Camera Models

CS635 Spring 2010

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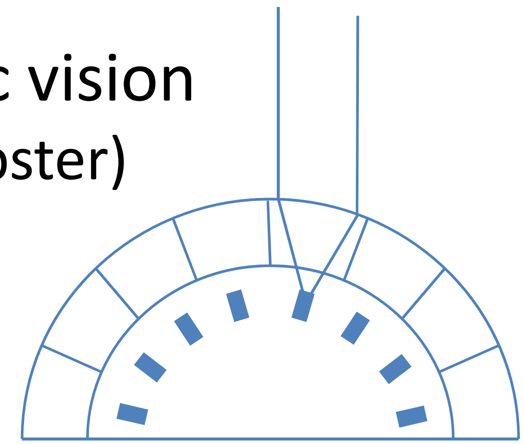
Camera Models

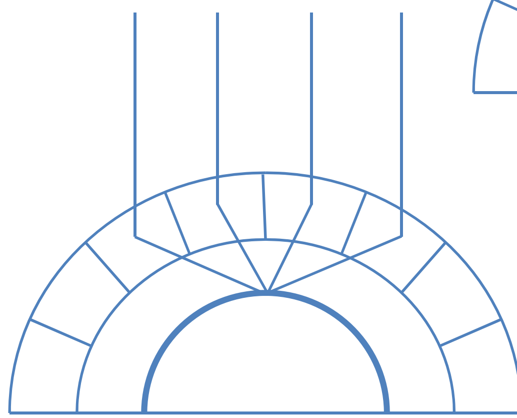
- **Biology 101**
- Pinhole Camera Models
- Non-Pinhole Camera Models
- Omnidirectional Camera Models
- Typical Camera Model

Biology 101

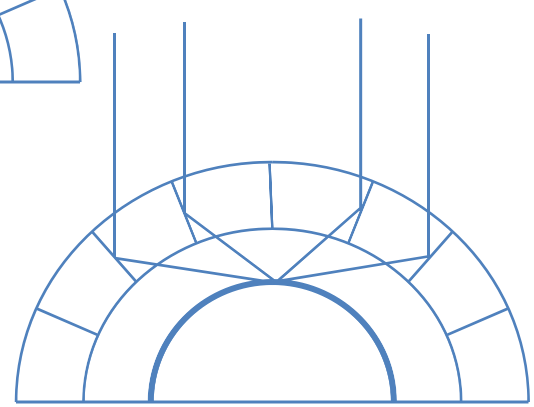
- Some animals are capable of panoramic vision
  - e.g., certain insects, crustaceans (e.g., lobster)
- Diurnal Insect Vision



- Nocturnal Insect Vision



- Crustacean Vision



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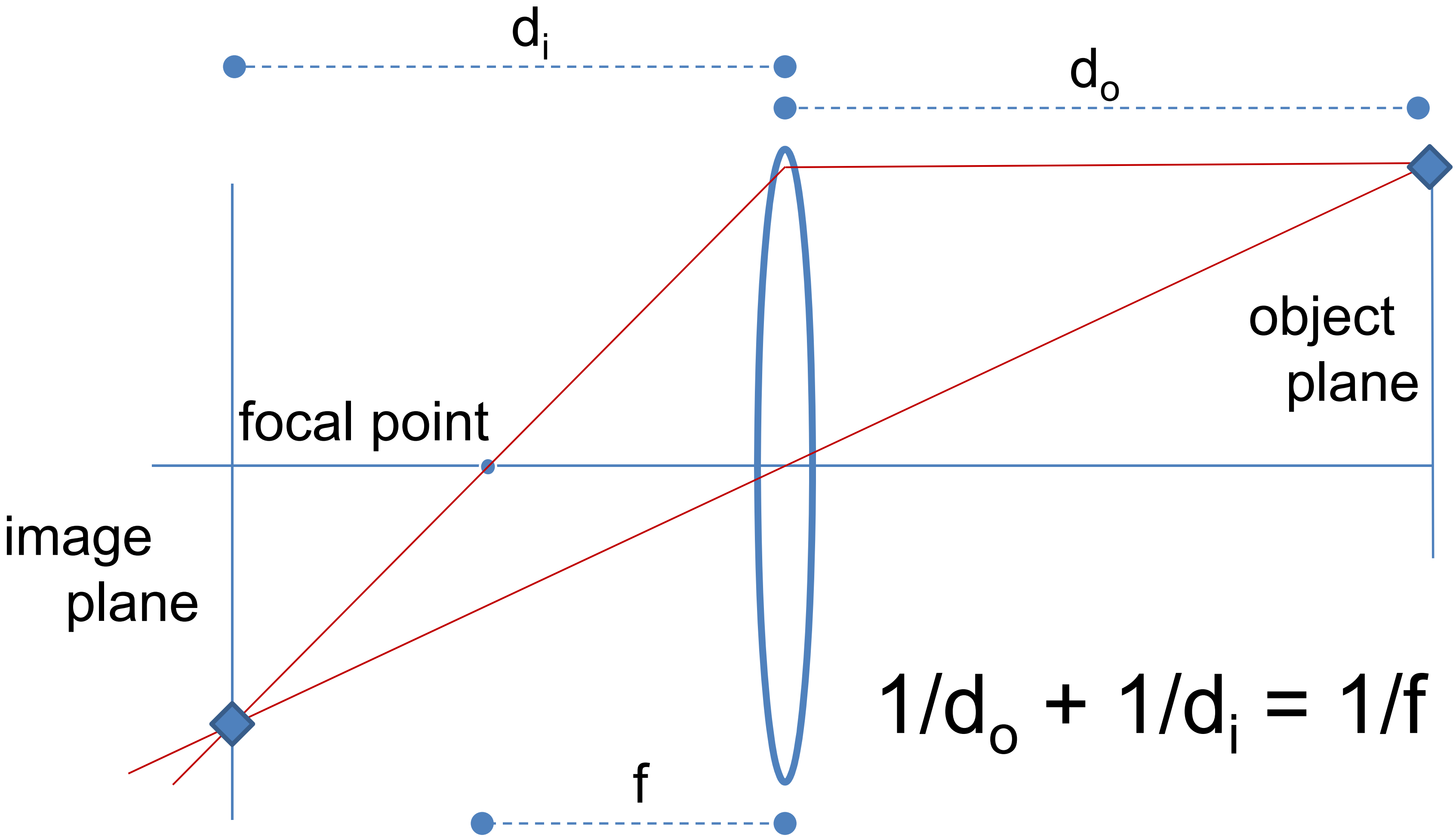
Optics: Terminology

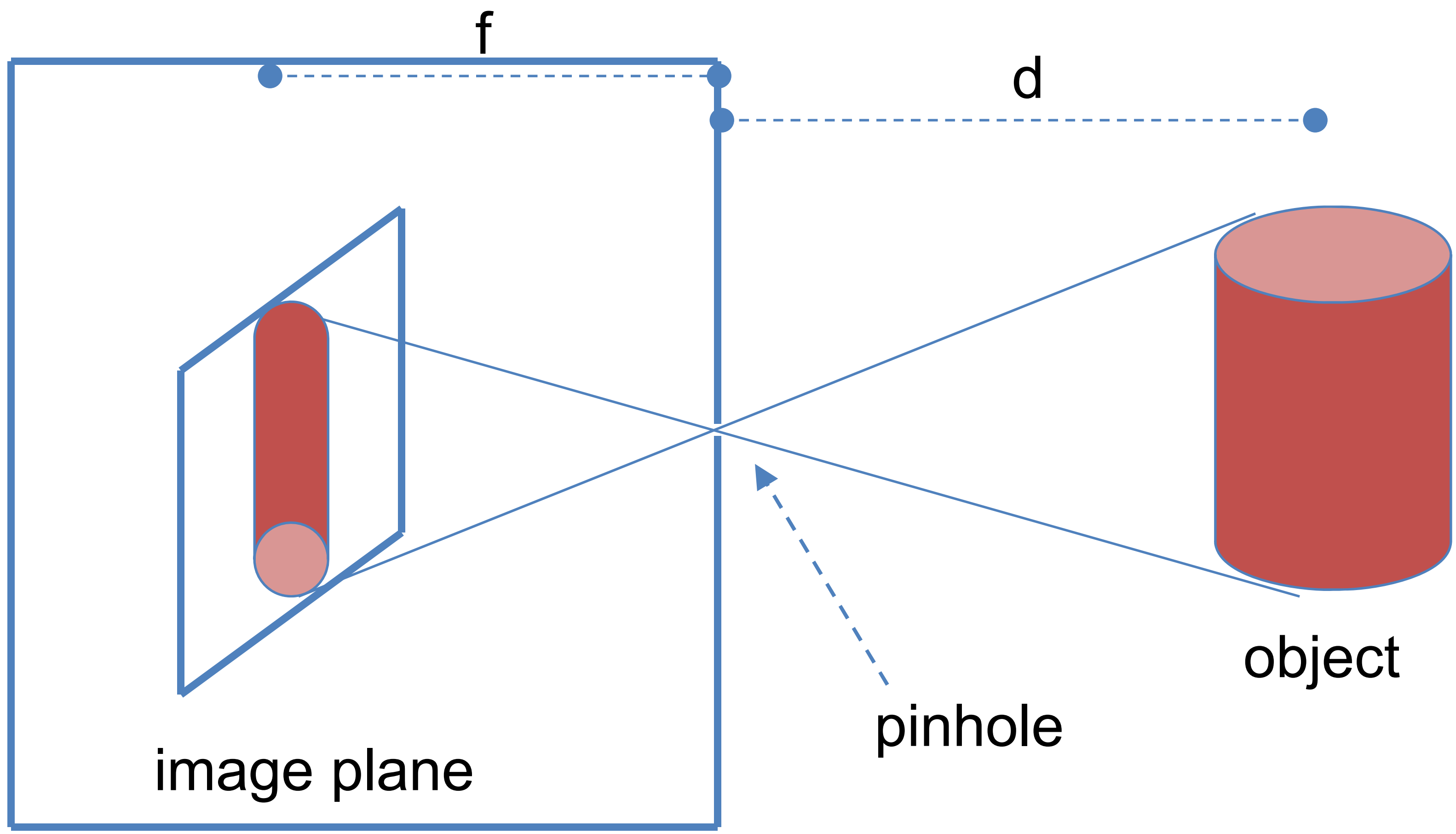
- Dioptric
  - All elements are refractive (lenses)
- Catoptric
  - All elements are reflective (mirrors)
- Catadioptric
  - Elements are refractive and reflective (mirrors + lenses)

