UNCONVENTIONAL VISION SENSORS

Shree K. Nayar

ACM SIGGRAPH 2000, Course Notes

Computer Science Department
Columbia University

Sponsors:
NSF, ONR MURI, DARPA,
Packard Foundation

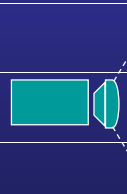
Depth Sensors

Depth from Focus and Defocus : (Nayar, Watanabe, Noguchi 95)

Performance : 512 x 480 Depth map at 30 frames per sec.

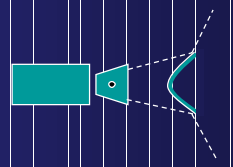
Different Approaches

Fish Eye Lens :



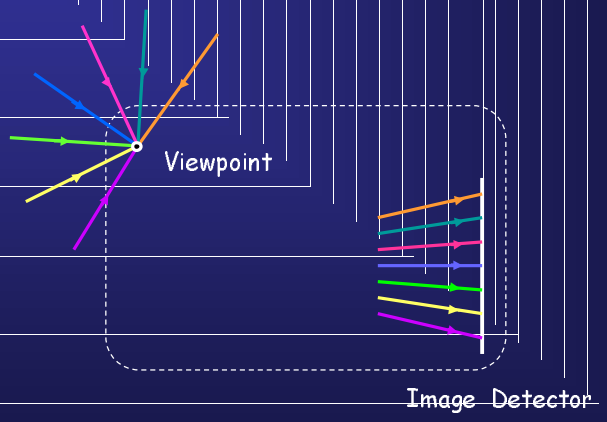
Examples: Wood 1906, Miyamoto 64, Hall 87, Zimmerman 93 , Poelstra 96 , Kuban et al. 94

Catadioptric Imaging :

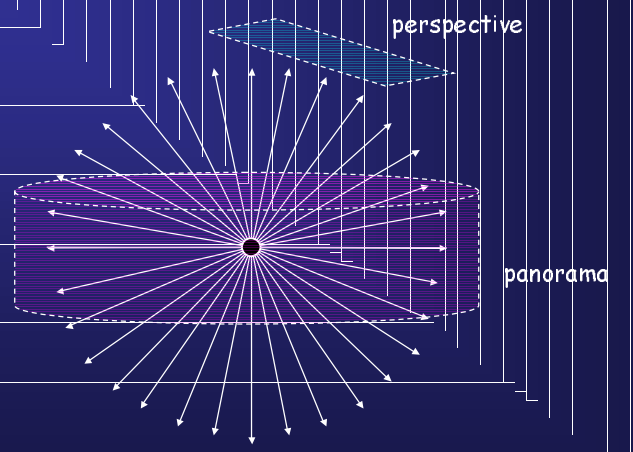


Examples: Rees 70, Rosendahl 83, Charles 87, Nayar 88, Yagi 90, Hong 91, Powell 95, Yamazawa 95, Bogner 95, Nalwa 96, Nayar 97, Chahl & Srinivasan 97

Single Viewpoint Imaging System

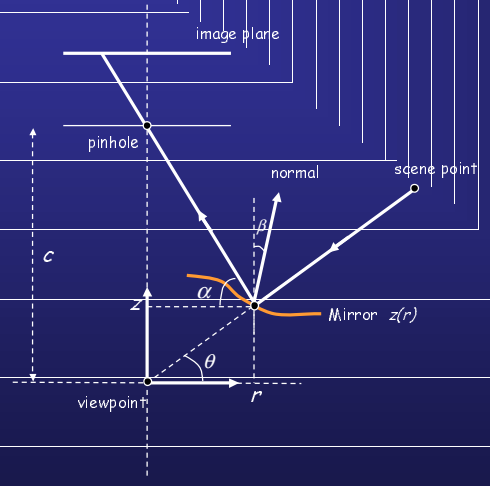


Single Viewpoint Omnidirectional Imaging



Single Mirror Systems : Problem Formulation

(Baker & Nayar 98)



Reflecting Mirror Point :

$$\tan\theta = \frac{z}{r}$$

Perspective Projection :

$$\tan\alpha = \frac{(c - z)}{r}$$

Specular Reflection :

$$2\beta = \alpha - \theta$$

Local Mirror Slope :

$$\frac{dz}{dr} = -\tan\beta$$

Single Mirror Systems : Solution

Quadratic First - Order Differential Equation :

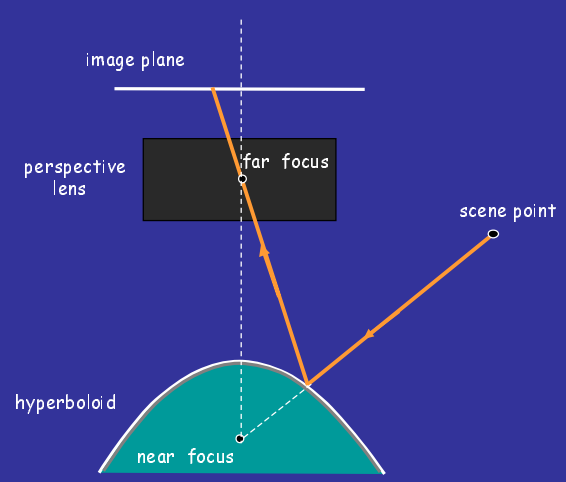
$$\frac{-2\dfrac{dz}{dr}}{1-\left(\dfrac{dz}{dr}\right)^2} = \frac{(c-2z)\,r}{r^2+cz-z^2}$$

Complete Class of Single Viewpoint Mirrors :

$$\left(z-\frac{c}{2}\right)^2 - r^2\left(\frac{k}{2}-1\right) = \frac{c^2}{4}\left(\frac{k-2}{k}\right) \qquad (k \geq 2)$$

