Multi-Projector Systems

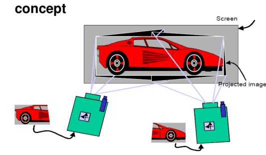
- use multiple projectors and one or more cameras
- applications
  - large, high resolution displays
  - panorama displays
  - very bright projections
  - shadow removal in front-projection systems

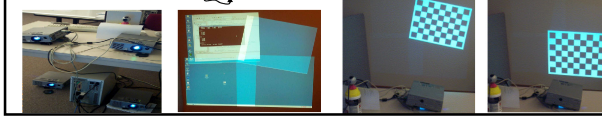


Display Technologies – Multi-Projector Systems

- high resolution
- project in partially overlapping regions to form a larger region of projection
  - geometric calibration
  - project checkerboards to compute projector pixel – screen correspondences
  - determine largest rectangle fitting into the projected area
  - split and pre-warp images before projection

concept

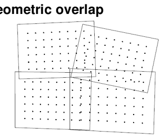




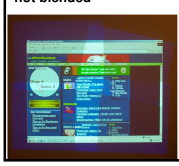
Display Technologies – Multi-Projector Systems

- blending in overlapping regions necessary
- compute geometric overlap in screen space
- blend linearly between projectors
- more accurately determine spatially varying brightness response of the projectors

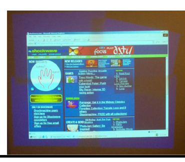
geometric overlap

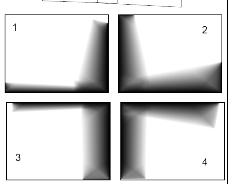


not blended



blended





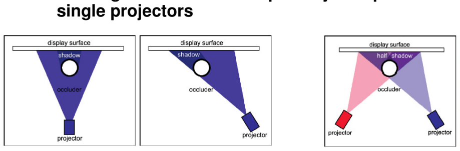
blending weights (alpha channel)

Display Technologies – Multi-Projector Systems

- examples for planar and curved screens

Display Technologies – Multi-Projector Systems

- shadow removal
- projectors form completely overlapping image
- multiple projectors at reduced intensity
- use intensity headroom for compensating shadows
- use camera to compare predicted view to the one actually projected
- use negative feedback loop to adjust alpha mattes of the single projectors



Display Technologies – Multi-Projector Systems

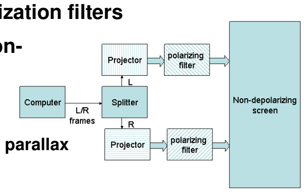
Display Technologies – 3D Displays

- Overview:
  - polarization based displays
    - static 3D view – no parallax
    - high resolution
  - integral photography
    - horizontal and vertical parallax
    - low resolution
  - 3D-TV [Matusik04]
    - based on lenticular lenses
    - horizontal parallax only
  - Autostereoscopic Light Field Display [Jones07]
    - 360 degree display system
    - opaque surfaces
    - horizontal parallax (vertical with head tracking)
  - holographic displays
  - combination of holographic and auto-stereoscopic displays

Computational Photography Hendrik Lensch, Summer 2007

Display Technologies – 3D Displays

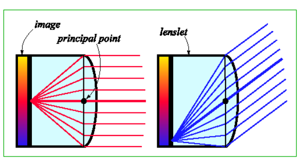
- polarization based projection displays
- require
  - 2 projectors with polarization filters
  - glasses with polarization filters
  - special, polarization-preserving screen
  - no parallax
    - with head tracking parallax is possible
    - but only for one user

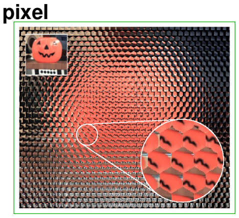


Computational Photography Hendrik Lensch, Summer 2007

Display Technologies – 3D Displays

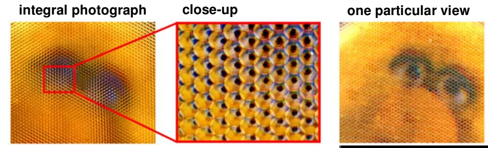
- integral photography, e. g. [Okano98]
- micro lens-array in front of screen
- screen at focal distance of micro lenses
  - → parallel rays for each pixel
  - → every eye sees a different pixel