Thin Lens Equation

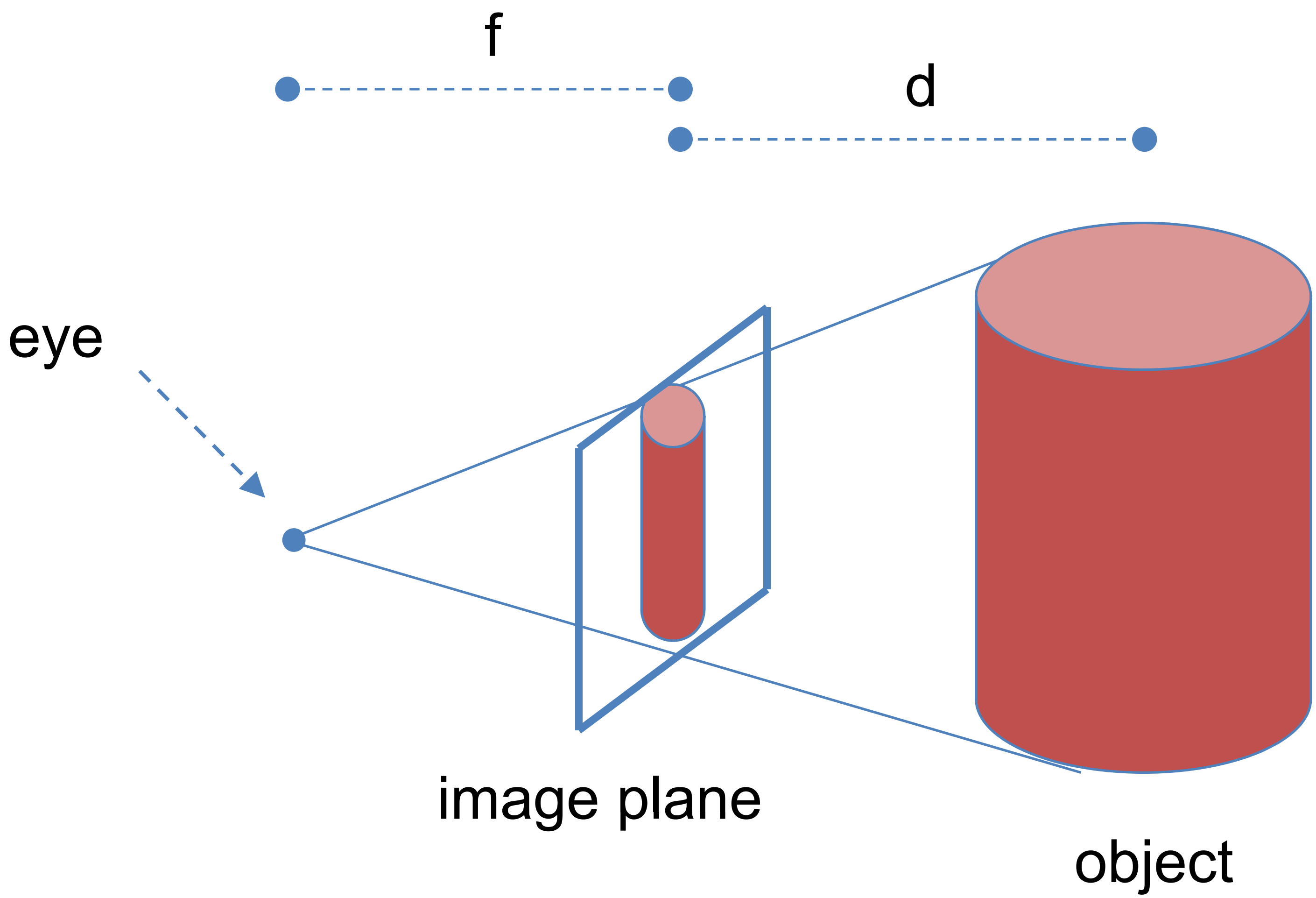


$$1/d_o + 1/d_i = 1/f$$

“Classic” Pinhole Camera



“Computer Graphics” Pinhole Camera



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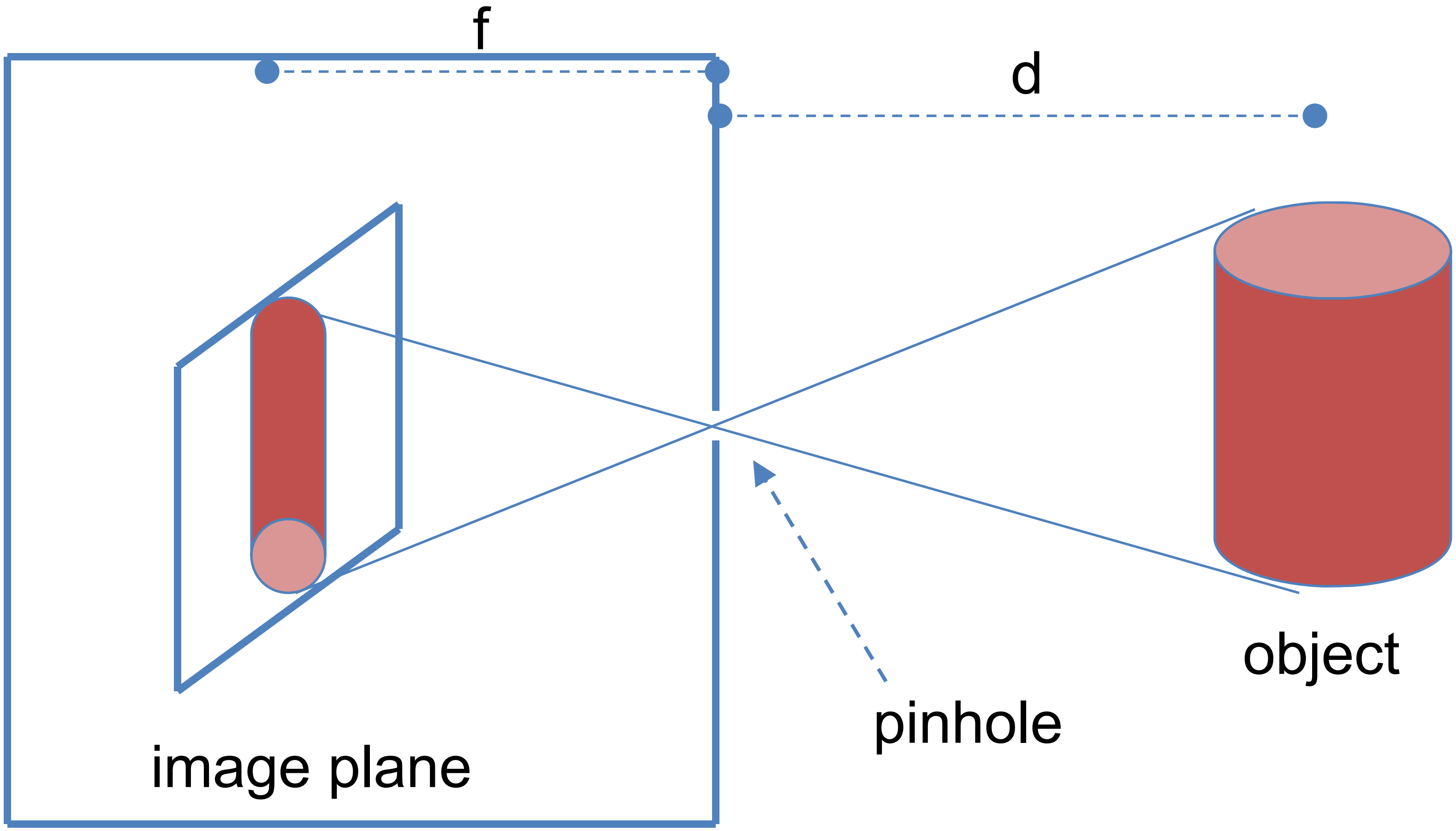
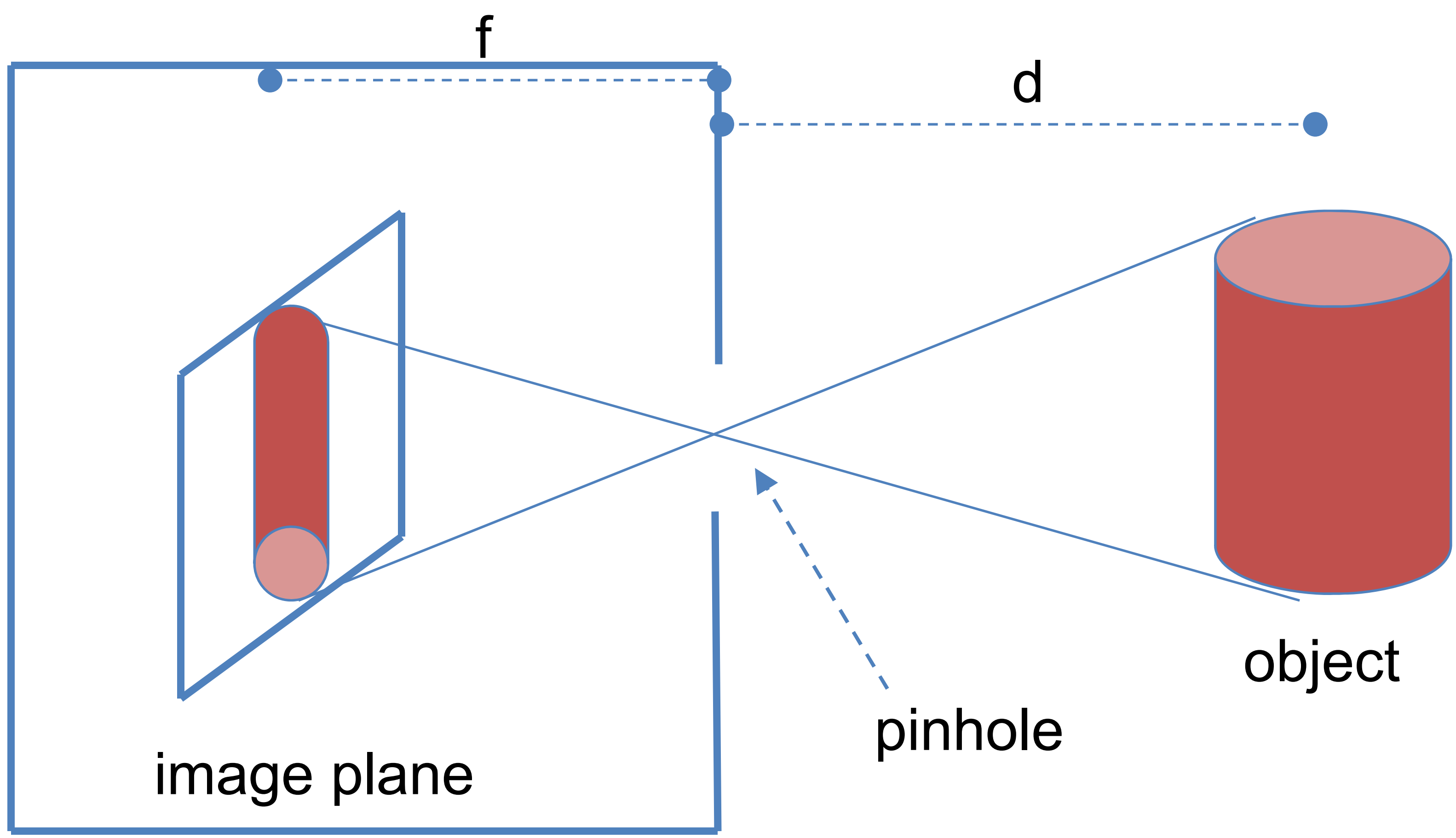
Non-Pinhole Camera Models

- Why restrict the camera to a pinhole camera model?
  - Aperture is large: lightfields/lumigraphs
  - Multi-perspective imaging
  - Sample-based camera
  - Tailored camera designs
    - Occlusion-resistant cameras (kinda…)
    - Graph cameras
    - and more!