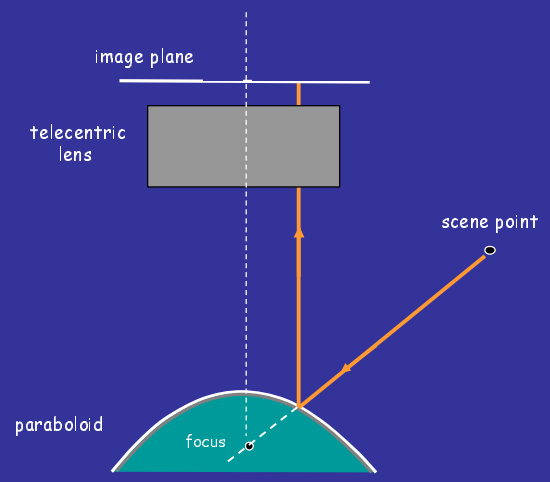
$$\left(z-\frac{c}{2}\right)^2 - r^2\left(1+\frac{c^2}{2k}\right) = \left(\frac{2k-c^2}{4}\right) \qquad (k > 0)$$

Single Mirror Systems



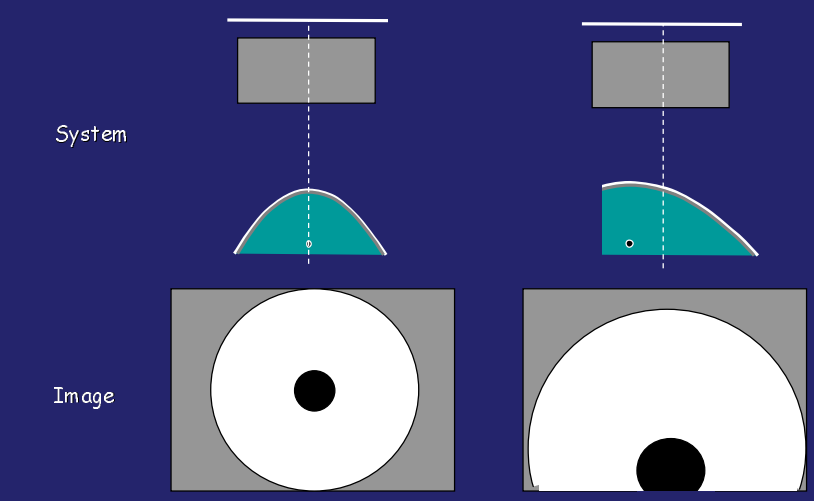
(Rees 70, Yamazawa 93)

Single Mirror Systems

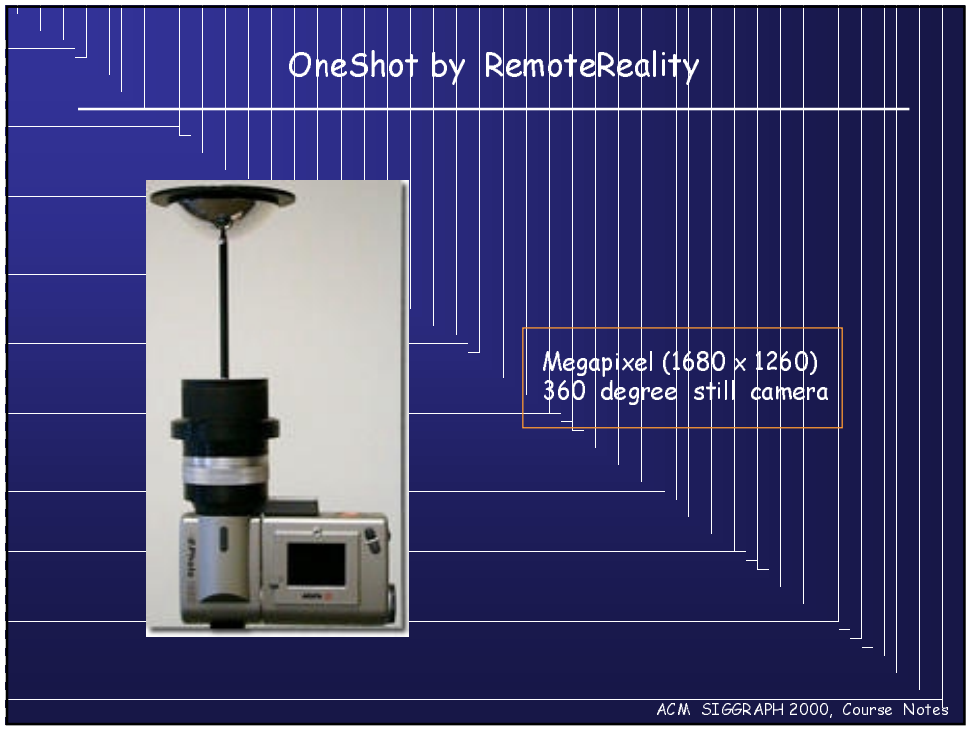


(Nayar 97)

Flexibility: Resolution vs. FOV

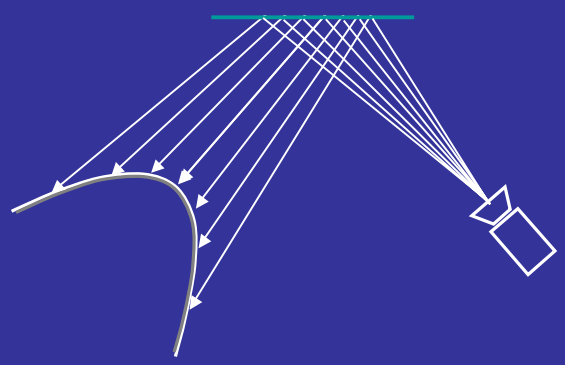


Field of View 360 180


OneShot by RemoteReality
Megapixel (1680 x 1260)
360 degree still camera
ACM SIGGRAPH 2000, Course Notes