Computational Photography Hendrik Lensch, Summer 2007

Display Technologies – 3D Displays

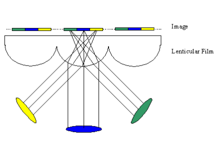


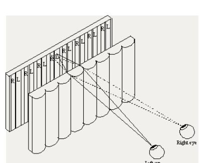
- need high resolution images
- taken with micro lens array
- arrays of graded index (GRIN) lenses
- screen is auto-stereoscopic
  - → no glasses, multiple users

Computational Photography

Display Technologies – 3D Displays

- 3D-TV system [Matusik04]
- uses lenticular lenses in a multi-projector system
- same principle as in integral photography, but only in one dimension (cylindrical lenses)





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Display Technologies – 3D Displays

- for 3D video, need a high resolution screen
- multiple projectors increase resolution
- two possibilities
  - rear-projection system
  - front-projection system

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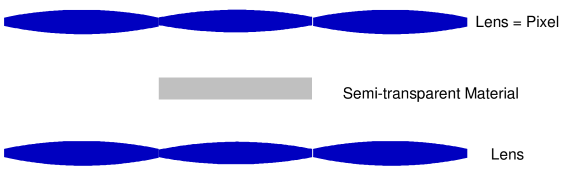
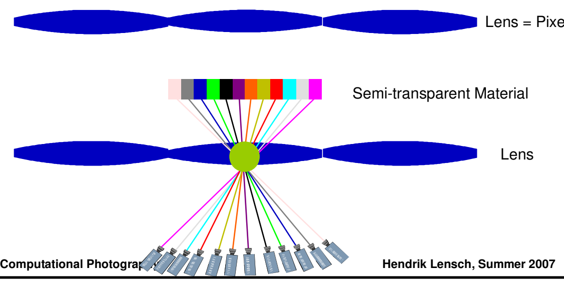
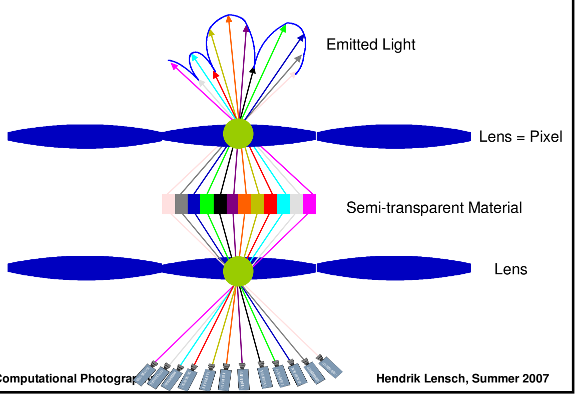
Rear Projection Design