Large Aperture Cameras



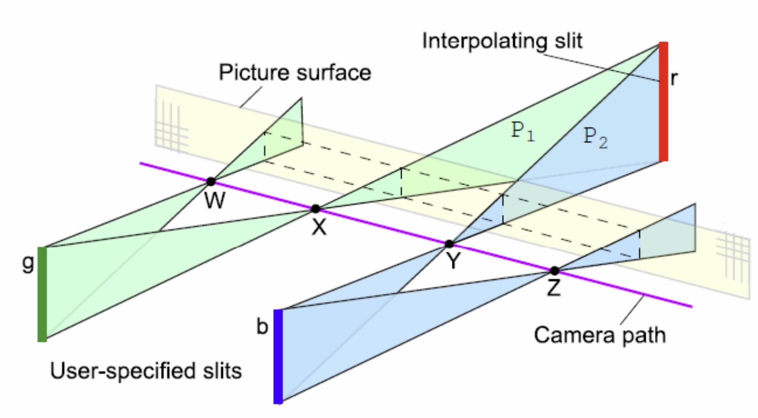
Large Aperture Cameras



Is this bad? Is this terrible? Is this bug a feature? More later…

Multiperspective Imaging

Hand-crafted

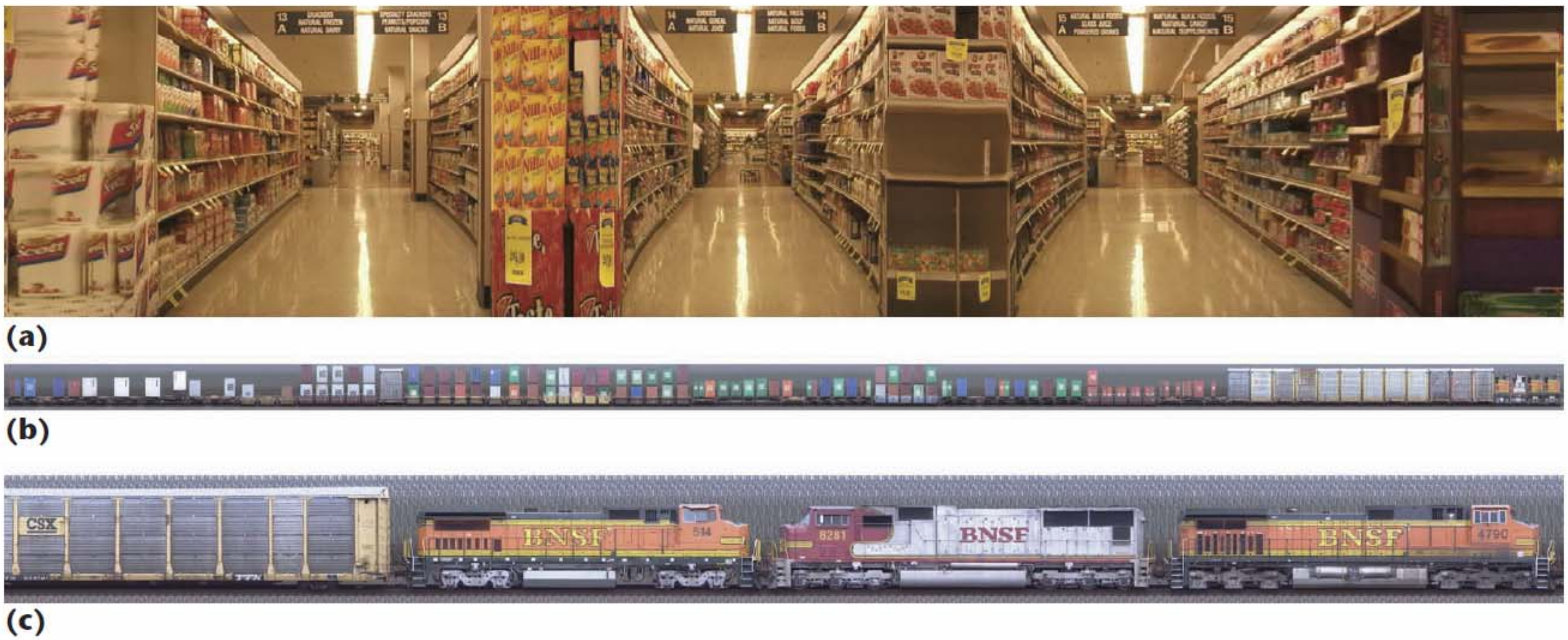


semi-automated…

to produce this…

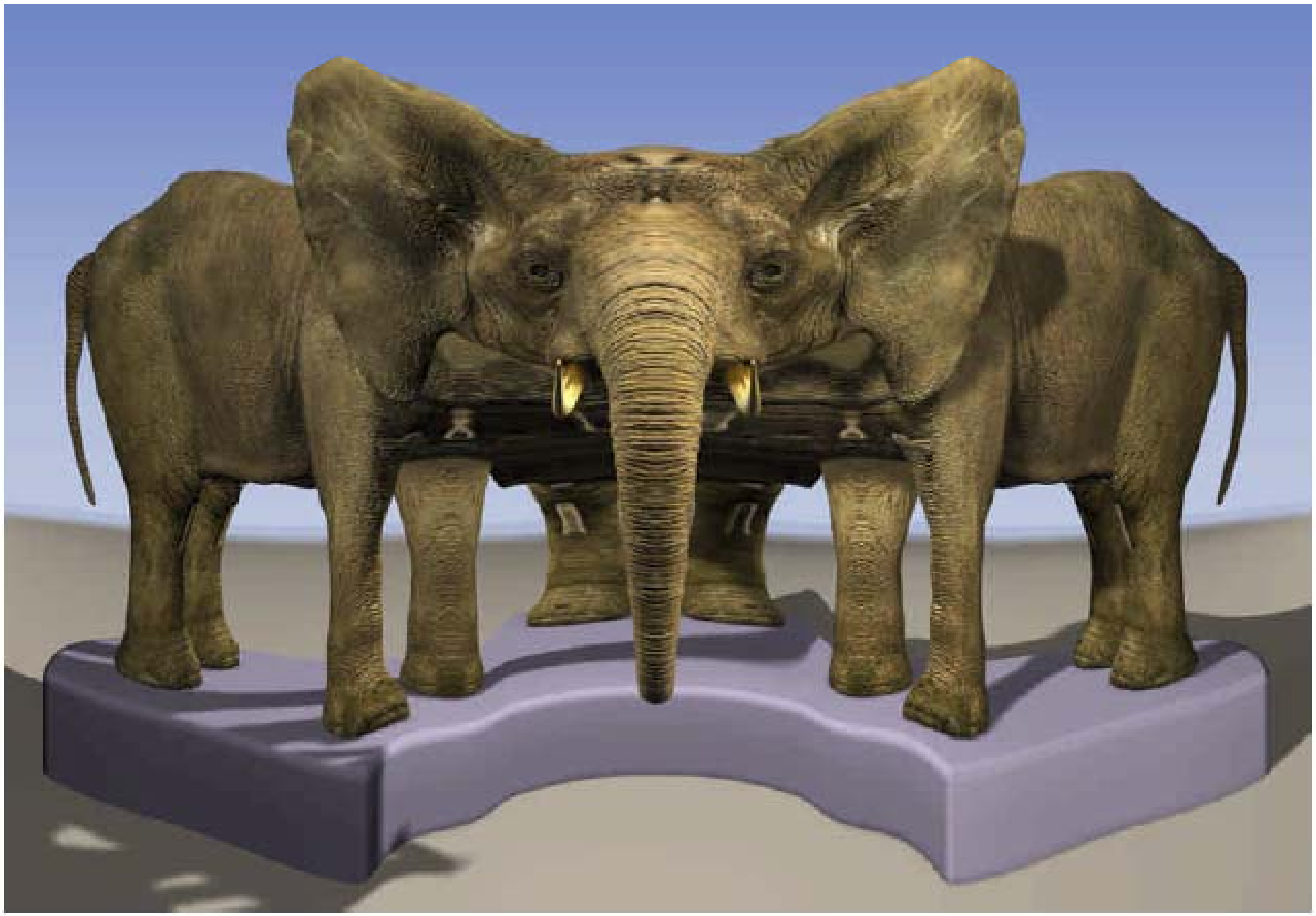
[Roman-Vis04]

Multiperspective Imaging



[Seitz-CGA03]

Multiple COP Images



[Rademacher-SIG98]

Multiple COP Images

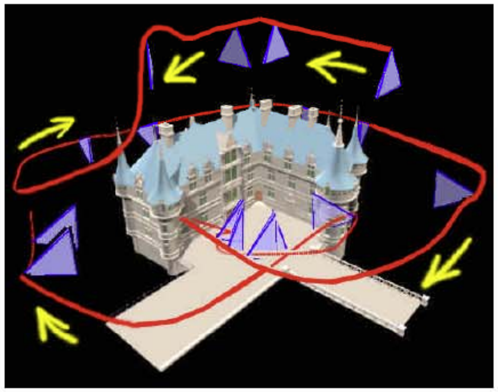


Figure 5 Castle model. The red curve is the path the camera was swept on, and the arrows indicate the direction of motion. The blue triangles are the thin frusta of each camera. Every 64th camera is shown.

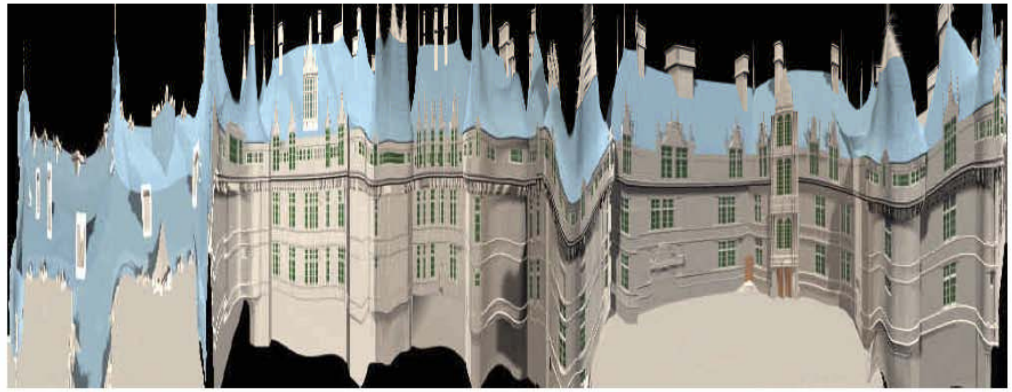


Figure 6 The resulting 1000×500 MCOP image. The first fourth of the image, on the left side, is from the camera sweeping over the roof. Note how the courtyard was sampled more finely, for added resolution.

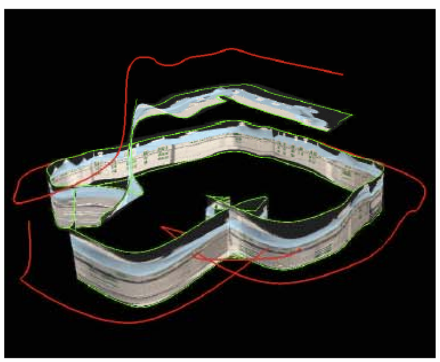


Figure 7 The projection surface (image plane) of the camera curve.

Figure 8 Three views of the castle, reconstructed solely from the single MCOP image above. This dataset captures the complete exterior of the castle.

[Rademacher-SIG98]

Multiperspective Imaging for Cel Animation

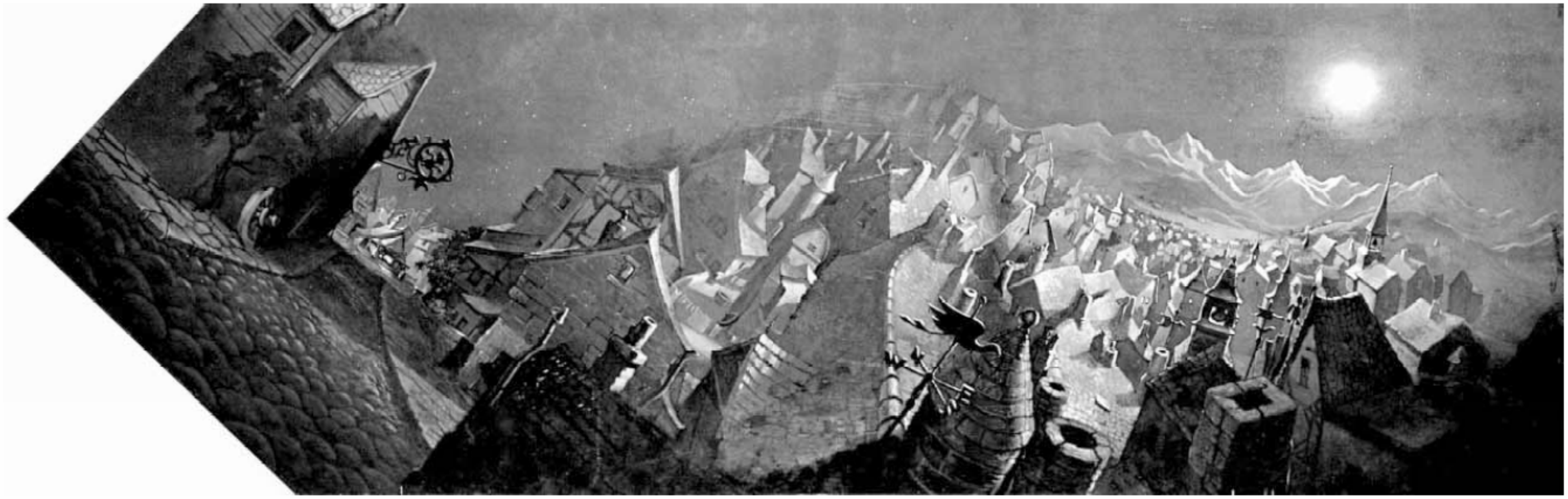
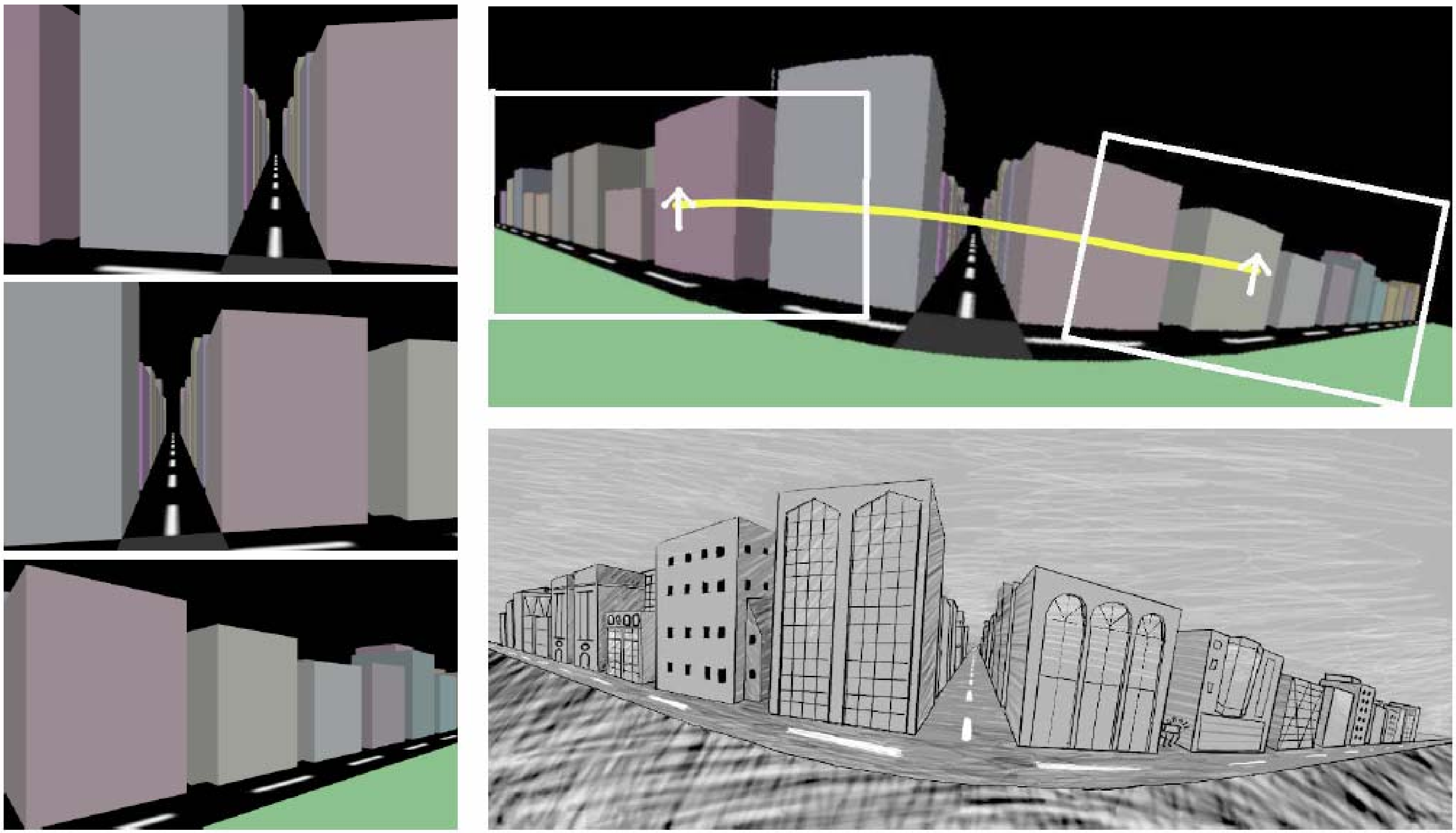


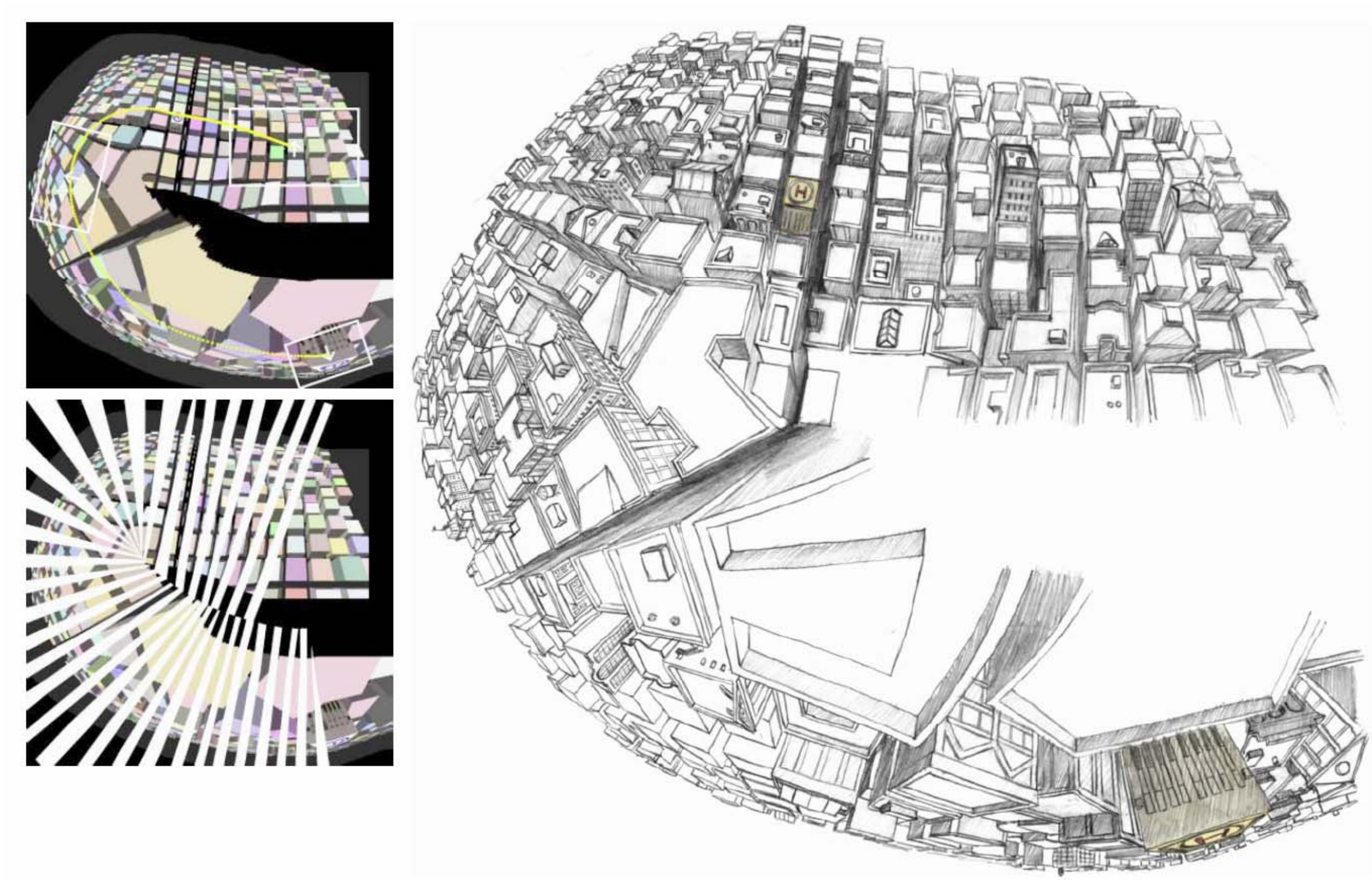
Figure 1 A multiperspective panorama from Disney's 1940 film *Pinocchio*. (Used with permission.)