ACM SIGGRAPH 2000, Course Notes

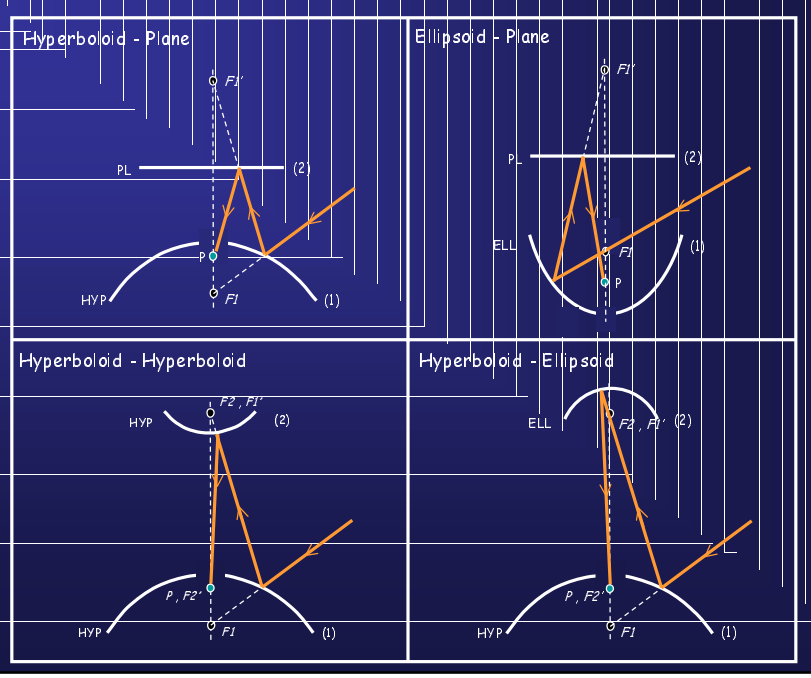
Optical Folding



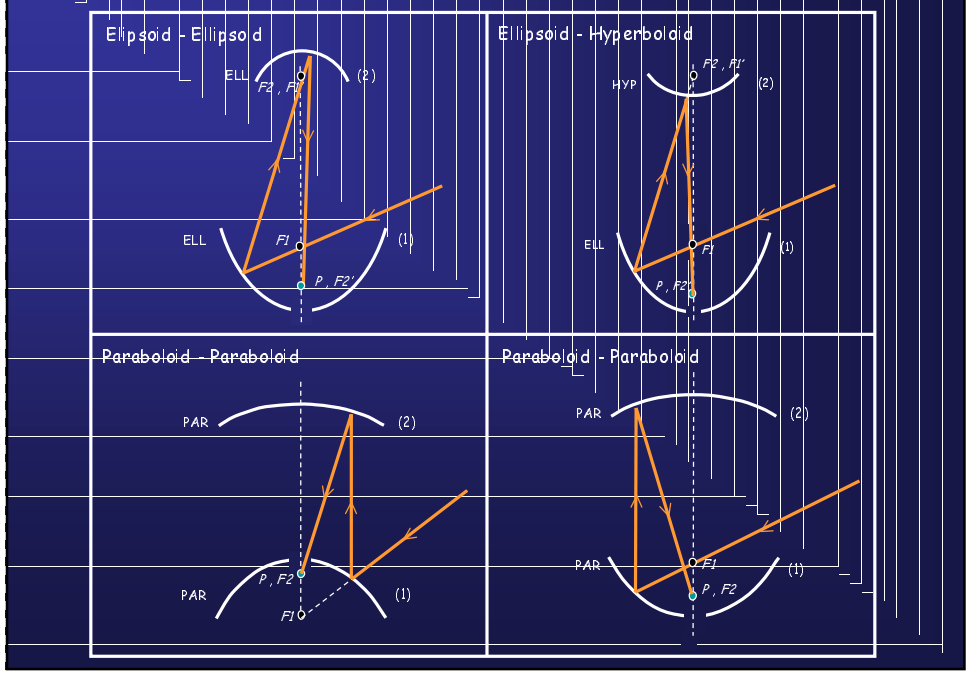
ACM SIGGRAPH 2000, Course Notes

Folded Catadioptric Cameras : Dictionary

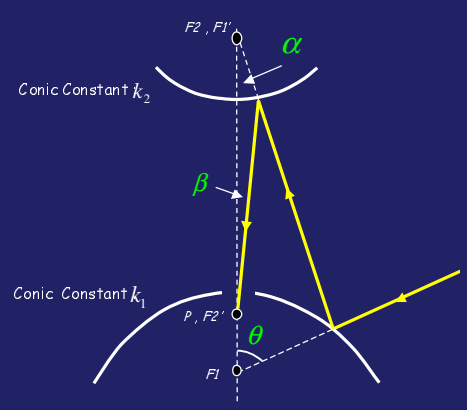
(Nayar & Peri 99)



Folded Catadioptric Cameras : Dictionary (Con't)



Equivalent Single Mirror System



Compression due to Primary Mirror :

$$\tan\alpha = \frac{(1+k_1)\sin\theta}{2\sqrt{-k_1}+(1-k_1)\cos\theta}$$

Compression due to Primary Mirror :

$$\tan\beta = \frac{(1+k_2)\sin\alpha}{2\sqrt{-k_2}+(1-k_2)\cos\alpha}$$

ACM SIGGRAPH 2000, Course Notes

Equivalent Single Mirror Systems

Total Compression for Folded System :

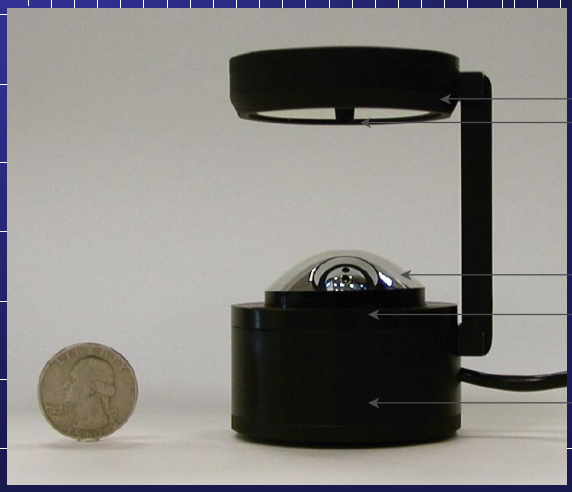
$$\tan^{-}\beta = \frac{(1+k_1)(1+k_2)\sin\theta}{[2\sqrt{-k_1}+\sqrt{-k_2}-k_1\sqrt{-k_2}-\sqrt{-k_1}k_2 + (1-k_1(k_2-1)+4\sqrt{-k_1}\sqrt{-k_2}-k_2)\cos\theta]}$$