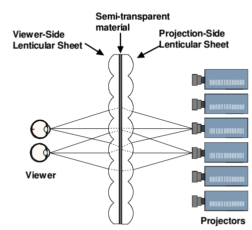
Rear Projection Design



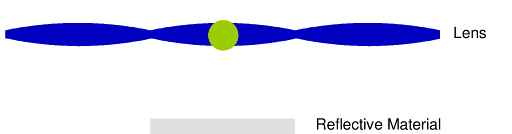
Rear Projection Design



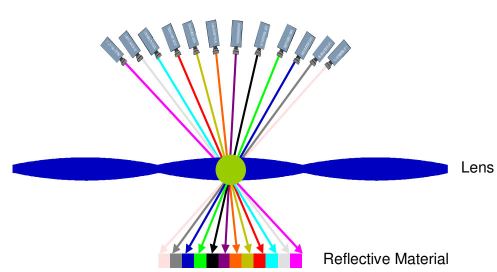
Realized Rear Projection Display



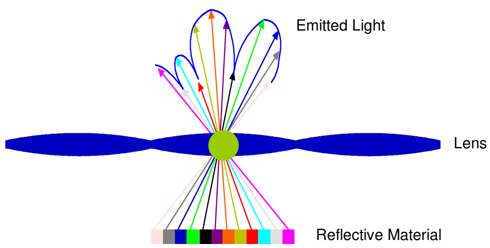
Front Projection Design



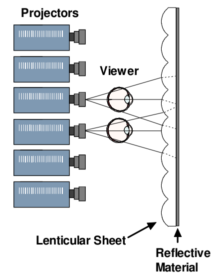
Front Projection Design

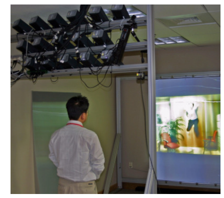


Front Projection Design



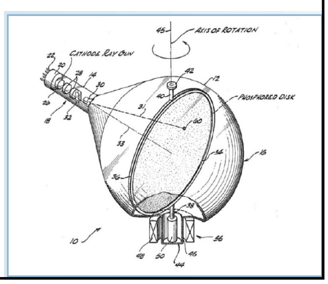
Realized Front Projection Display





Display Technologies – 3D Displays

- rotating diffusers [Ketchpel64]
- cathode ray illuminates quickly rotating phosphor screen
- voxels can be adressed individually
- volumetric display is transparent (no opaque surfaces)



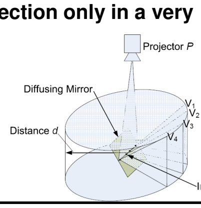
Display Technologies – 3D Displays

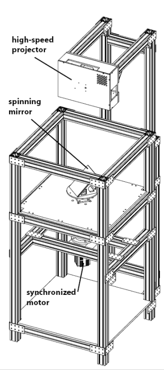
- modern version - Autostereoscopic Light Field Display [Jones07]
- enables
  - opaque surfaces
  - horizontal parallax built-in
  - vertical parallax with head-tracking
  - multiple users possible
  - auto-stereoscopic
  - display of dynamic light fields in 3D

Display Technologies – 3D Displays

principle of operation

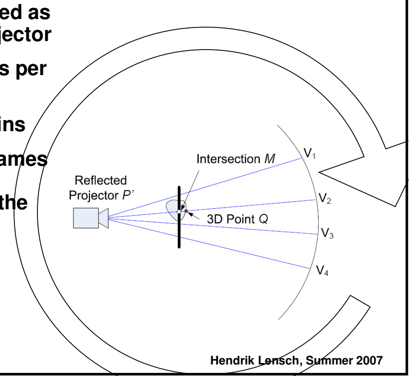
- rotating front surface mirror with anisotropic diffusion filter on top
- diffuses light in vertical direction perfectly
- in horizontal direction only in a very limited angle





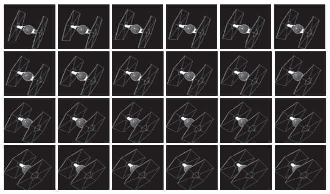
Display Technologies – 3D Displays

- can be regarded as a rotating projector
- ~17 3D frames per second
- 288 angular bins
- need ~5000 frames per second rendering for the projector



Display Technologies – 3D Displays

- render only binary images (dithered)
- specially encoded DVI signal (every bit is a pixel instead of RGB value → 24 pixels per normal color pixel)
- 200 Hz refresh rate (GeForce 8800) = 4800 fps
- special decoder chip necessary



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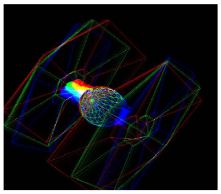
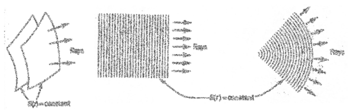


Display Technologies – 3D Displays

- holographic displays
- wave optics background

wave fronts always normal to rays

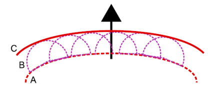
have phase and amplitude



Huygens principle:

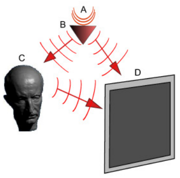
any wavefront can be described as a superposition of spherical waves centered on a previous wavefront