Multiperspective Imaging for Cel Animation



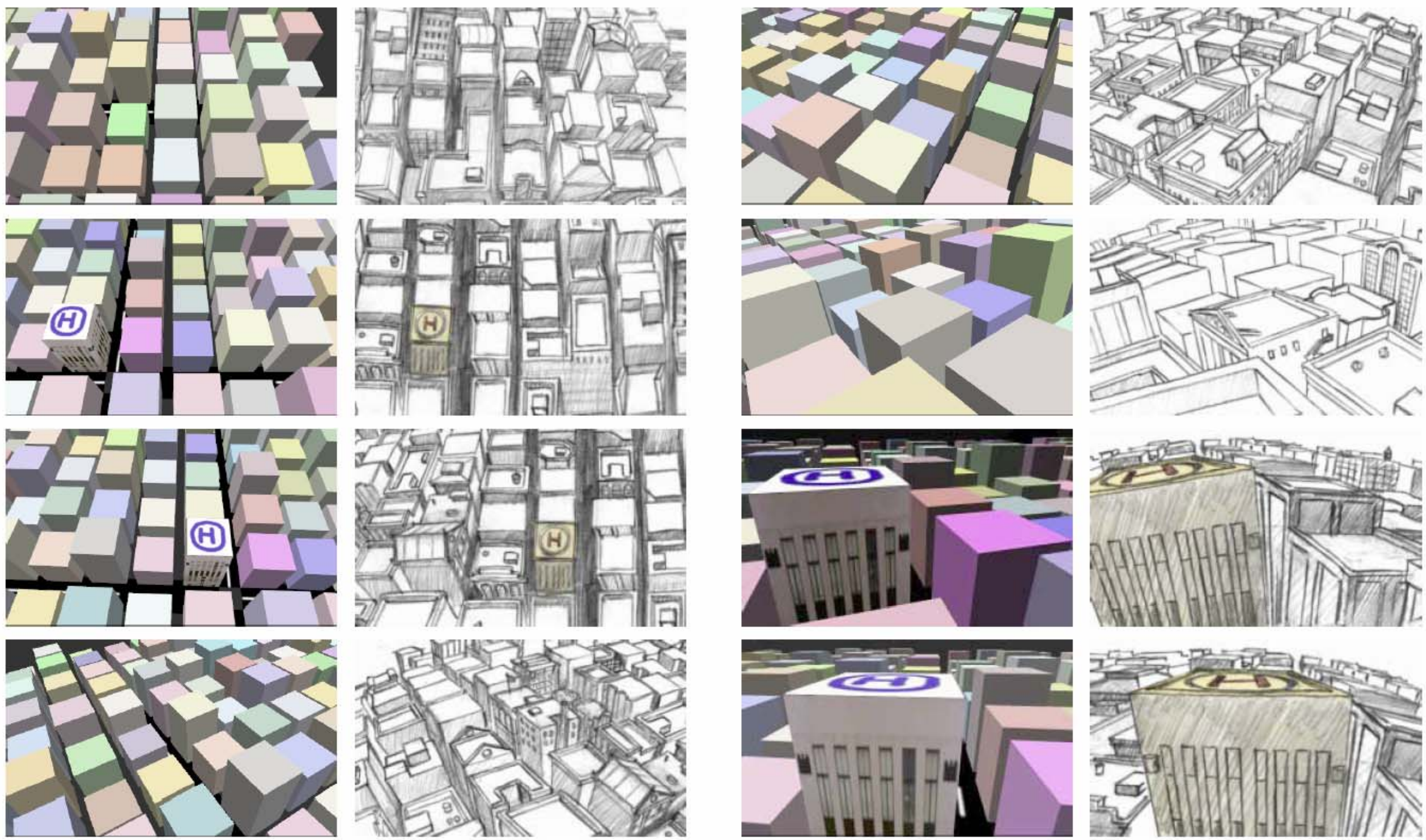
[Wood-SIG97]

Multiperspective Imaging for Cel Animation



[Wood-SIG97]

Multiperspective Imaging for Cel Animation



[Wood-SIG97]

General Linear Camera

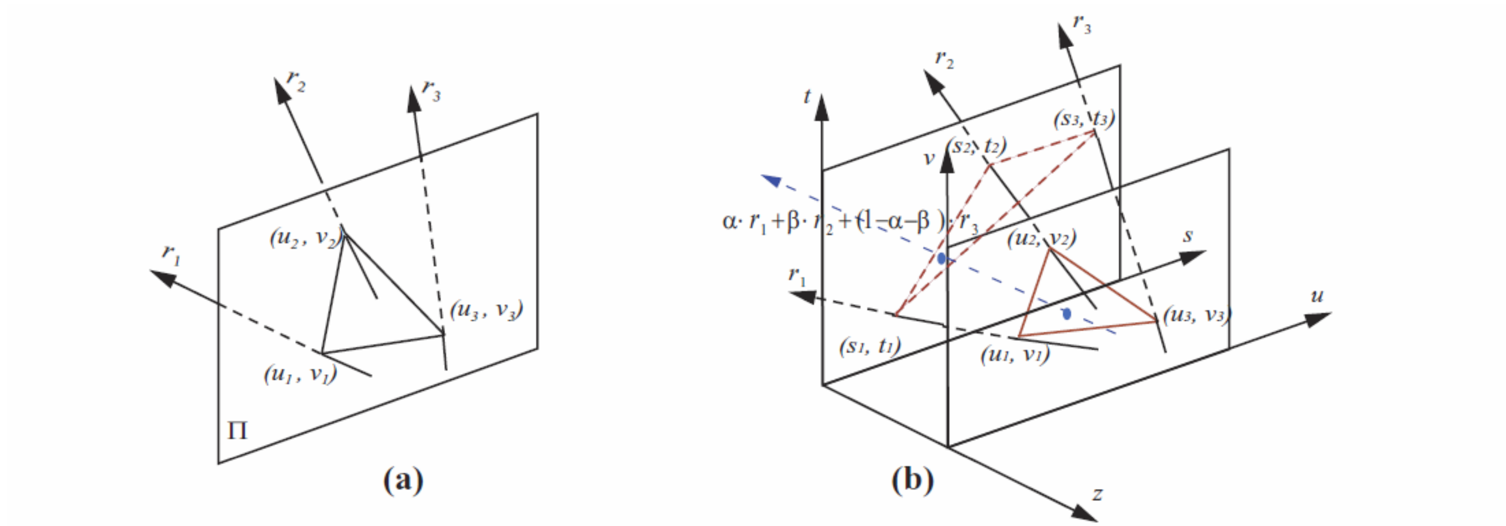


Fig. 1. General Linear Camera Model. a)A GLC is characterized by three rays originated from the image plane. b)It collects all possible affine combination of three rays.

[Yu-ECCV04]

General Linear Camera

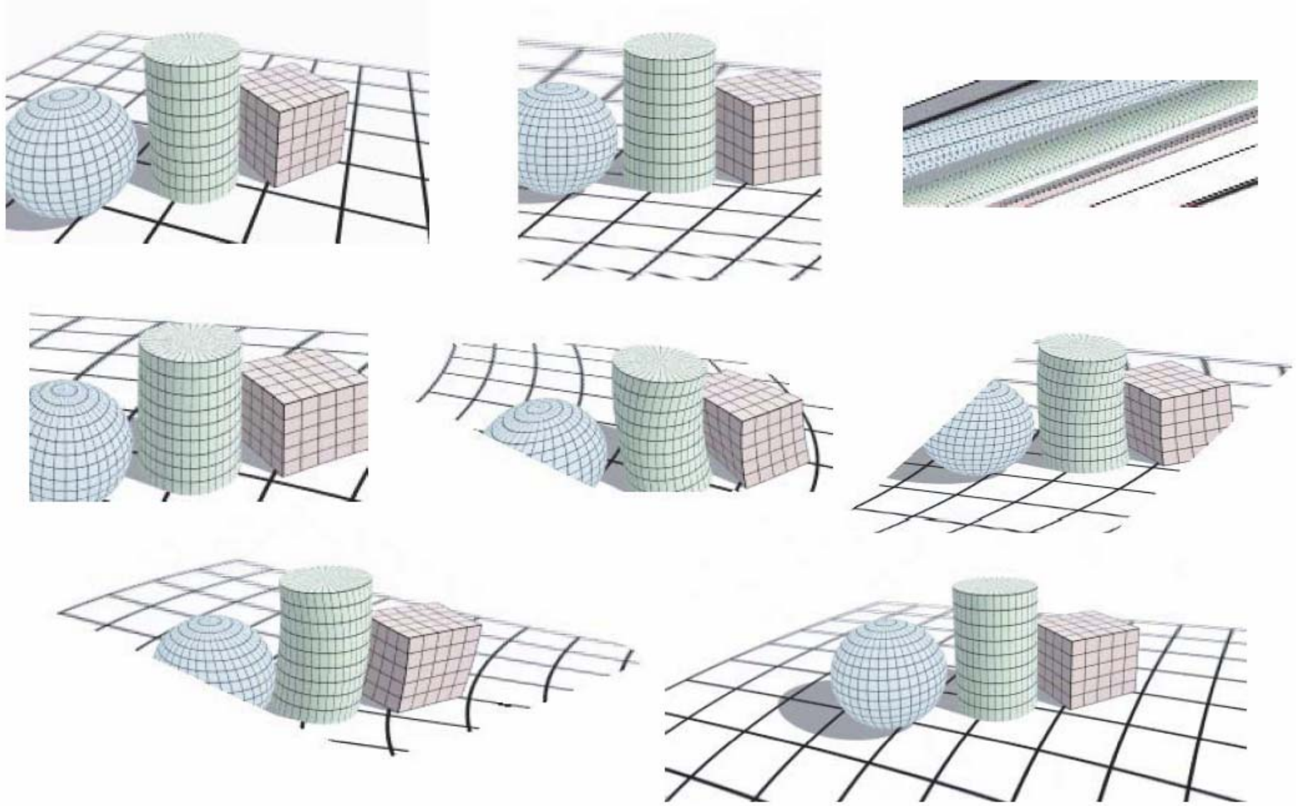


Fig. 5. Comparison between synthetic GLC images. From left to right, top row: a pinhole, an orthographic and an EPI; middle row: a pushbroom, a pencil and an twisted orthographic; bottom row: a bilinear and an XSlit.

[Yu-ECCV04]