Conic Constant of Equivalent Single Mirror :

$$k_e = \left(\frac{\sqrt{-k_1}+\sqrt{-k_2}}{1+\sqrt{-k_1}\sqrt{-k_2}}\right)^2$$

Compact Panoramic Camera

(Nayar & Peri 99)



SIZE : 9 CM X 5 CM

Urbie : Tactical Mobile Robot

Collaborators : JPL , IS Robotics , CMU , Columbia , CycloVision

Sponsor : DARPA TMR Project

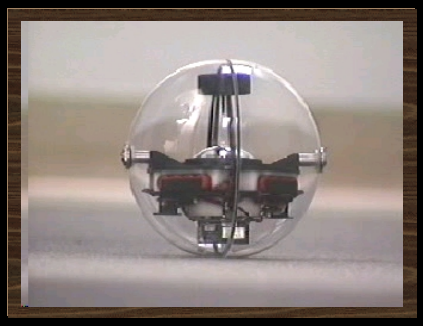
Deployable Omnicameras

PASSIVE CYCLOPS

ACTIVE CYCLOPS

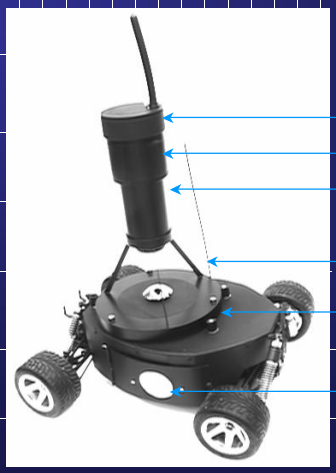
COLLABORATION: **COLUMBIA** (OPTICS AND IMAGING) AND **CMU** (MECHANICS - SCHEMPF GROUP)

Columbia-CMU Cyclops

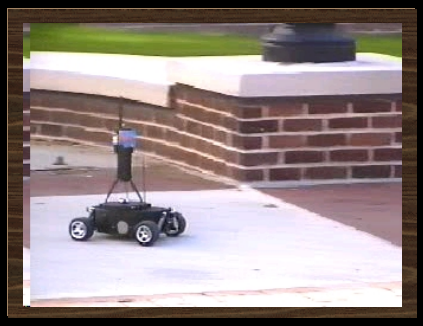


Remote Controlled ParaRover

(Lok & Nayar 98)
(Boult et al. 98)



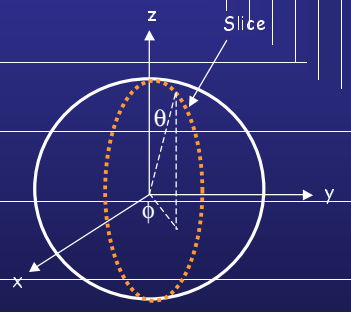
ParaRover



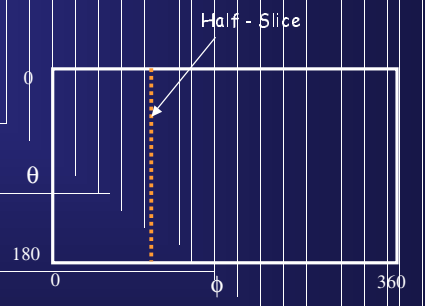
Spherical Mosaics from Slices

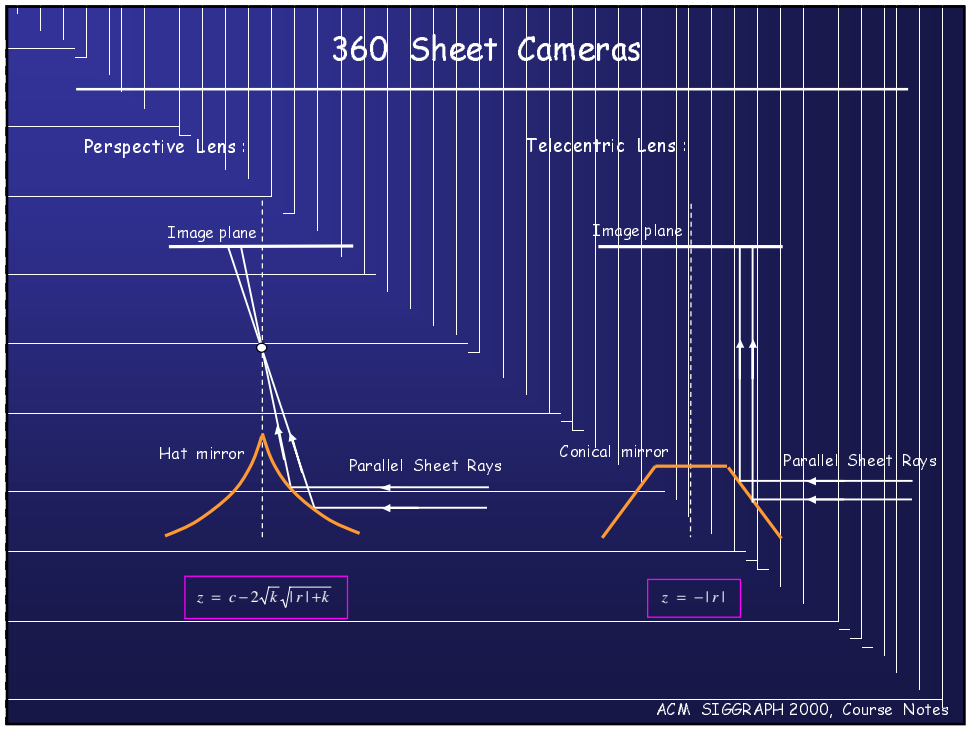
(Nayar & Karmarkar 99)