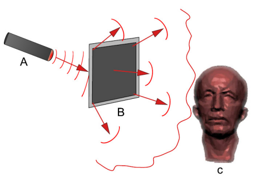
diffraction generates spherical waves behind narrow slit



Display Technologies – 3D Displays

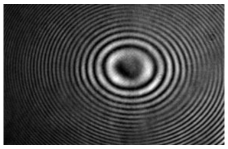
- principle of holographic imaging
- interference between reference wave D and object wave from C is recorded on film
- reconstruction by diffraction at the film plane
- reconstructs object wave – all parallax and view dependent effects are preserved





Display Technologies – 3D Displays

- interference pattern of a point light source with a reference wave

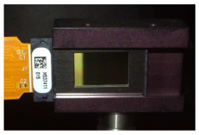


- in film: bright areas are transparent, dark areas block light
- very fine holes cause diffraction
- when illuminated with the reference wave, the object wave is reconstructed

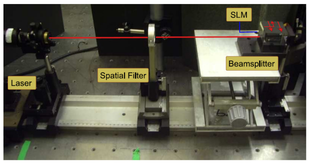
Display Technologies – 3D Displays

- digital replacement for film is Spatial Light Modulator (SLM)
- high resolution LCD
- can be used to display dynamic diffraction gratings

SLM



holographic display



Display Technologies – 3D Displays

- Rendering for holographic displays [Ahrenberg06]
- GPU-based superposition of spherical waves in the virtual film plane
- object consists of points
- no occlusion
- <movies>

Display Technologies – 3D Displays

- combined holograms and auto-stereoscopic displays

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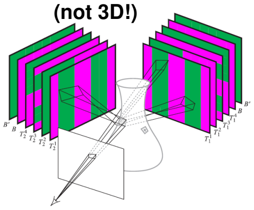
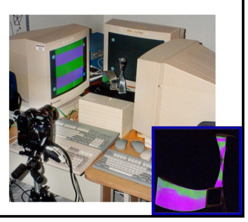
Remote Sensing – Image-Based Object Representations

- environment matting [Zongker99]
- capture pixel – exitant ray mapping
- use with environment look-up to place objects into new environments
- 2D structured light scanning from several directions (not 3D!)





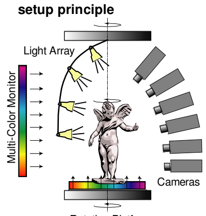
Remote Sensing – Image-Based Object Representations

- Movies

Remote Sensing – Image-Based Object Representations

- Opacity Hulls [Matusik02a,Matusik02b]
- Geometry Assisted Environment Matting
- acquire coarse geometry (visual hull) + view dependent alpha and environment mattes

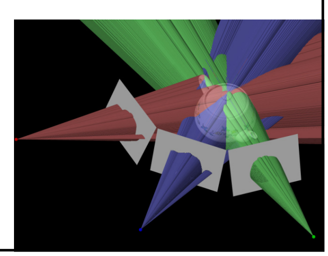
setup principle



setup realization

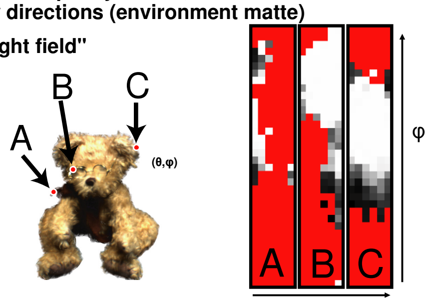
Remote Sensing – Image-Based Object Representations

- geometry acquisition: visual hull
- conservative approximation of true surface shape (real object is contained in visual hull)
- back-project object silhouettes and intersect in space (CSG)



Remote Sensing – Image-Based Object Representations

- per surface point on coarse geometry, assign a hemisphere of opacity values, radiance values and exitant ray directions (environment matte)
- "surface light field"



Remote Sensing – Image-Based Object Representations

- Movies

Image-Based Relighting

- use images taken under different lighting conditions

ambient light

light from top

- recombine (add) RGB - modulated versions of the images
- superposition principle

light from left

light from right