General Linear Camera

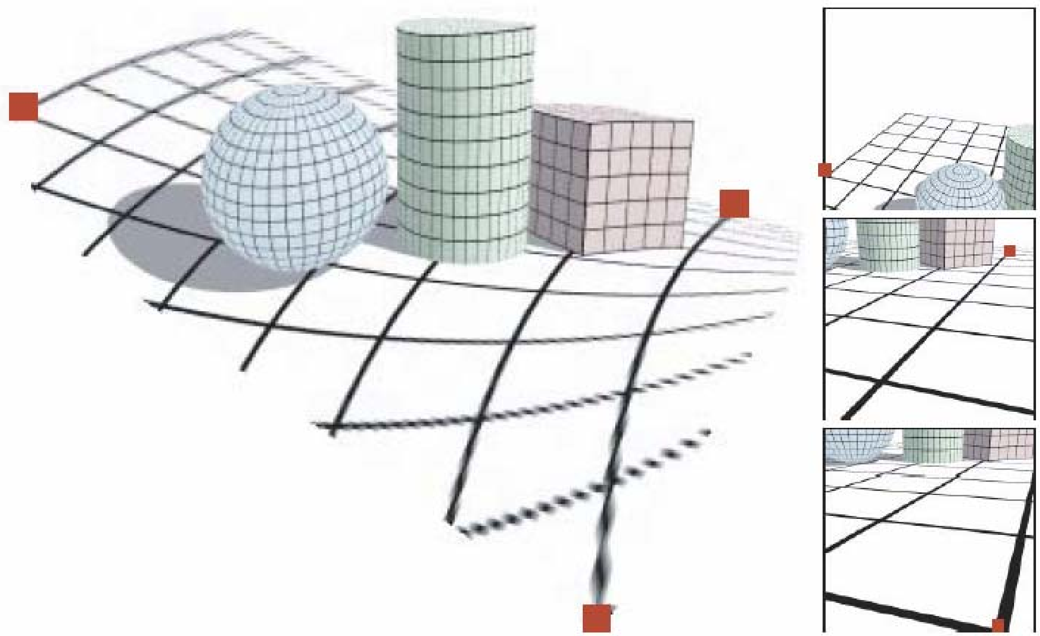
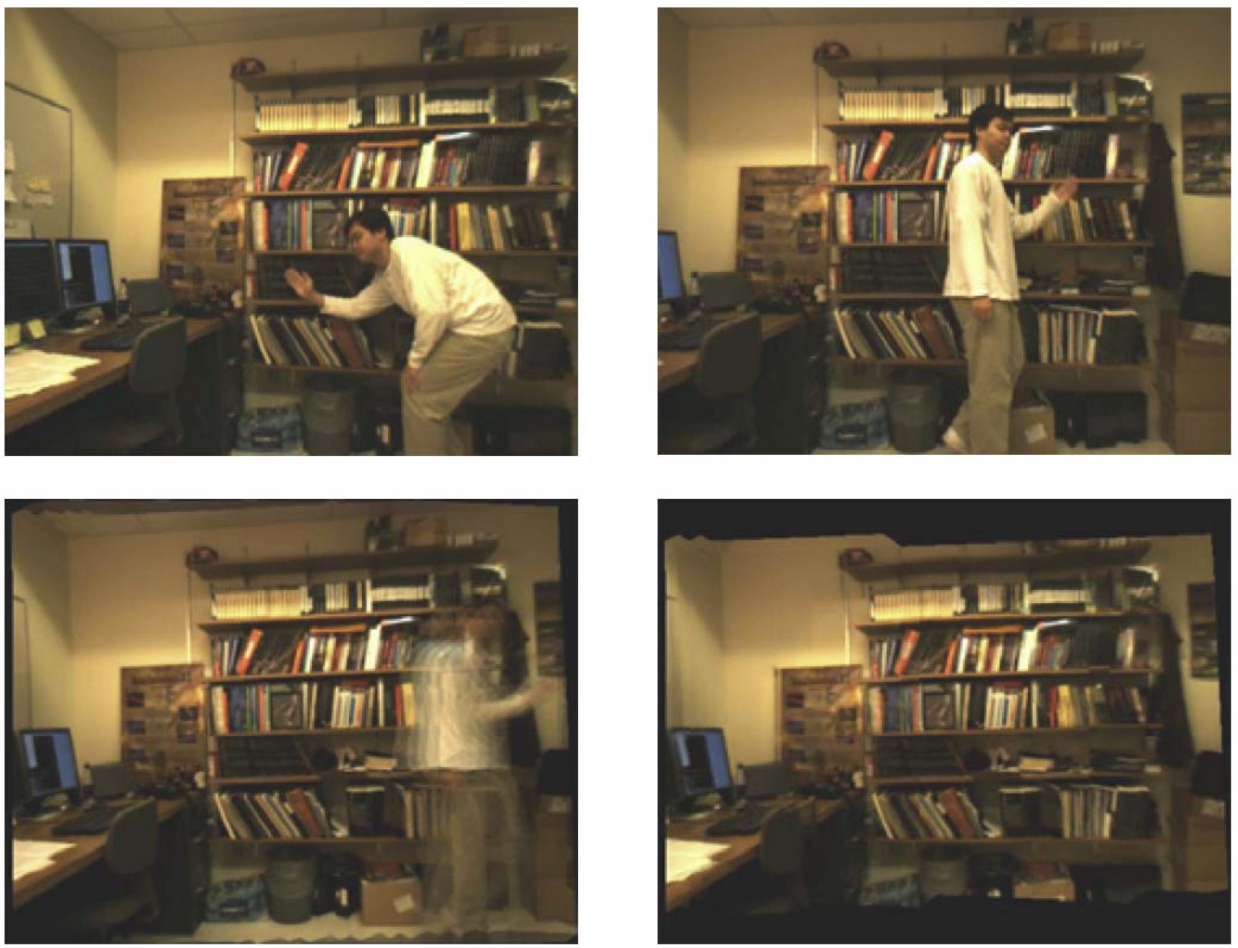


Fig. 7. A multiperspective bilinear GLC image synthesized from three pinhole cameras shown on the right. The generator rays are highlighted in red.

[Yu-ECCV04]

Occlusion-Resistant Cameras

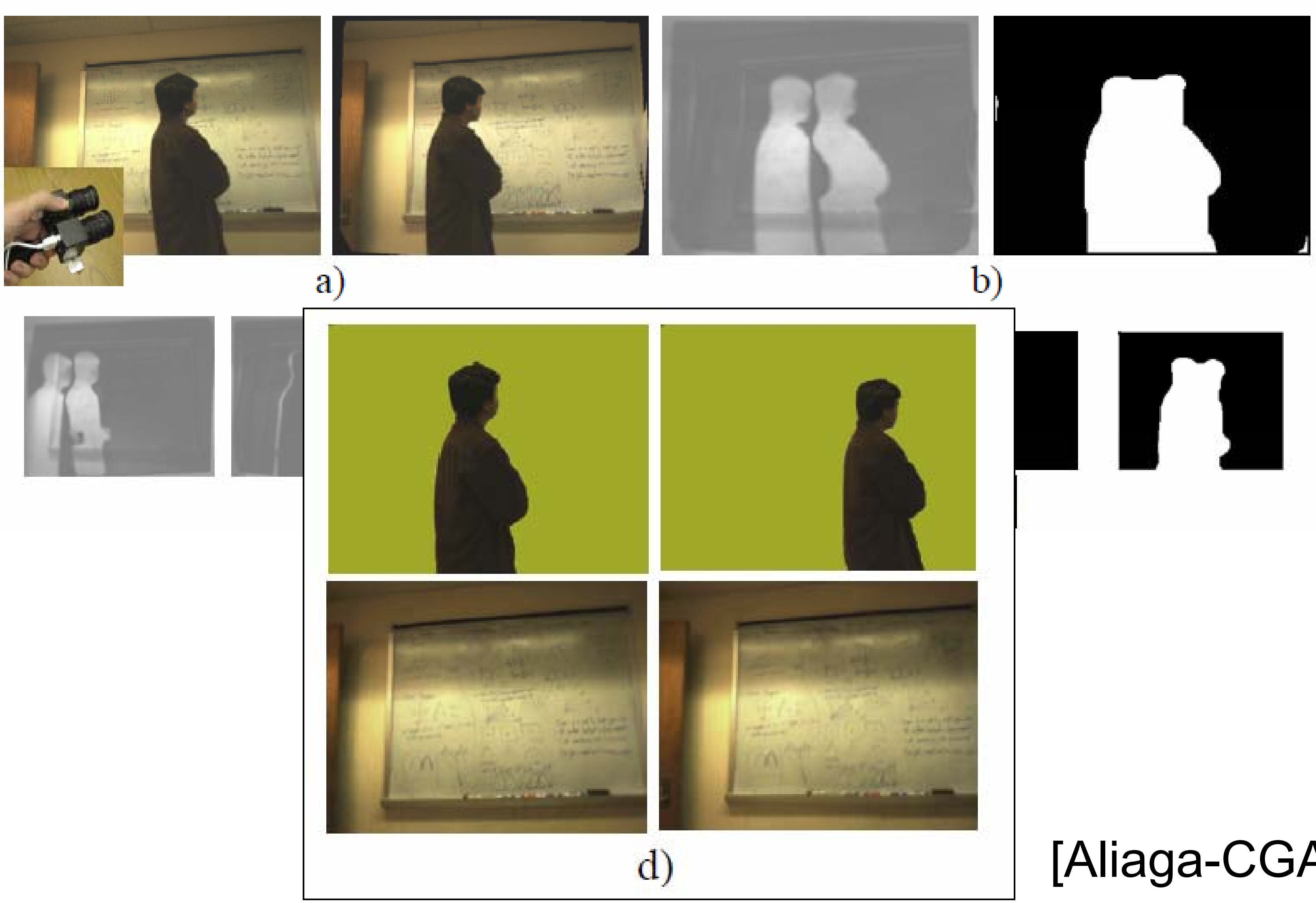


Input images

Output images

[Aliaga-CGA07]

Occlusion-Resistant Cameras



[Aliaga-CGA07]

Occlusion-Resistant Cameras

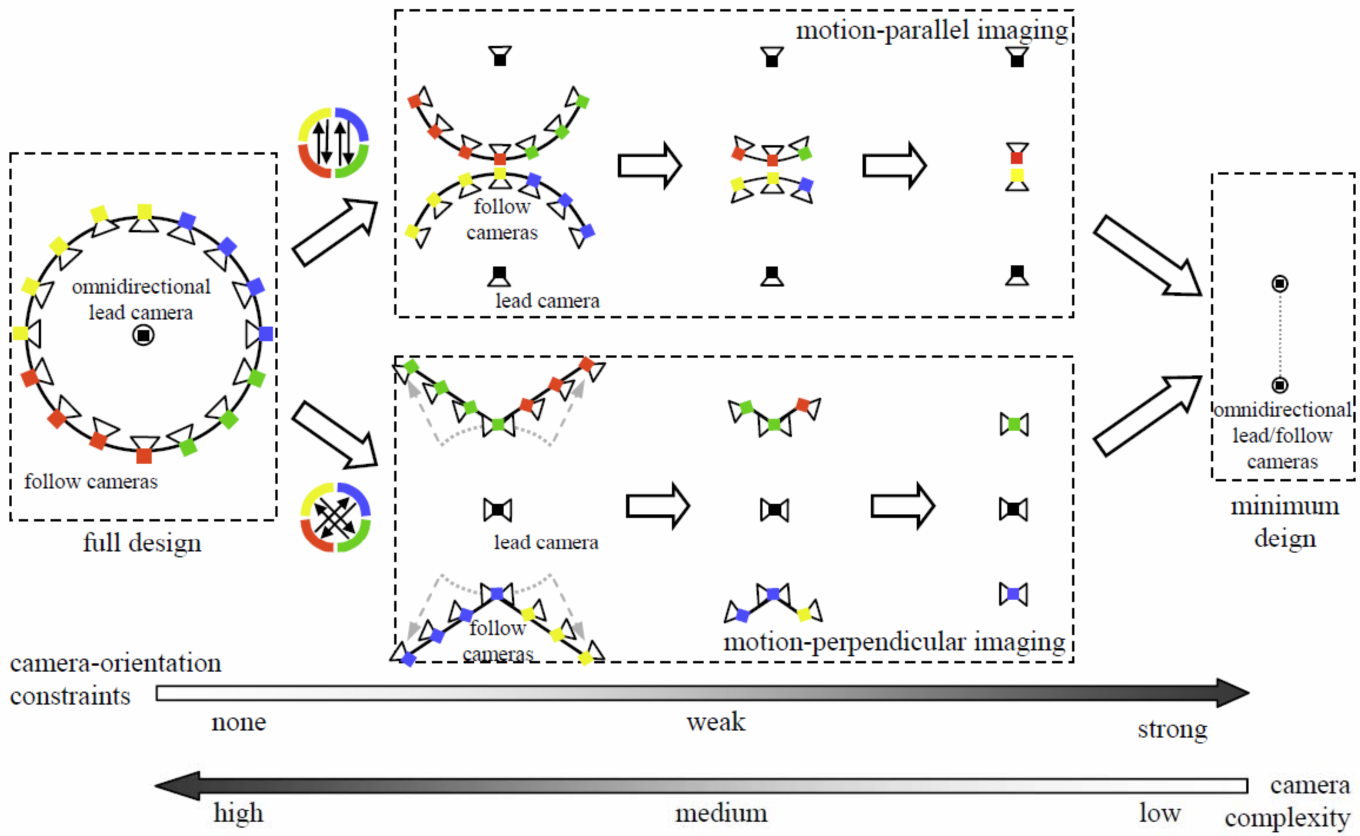
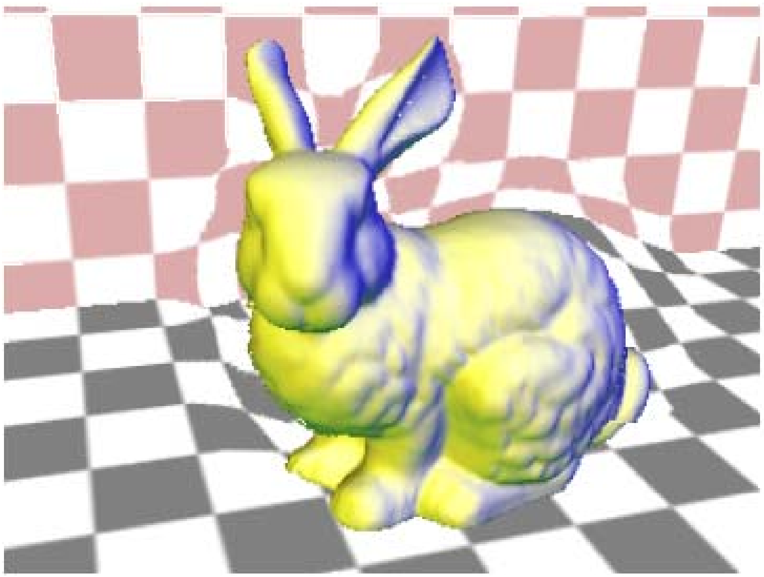


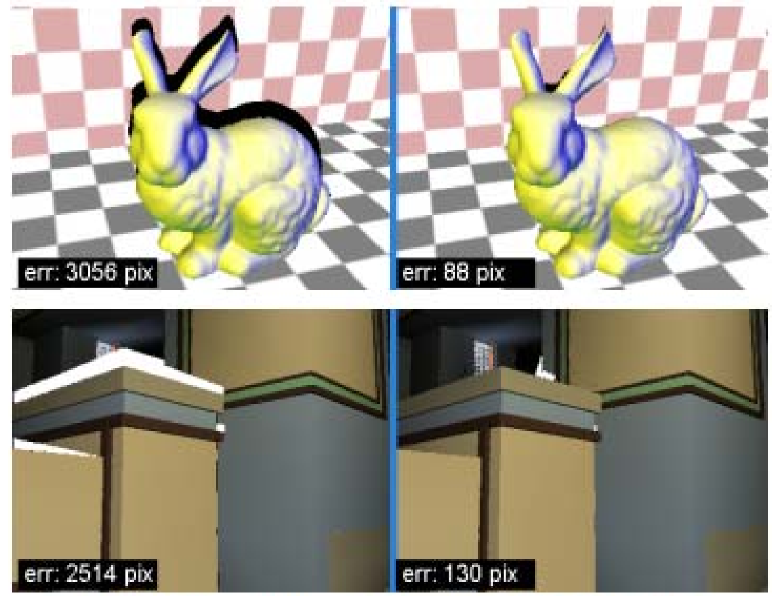
Figure 1. Family of ORC Designs. *This diagram shows 2D versions of our family of cameras. Individual cameras are represented by small (colored) squares. The camera's field-of-view is drawn using a small triangle for limited field-of-view cameras and as a circle for omnidirectional cameras. Left: a full design of a sphere of follow cameras (color-coded) surrounding an omnidirectional lead camera (black) produces occlusion-resistant images for all imaging directions and camera orientations. Middle: progressively simpler cameras require stricter control of the camera's orientation, providing*