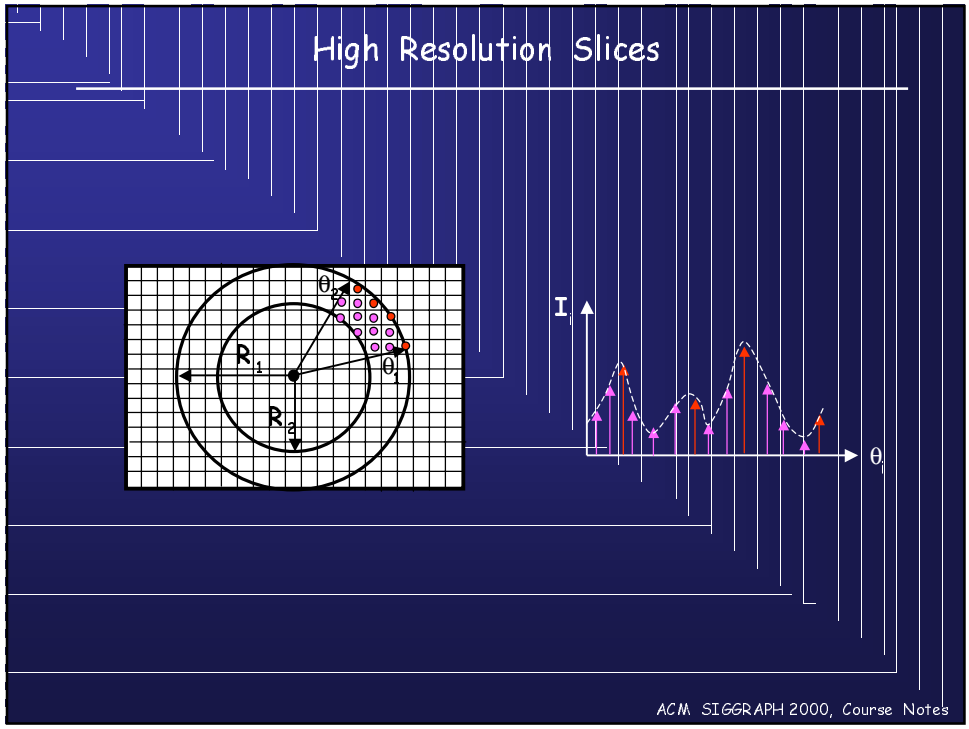
Unit Sphere :



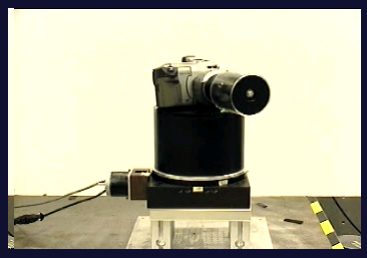
Spherical Panorama :

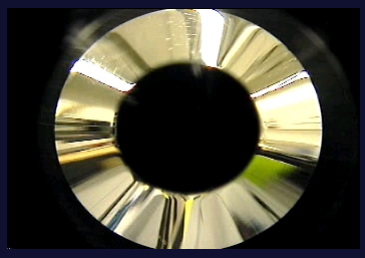



360 Sheet Cameras
Perspective Lens :
Telecentric Lens :
Image plane
Image plane
Hat mirror
Parallel Sheet Rays
Conical mirror
Parallel Sheet Rays
$z = c - 2\sqrt{k}\sqrt{|r|+k}$
$z = -|r|$
ACM SIGGRAPH 2000, Course Notes


High Resolution Slices
θ_2
R_1
θ_1
R_2
I
θ
ACM SIGGRAPH 2000, Course Notes

360 Sheet Camera Rotation

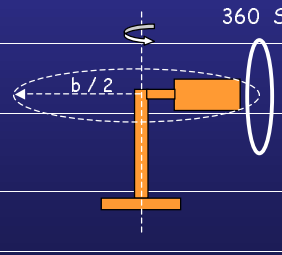




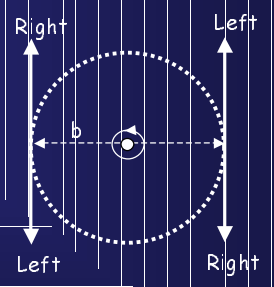
360 x 360 Spherical Mosaic

360 x 360 Stereo Mosaics

Slice Camera Rotation :



Left and Right Views :

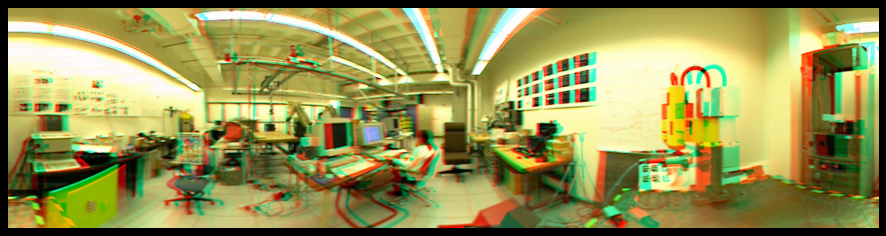


Stereo Panoramas:
Ishiguro et al. 92, Huang and Hung 92
Peleg and Ben-Ezra 99, Shum et al. 99

Left Panorama

Right Panorama

Stereoscopic Panorama



Problem of Dynamic Range

(Mitsunaga & Nayar 99)

- 8-bit Images and the Real World

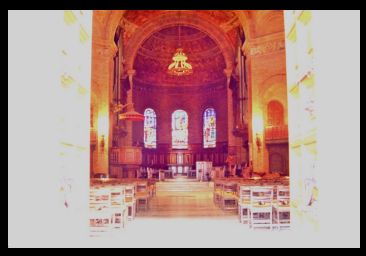


Image M_1
(High exposure)