[Aliaga-CGA07]

Occlusion Cameras



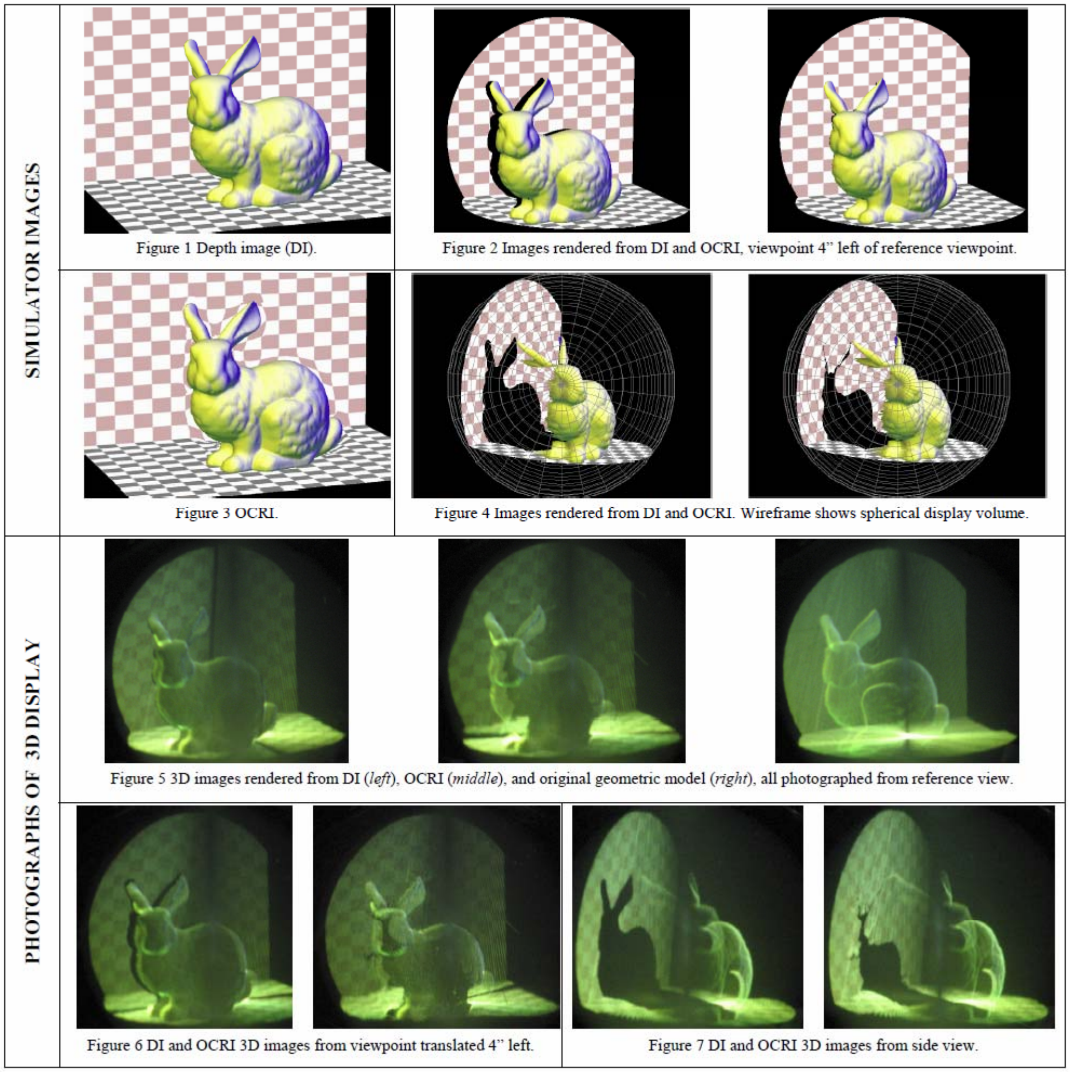
DDOC reference image.



Frames rendered from depth image and DDOC image

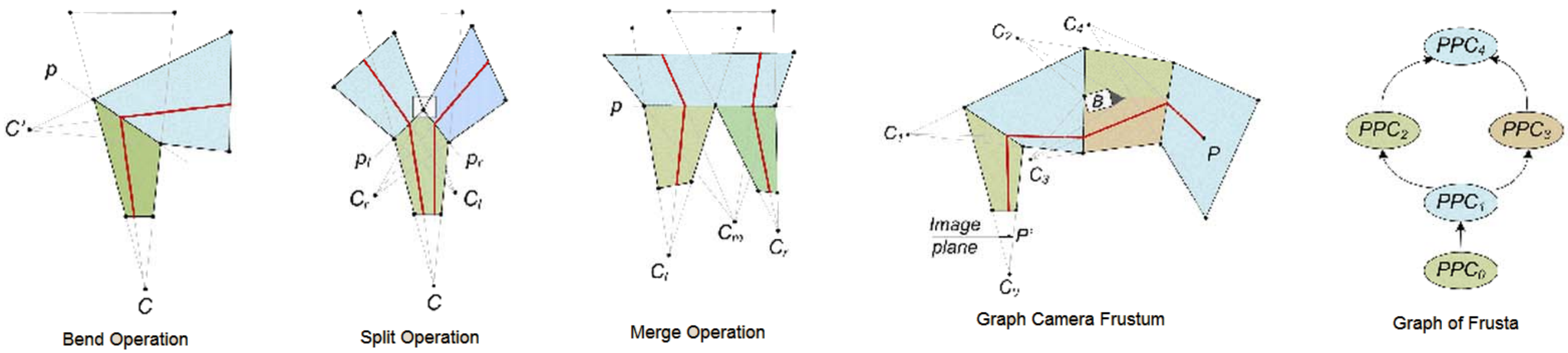
[Popescu-I3D06]

Occlusion Cameras



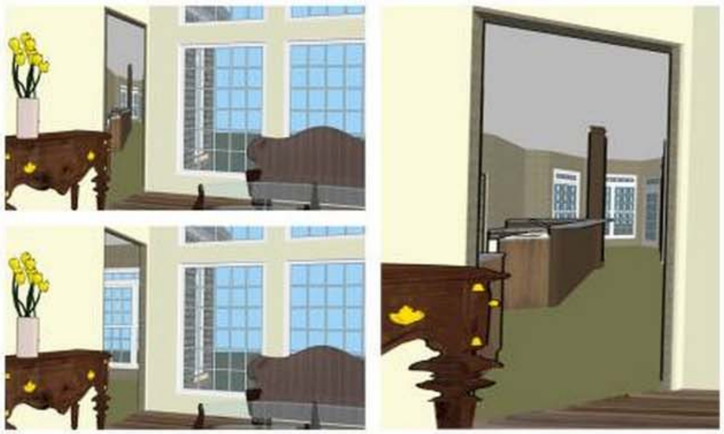
[Popescu-JDT06]

Graph Cameras

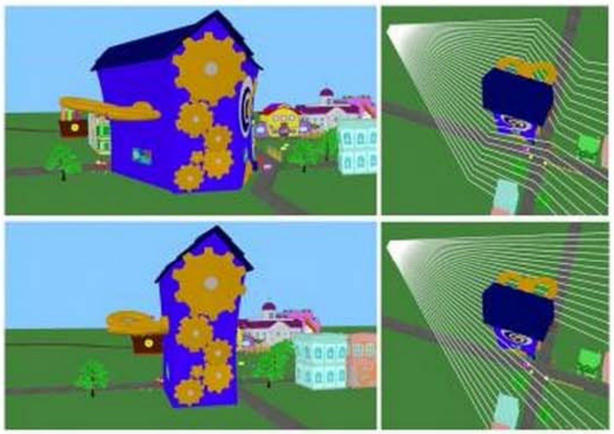


[Popescu-SIGA09]

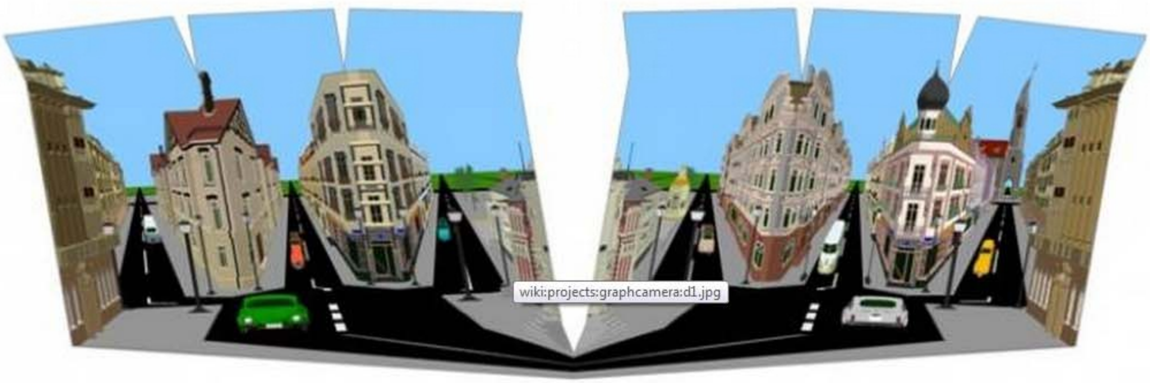
Graph Cameras



Portal-based graph camera image (top left and fragment right) and PPC image for comparison (bottom left)



Occluder-based graph camera image (top left), PPC image for comparison (bottom left), and ray visualizations (right)



Enhanced street-level navigation

[Popescu-SIGA09]

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A little bit of history…

- Omnidirectional cameras are also called panoramic cameras
  - “Panorama” comes from the Greek phrase “all sight”
- Originally used for artistic purposes
- Robert Barker obtained a patent for the idea of a panorama in 1794
  - “A Painting without Equal”
- In 1800s, panorama became a common European word

Taxonomy of Omnidirectional Camera Designs

- Single center-of-projection
  – Like a traditional camera, light rays meet at a single "focal point"
- Multiple center-of-projection
  – Camera does not have a single focal point
  – Sampled surfaces can be missing or duplicated in full image
  – Mathematical (re)projections are more complicated

- Single Camera/Image
  – One "view" is acquired per image
- Multiple Camera/Image
  – A single "view" composed by compositing several images

Some Omnidirectional Cameras

- Rotating camera design
- Fish-eye lens design
- Multiple camera planar mirror design
- Single COP curved mirror design

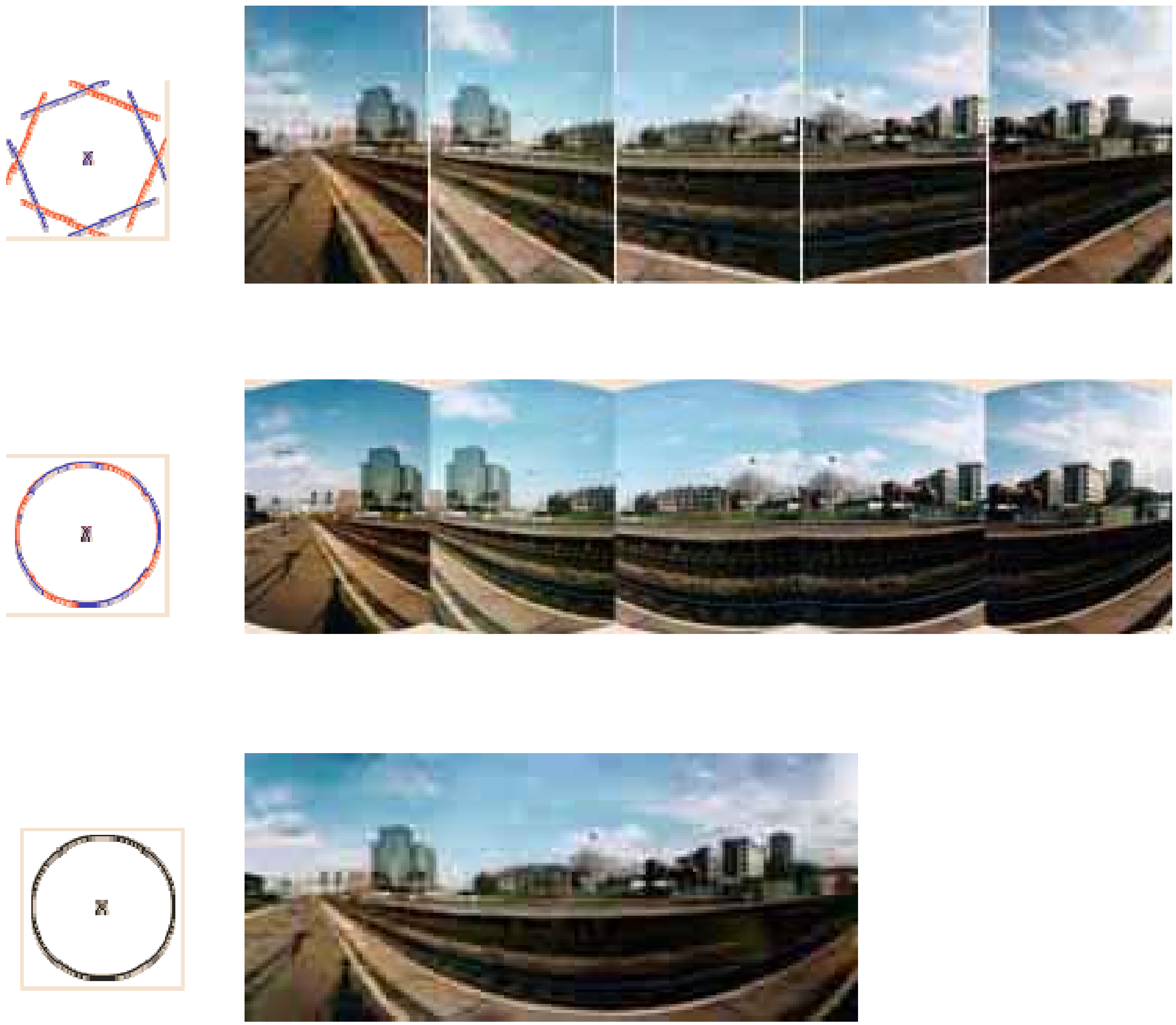
Rotating Camera Design

- Place a camera on a tripod and spin it around snapping pictures every so often

- Pros
  - Simple

- Cons
  - Multiple centers-of-projection
  - Multiple (overlapping images) to composite
  - Vertical “jitter”
  - Slow acquisition process

Rotating Camera Design



Rotating Camera Design

- Tienamen

Panoramic Video Textures

[Agarwala-SIG05]

Panoramic Video Textures

- pvViewer

[Agarwala-SIG05]

Panoramic Video Textures

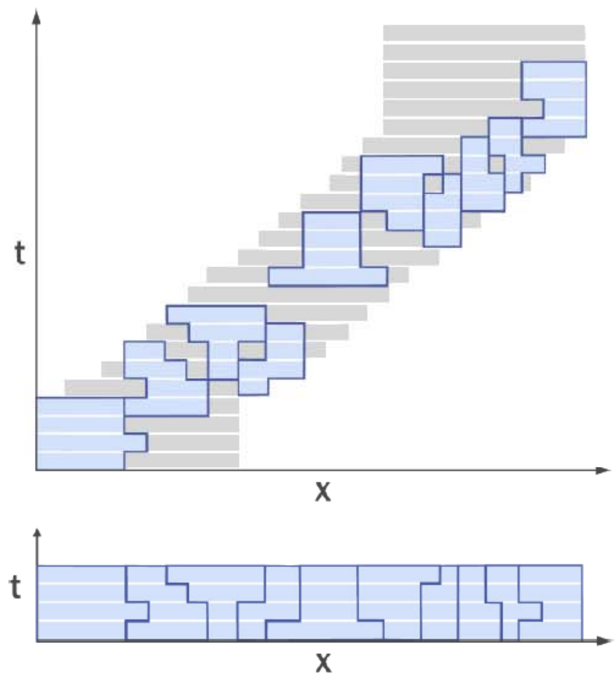


Figure 2 The top diagram shows an x,t slice of an input video volume $V(x,y,t)$. Each input video frame is shown as a grey rectangle. The frames are registered, and in this case, the camera is panning to the right. The bottom diagram shows an output video volume. The duration of the output is shorter, but each output frame is much wider than each input frame. Finally, the two diagrams show how a PVT can be constructed. The output video is mapped to locations in the input in coherent fragments; the mapping takes place in time only (as time offsets), never in space.

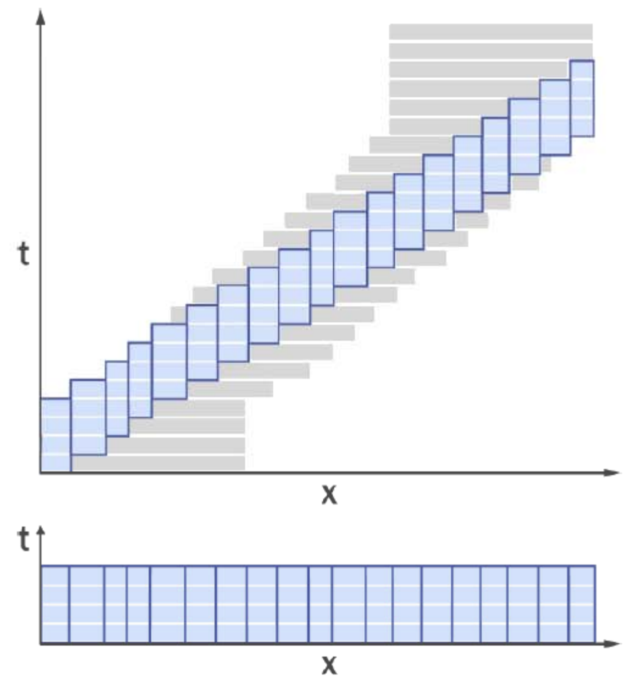


Figure 3 A simple approach to creating a PVT would be to map a continuous diagonal slice of the input video volume to the output panorama, regardless of appearance. This approach creates a valid result, but unnecessarily shears spatial structures across time (see Figure 4).

[Agarwala-SIG05]

Fish-Eye Lens Design

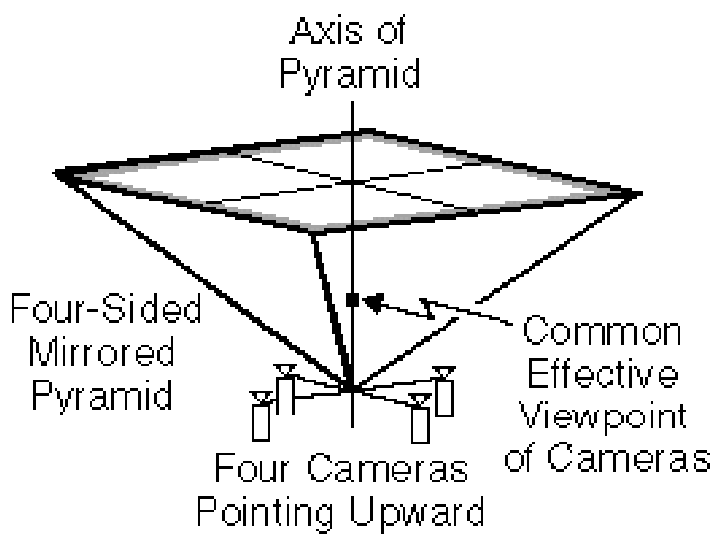
- Use a wide field-of-view lens (~180 degrees) placed in front of a traditional camera

- Pros:
  - Also relatively simple for users (making the lens can be troublesome for designers)

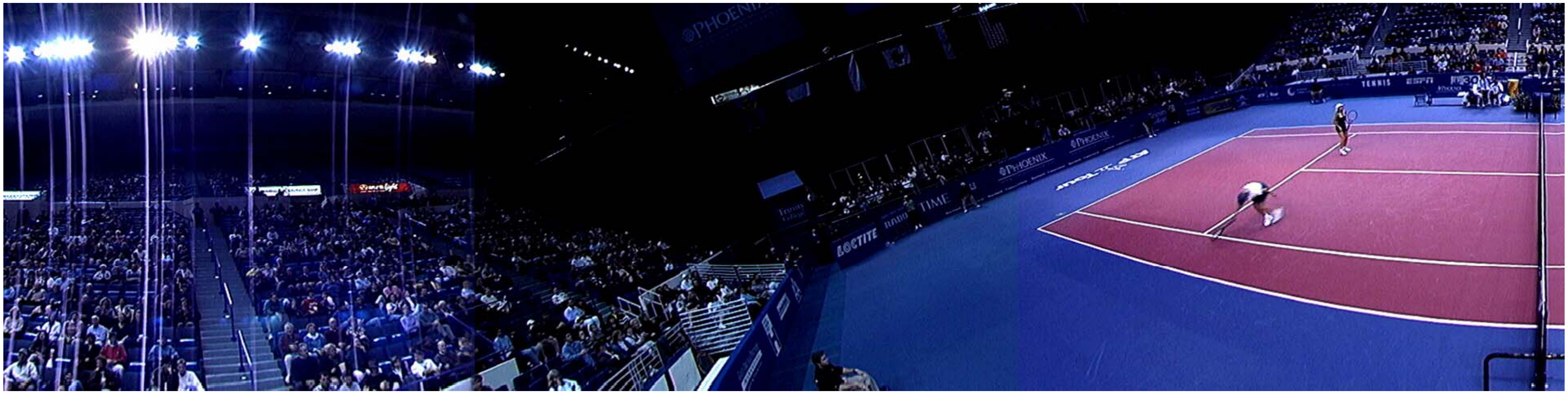
- Cons:
  - *Very* severe image distortion
  - Low resolution around perimeter of field-of-view
  - Almost a single center-of-projection

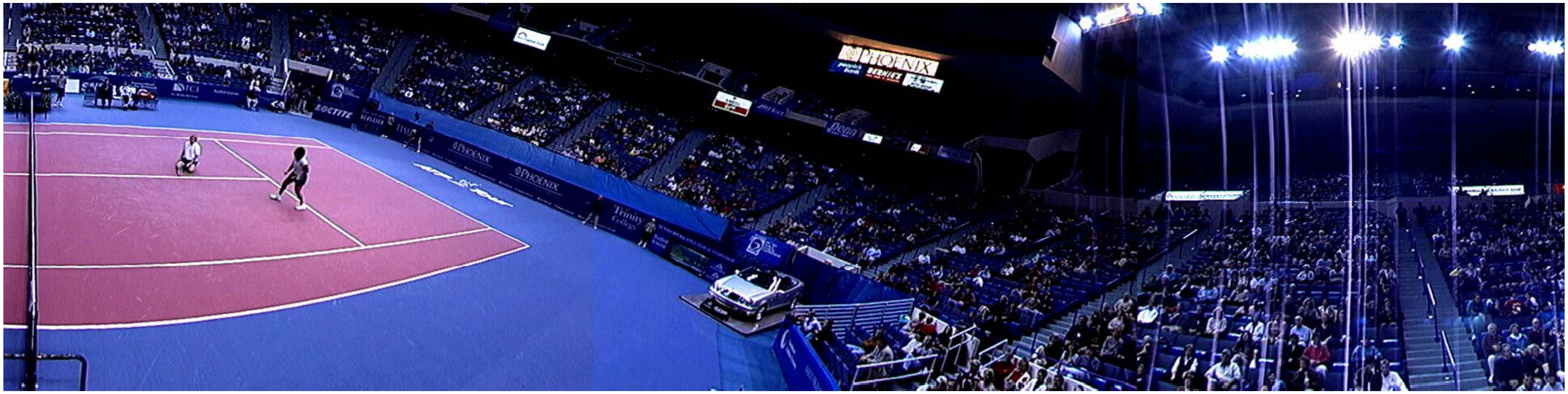
Multiple Planar Mirror Design

- Catadioptric = reflective (mirror) + refractive (lens)
- http://www.fullview.com [Nalwa96]



Multiple Planar Mirror Design





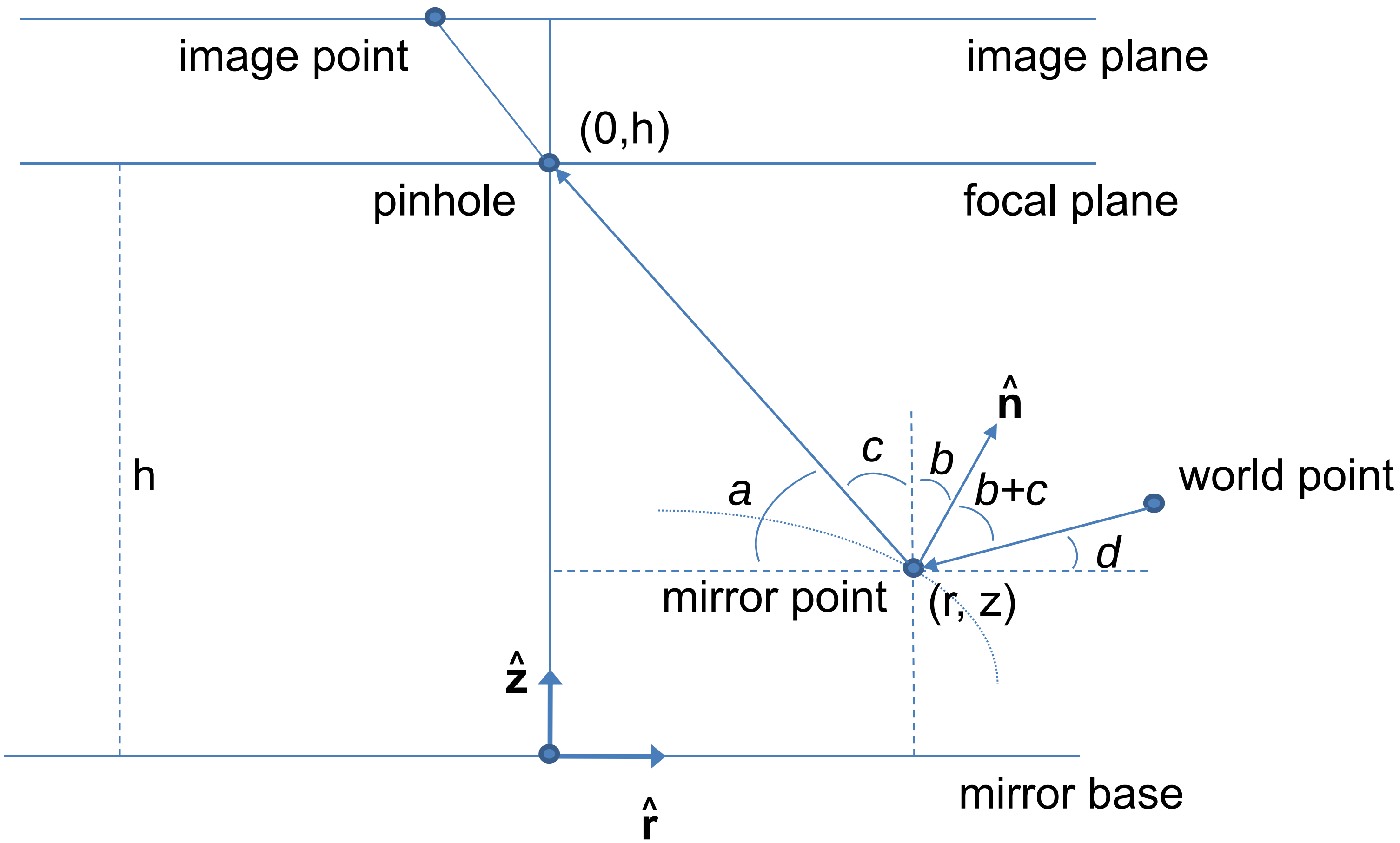
[Fullview]