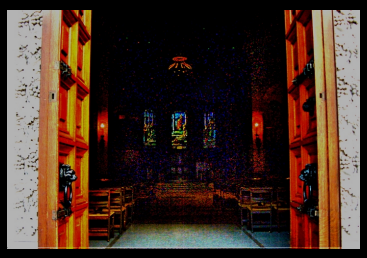
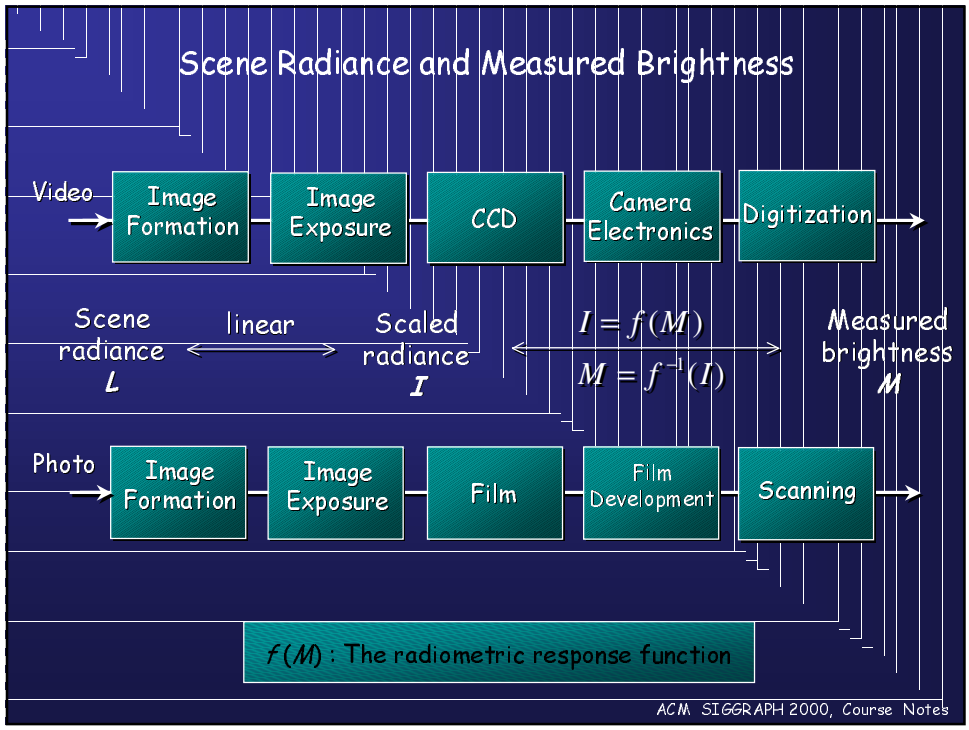


Image M_2
(Low exposure)



Response Function from Images : Previous Work

Mann and Picard (95) :

- Restrictive Model for f : $M = \alpha + \beta I^{\gamma}$
- Precisely Known Exposures

Debevec and Malik (97) :

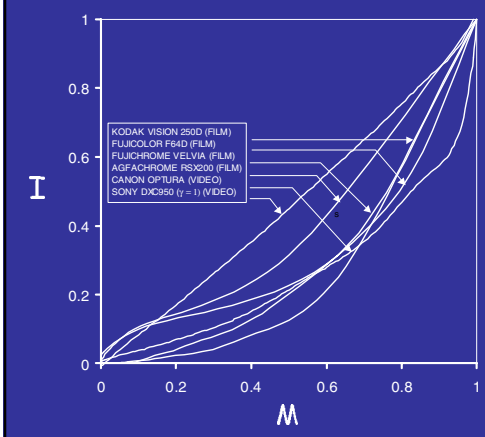
- General Model for f : Only Smoothness Constraint
- Precisely Known Exposures

Goal : Rough Exposure Ratios and Noisy Images

ACM SIGGRAPH 2000, Course Notes

Response Function : General Characteristics

Some Popular Imaging Systems :



High Order Polynomial :

$$I = f(M) = \sum_{n=0}^{N} c_n M^n$$

Scene Radiance Image Brightness

- f is semi-monotonic
- f is smooth

ACM SIGGRAPH 2000, Course Notes

Self Calibration Algorithm

(Mitsunaga and Nayar 98)

Radiance Ratio: $\frac{I_{p,q}}{I_{p,q+1}} = \frac{f(M_{p,q})}{f(M_{p,q+1})} = R_{q,q+1}$ (exposure ratio)

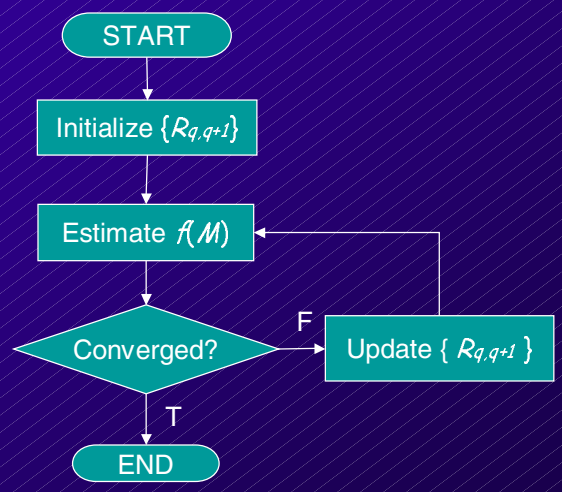
Using Polynomial Model : $\frac{\sum_{n=0}^{N} c_n M_{p,q}^{\ n}}{\sum_{n=0}^{N} c_n M_{p,q+1}^{\ n}} = R_{q,q+1}$

Objective Function : $\varepsilon = \sum_{q=1}^{Q-1} \sum_{p=1}^{P} \left[\sum_{n=0}^{N} c_n M_{p,q}^{\ n} - R_{q,q+1} \sum_{n=0}^{N} c_n M_{p,q+1}^{\ n} \right]^2$

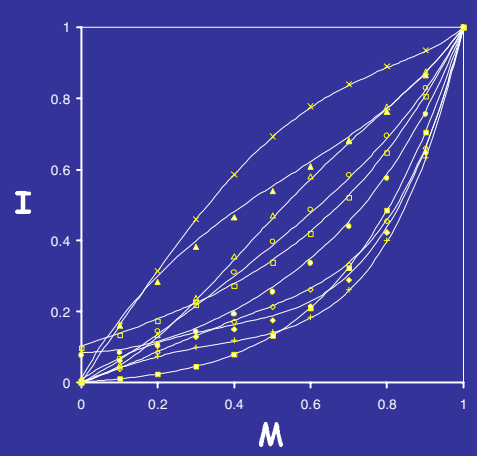
Iterative Algorithm : ratios $R_{q,q+1}$ coeff c_n

Images: $q = 1,2,\ldots Q$
Pixels: $p = 1, 2, \ldots P$

Self Calibration Algorithm : Flow Chart



100 Tests with Noisy Synthetic Images

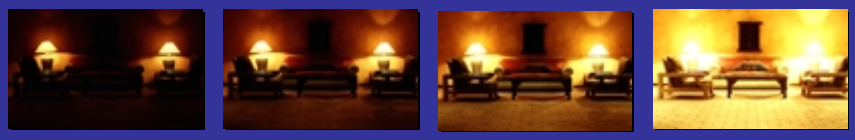


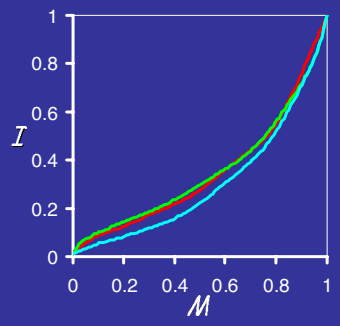
Actual Exposure Ratios : $0.45 < R < 0.55$
Initial Ratio Guess : $R = 0.5$

Solid : Computed Response Function
Dots : Actual Response Function

Results : Adobe Room

Captured images



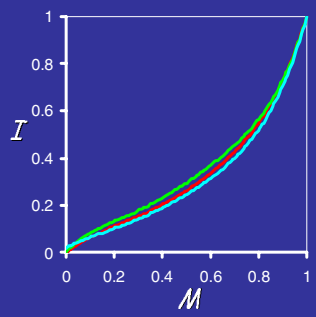


Computed response function

Computed radiance image

Results : Taos Clay Oven

Captured images



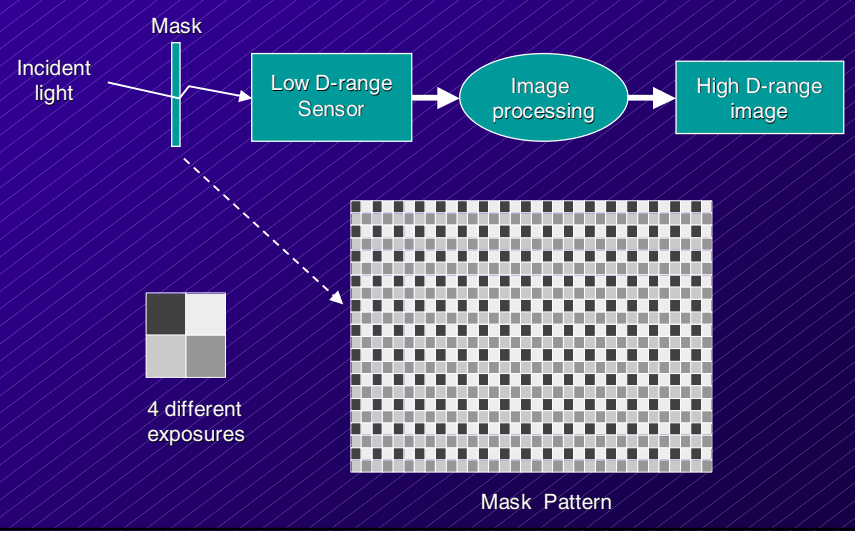
Computed response function

Computed radiance image

High Dynamic Range from Single Image

(Nayar & Mitsunaga 00)

- Spatially Varied Exposure (SVE) Camera



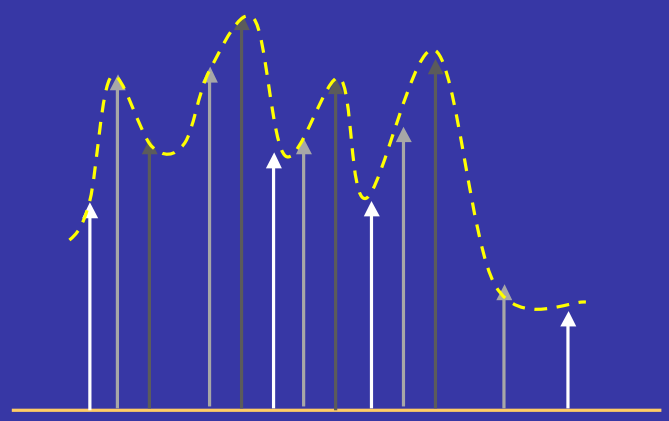
Characteristics

	Conventional Camera	SVE Camera
Dynamic Range	$DR = 20 \log \frac{I_{\max}}{I_{\min}}$ 48.13 db (8 bits)	$DR_{SVE} = 20 \log \frac{I_{\max}}{I_{\min}} \left(\frac{e_{\max}}{e_{\min}} \right)$ 64:1 84.25 db (14 bits)
Gray Levels	$Q = q$ 256	$Q_{SVE} = q + \sum_{k=0}^{K-1} Round((q-1) - (q-1)\frac{e_k}{e_{k-1}})$ 869

ACM SIGGRAPH 2000, Course Notes

High Dynamic Range Image Reconstruction

Exposure Normalized Image



ACM SIGGRAPH 2000, Course Notes

8-Bit Images with Different Exposures

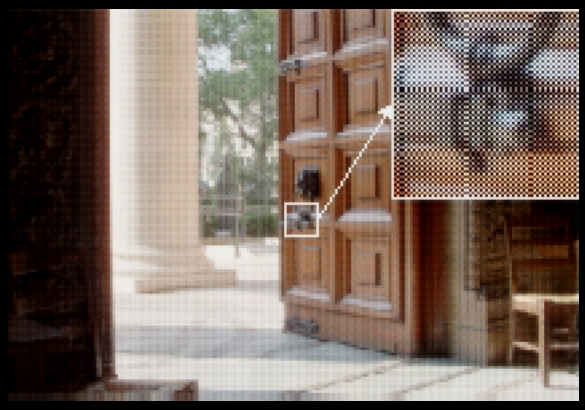
Exposure: T

Exposure: 4 T

Exposure: 16 T

Exposure: 64 T

Spatially Varying Exposure (SVE) Image



ACM SIGGRAPH 2000, Course Notes

Computed High Dynamic Range Image

ACM SIGGRAPH 2000, Course Notes

Summary

- Bigger Images and Clearer Images
- General Approach :

References

1 E. H. Adelson and J. R. Bergen.
The Plenoptic Function and the Elements of Early Vision.
MIT Press, Cambridge, MA, 1991.