Multiple Planar Mirror Design

[Fullview]

Multiple Planar Mirror Design

Fixed Viewpoint Constraint



Property 1: $c = 90^o - a$

Property 2: $a + d + 2b + 2c = 180^o$

Fixed Viewpoint Constraint

Property 1: $c = 90^\circ - a$

Property 2: $a + d + 2b + 2c = 180^\circ$

$$\Downarrow$$

$$2b = a - d$$

$$\Downarrow$$

$$\frac{2\tan(b)}{1-\tan^2(b)} = \frac{\tan(a)-\tan(d)}{1+\tan(a)\tan(d)}$$

$$\Downarrow$$

$$\boxed{r(h-2z)(dz/dr)^2 - 2(r^2+hz-z^2)(dz/dr) + r(2z-h) = 0}$$

Quadratic first-order ODE (constraint equation)

Fixed Viewpoint Constraint

Property 1: $c=90^o-a$

Property 2: $a+d+2b+2c=180^o$

$$2b=a-d$$

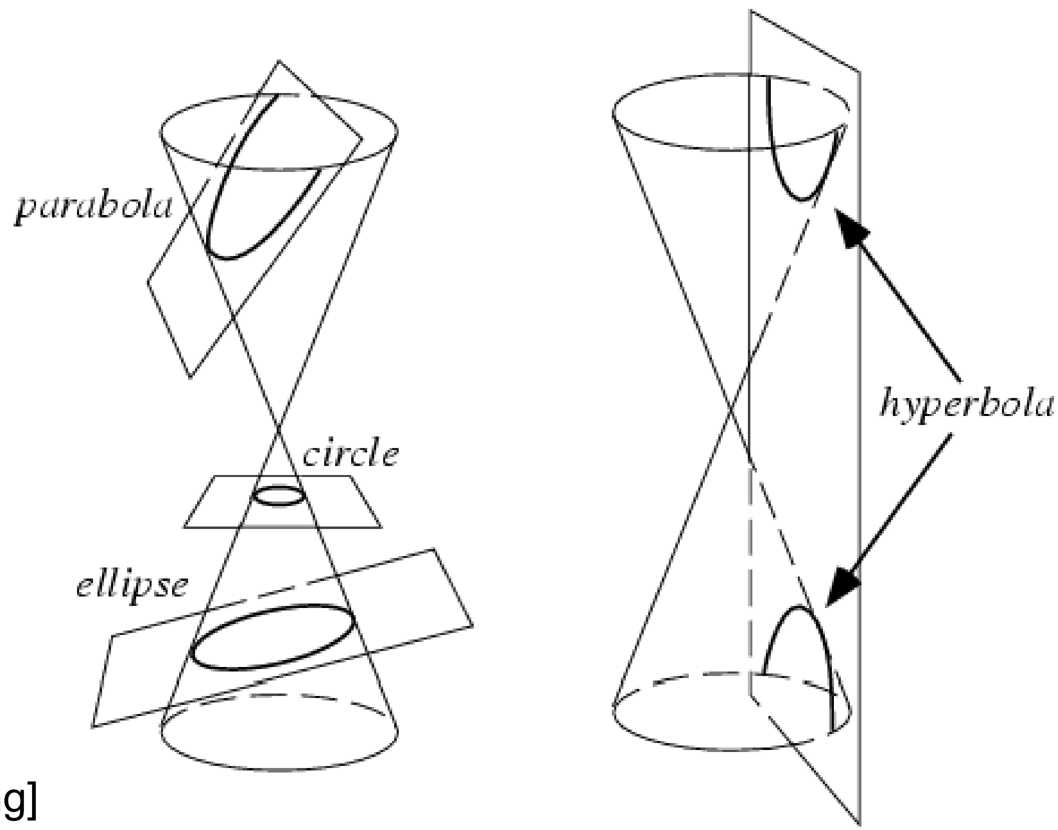
$$\frac{2\tan(b)}{1-\tan^2(b)} = \frac{\tan(a)-\tan(d)}{1+\tan(a)\tan(d)}$$

$$\boxed{\begin{array}{ll} (z-h/2)^2-r^2(k/2-1)=h^2(k-2)/4k & \text{for } k\geq 2 \\ (z-h/2)^2+r^2(1+h^2/2k)=(2k+h^2)/4 & \text{for } k\geq 0 \end{array}}$$

Generalized solution to constraint equation

Single Curved Mirror Design

- Theoretical solutions to a single center-of-projection panoramic camera use mirrors that are subsets of swept conic sections
  - Cones
  - Spheres
  - Ellipsoids
  - Hyperboloids
  - Paraboloids



["Panoramic Vision", Benosman/Kang]

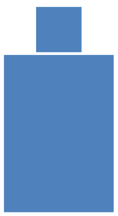
Examples

- Walking in the mirror
- Museum

Conical Mirror

Spherical Mirror

Ellipsoidal Mirror



Hyperboloidal Mirror

Hyperboloidal Mirror

- ACCOWLE Co., LTD, A Spin-off at Kyoto University
  - http://www.accowle.com/english/
- Spherical Mirror
- Hyperbolic Mirror

Image: High res. in the top

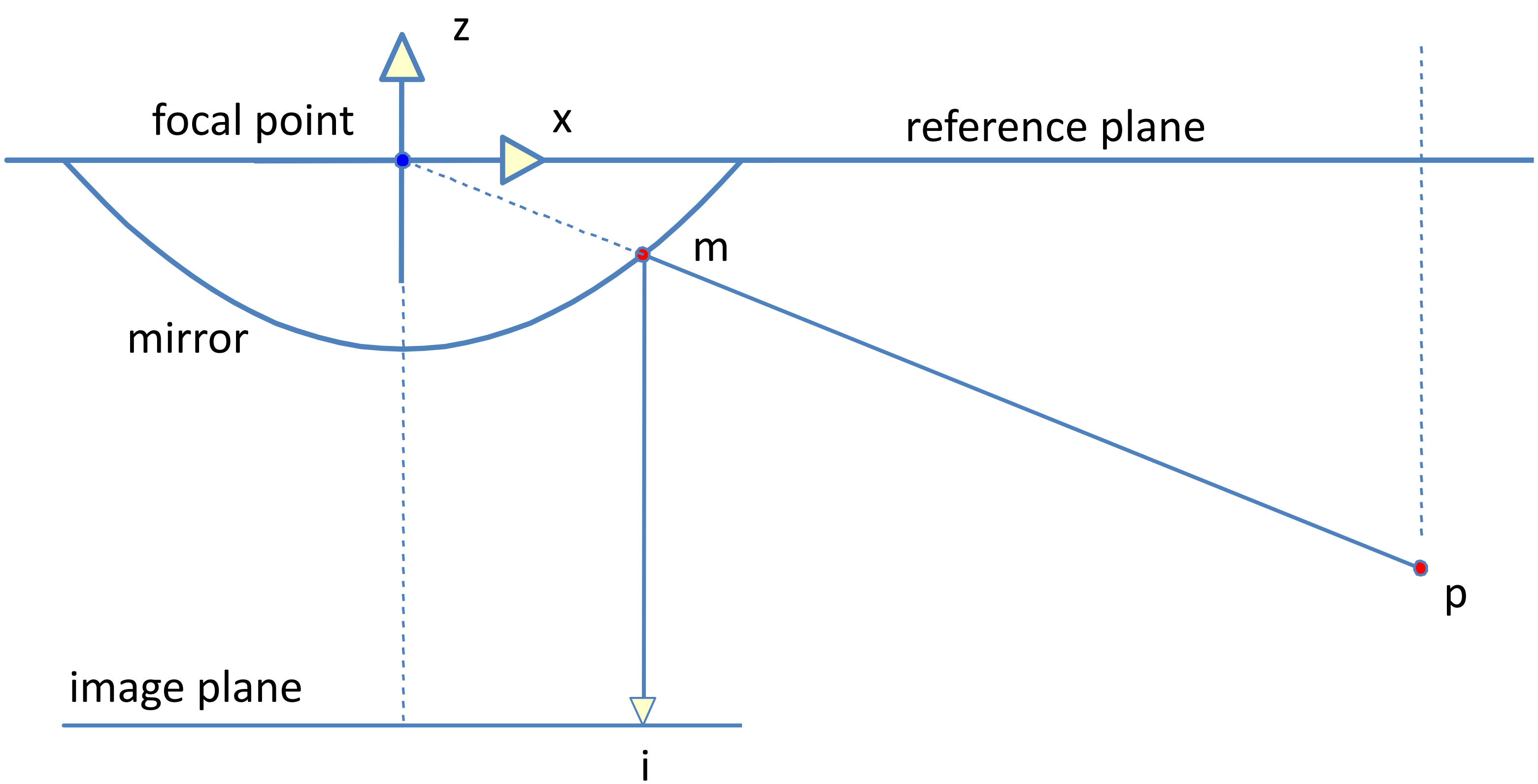
Paraboloidal Mirror

Catadioptric Paraboloidal Camera

Design by [Nayar97]

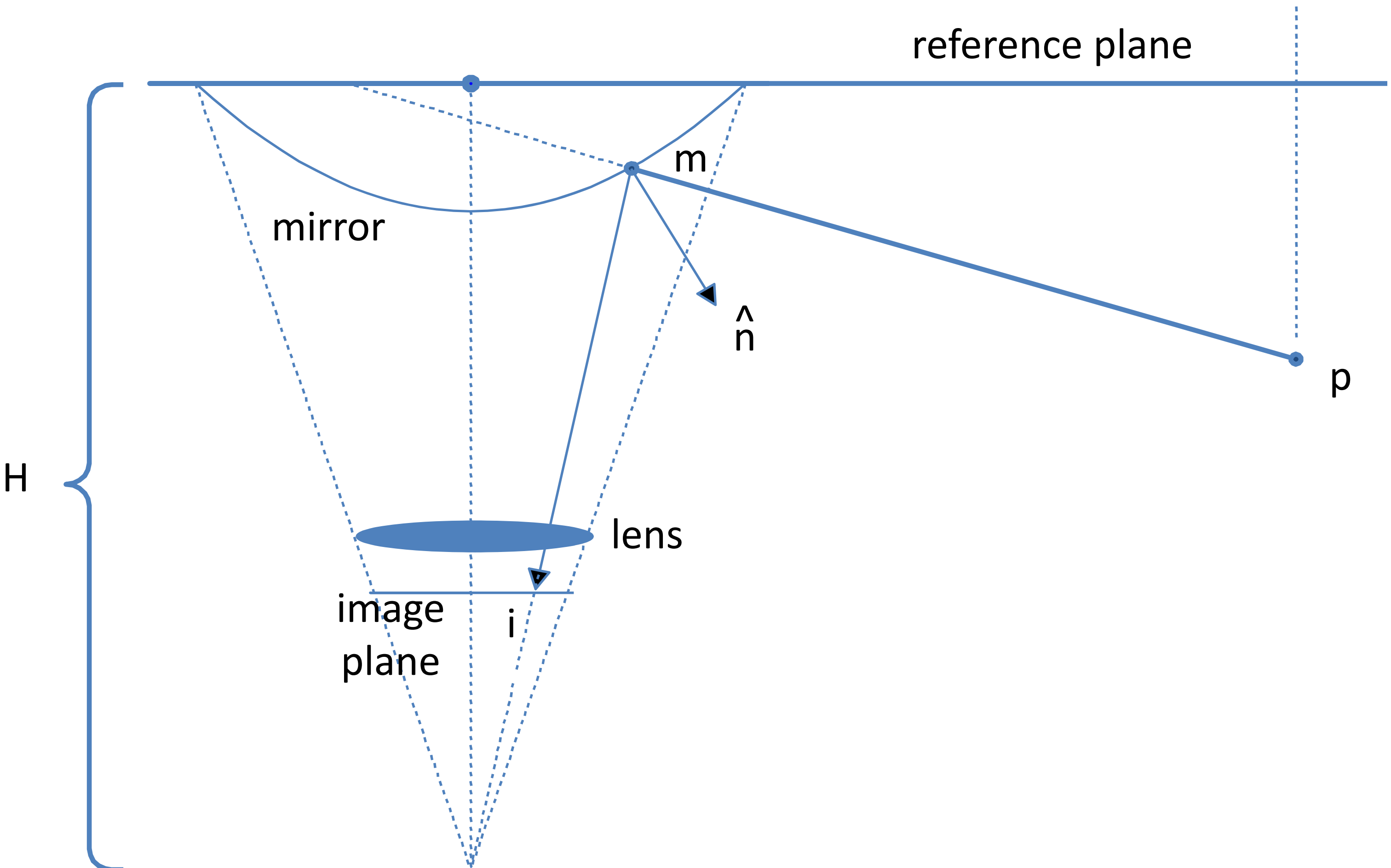
Motorized cart with camera, computer, battery, radio remote control [Aliaga01,02]

Catadioptric Paraboloidal Camera



Theoretical camera model

Catadioptric Paraboloidal Camera



[Aliaga-ICCV01]

Catadioptric Paraboloidal Camera Calibration

- Assuming incident equals reflected angle:

$$\frac{i - m}{i - m} \times \frac{\hat{n}}{\hat{n}} = \frac{p - m}{p - m} \times \frac{\hat{n}}{\hat{n}}$$

- And given a 3D point *p*, mirror radius *r*, convergence distance *H*, we group and rewrite in terms of m_r:

$$m_r^5 - p_r m_r^4 + 2r^2 m_r^3 + (2p_r rH - 2r^2 p_r)m_r^2 + (r^4 - 4r^2 p_z H)m_r - (r^4 p_r + 2r^3 H p_r) = 0$$

[Aliaga-ICCV01]

Omnidirectional Vision Home Page

- http://www.cis.upenn.edu/~kostas/omni.html