2 S. Baker and S. K. Nayar.
Catadioptric Image Formation.
Proc. of International Conference on Computer Vision, January 1998.

3 S. Bogner.
Introduction to Panoramic Imaging.
Proc. of IEEE SMC Conference, pages 3100-3106, October 1995.

4 J. S. Chahl and M. V. Srinivasan.
Reflective surfaces for panoramic imaging.
36(31):8275-8285, 1997.

5 P. Debevec and J. Malik.
Recovering High Dynamic Range Radiance Maps from Photographs.
Proc. of ACM SIGGRAPH 1997, pages 369-378, 1997.

6 J. Gluckman and S. K. Nayar.
Egomotion and Omnidirectional Cameras.
Proc. of International Conference on Computer Vision, January 1998.

7 H. C. Huang and Y. P. Hung.
Panoramic stereo imaging system with automatic disparity warping and s eaming.
Graphical Models and Image Processing, 60(3):196-208, May 1998.

8 H. Ishiguro, H. Yamamoto, and S. Tsuji.
Omnidirectional Stereo.
IEEE Transactions on Pattern Analysis and Machine Intelligence, 14:257-262, 1992.

9 B. Madden.
Extended Intensity Range Imaging.
Technical Report MS-CIS-93-96, Grasp Laboratory, University of Pennsylvania, 1993.

10 P. L. Manley.
Unusual Telescopes.

11 S. Mann and R. Picard.
Being `Undigital' with Digital Cameras: Extending Dynamic Range by Combining Differently Exposed Pictures.
Proc. of IST's 48th Annual Conference, pages 442-448, May 1995.

12 T. Mitsunaga and S. K. Nayar.
Radiometric Self Calibration.
In Proc. of Computer Vision and Pattern Recognition '99, volume 1, pages 374-380, June 1999.

13 K. Miyamoto.
Fish Eye Lens.
Journal of Optical Society of America, 54(8):1060-1061, August 1964.

14 J. R. Murphy.
Application of Panoramic Imaging to a Teleoperated Lunar Rover.
Proc. of IEEE SMC Conference, pages 3117-3121, October 1995.

15 V. Nalwa.
A True Omnidirectional Viewer.
Technical report, Bell Laboratories, Holmdel, NJ 07733, U.S.A., February 1996.

16 S. K. Nayar.
Sphereo: Recovering depth using a single camera and two specular spheres.
Proc. of SPIE: Optics, Illumination, and Image Sensing for Machine Vision II, November 1988.

17 S. K. Nayar.
Catadioptric Omnidirectional Camera.
Proc. of IEEE Conf. on Computer Vision and Pattern Recognition, June 1997.

18 S. K. Nayar and T. Mitsunaga.
High Dynamic Range Imaging: Spatially varying pixel exposures.
In Proc. of Computer Vision and Pattern Recognition '00, June 2000.

19 S. K. Nayar and V. Peri.
Folded Catadioptric Cameras.
Proc. of IEEE Conference on Computer Vision and Pattern Recognition, June 1999.

20 Shree K. Nayar and Amruta Karmarkar.
360 x 360 mosaics.
In Proc. of Computer Vision and Pattern Recognition '00, 2000.

21 S. A. Nene and S. K. Nayar.
Stereo Using Mirrors.
Proc. of International Conference on Computer Vision, January 1998.

22 S. Peleg and M. Ben-Ezra.
Stereo Panorama with a Single Camera.
Proc. of IEEE Conference on Computer Vision and Pattern Recognition, pages 395-401, June 1999.

23 S. Peleg and J. Herman.
Panoramic Mosaics by Manifold Projection.
Proc. of IEEE Conference on Computer Vision and Pattern Recognition, pages 338-343, June 1997.

24 V. Peri and S. K. Nayar.
Generation of Perspective and Panoramic Video from Omnidirectional Video.
Proc. of DARPA Image Understanding Workshop, May 1997.

25 D. W. Rees.
Panoramic Television Viewing System.
United States Patent, (3,505,465), April 1970.

26 H-Y. Shum and L-Wei He.
Rendering with Concentric Mosaics.
Proc. of ACM SIGGRAPH'99, August 1999.

27 H-Y. Shum, A. Kalai, and S. M. Seitz.
Omnivergent stereo.
Proc. of Seventh International Conference on Computer Vision, pages 22-29, September 1999.

28 R. Szeliski.
Image Mosaicing for Tele-reality Applications.
Proc. of IEEE Workshop on Applications of Computer Vision, pages 44-53, December 1994.

29 A. J. P. Theuwissen.
Solid State Imaging with Charge-Coupled Devices.
Kluwer Academic Press, Boston, 1995.

30 Y. Xiong and K. Turkowski.
Creating Image-Based VR Using a Self Calibrating Fishe ye Lens.
Proc. of IEEE Conf. on Computer Vision and Pattern Recognition, June 1997.

31 Y. Yagi.
Omnidirectional Sensing and Its Applications.
IEICE Transactions, E82-D(3), March 1999.

32 Y. Yagi and S. Kawato.
Panoramic Scene Analysis with Conic Projection.
Proc. of International Conference on Robots and Systems (IROS), 1990.

33 K. Yamazawa, Y. Yagi, and M. Yachida.
Omnidirectional Imaging with Hyperboloidal Projection.
Proc. of International Conference on Robots and Systems (IROS), 1993.

34 J. Y. Zheng and S. Tsuji.
Panoramic Representation of Scenes for Route Understanding.
Proc. of the Tenth International Conference on Pattern Recognition, 1:161-167, June 1990.

The End