Single-lens Dual-Aperture Stereo Imaging system

Sam Y. Bae

Outline

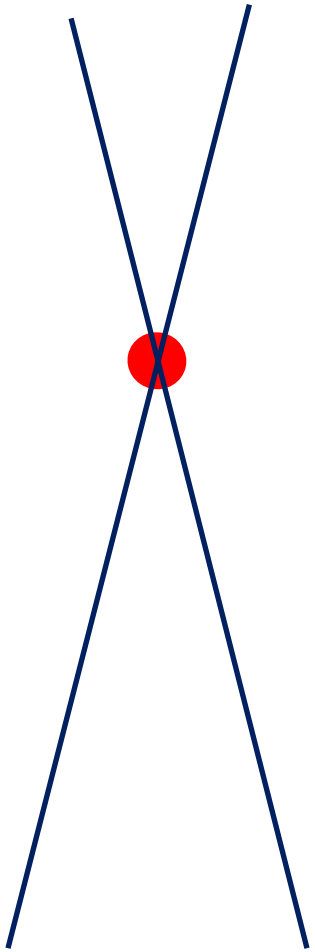
- Background
  - Depth perception)
  - 3D imaging system
- Objectives
- Dual aperture scheme
- Thesis statement
- Data
- Conclusion

Pictorial cues

Binocular cues

- A demonstration
  - Fixation enabled by accommodation and convergence
  - Dual image → Disparity → Depth perception
- Sir Charles Wheastone

  (Binocular vision in 1838)



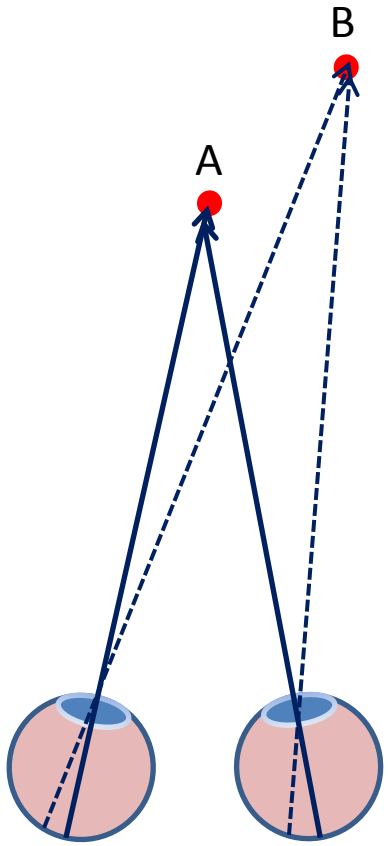
Stereo Depth Effect (SDE)

$$\text{Disparity} = M \cdot SB \cdot \frac{FD_o}{z_o}$$

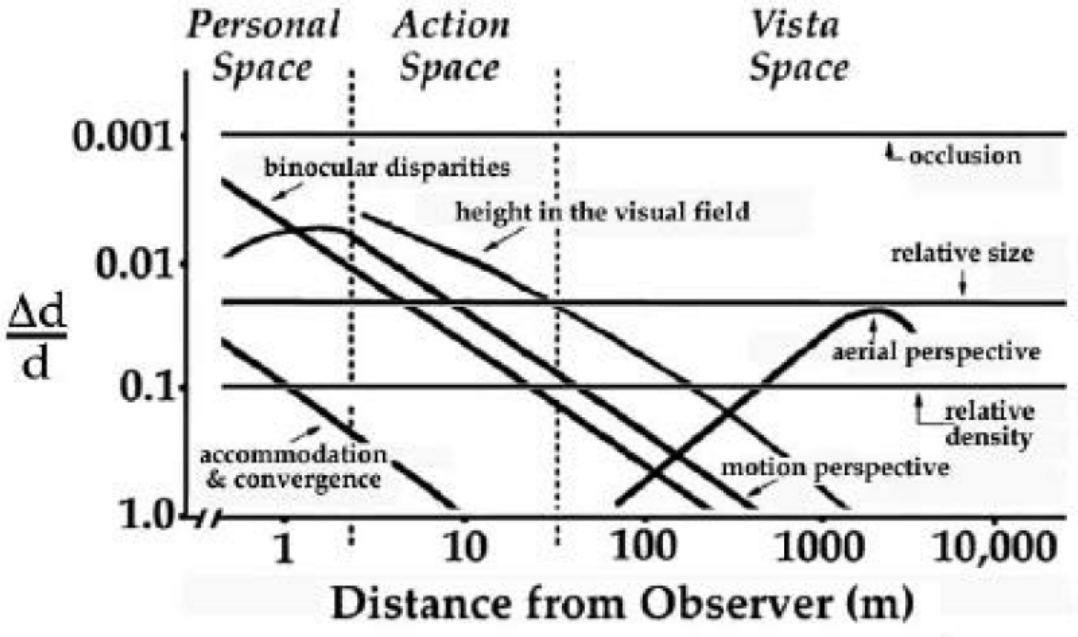
- SDE is a derivative of disparity w.r.t. object's distance.

$$SDE = M \cdot SB \cdot FD_o$$

- The equation is the same for a dual lens stereo camera.



Depth cues in spaces



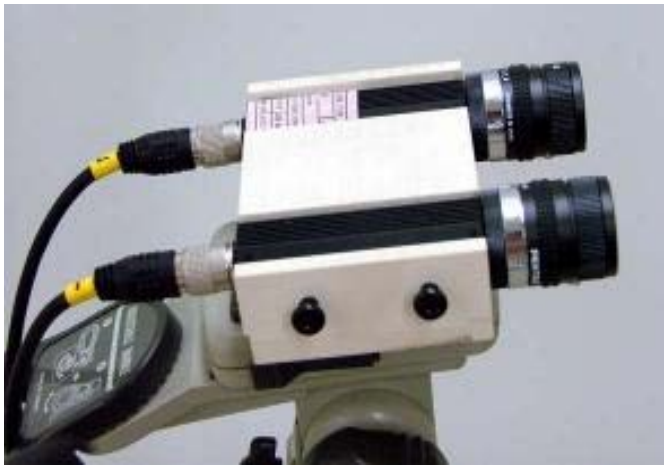
- Disparity
  - The most potent cue in an arm-length reach.
  - Visuomotor coordination

J. E. Cutting et. al., *Perception of space and motion,* Academic press (1995)

Stereo imaging

- Presents disparity to an observer
- Provide matched SDE
- Mismatched convergence and accommodation

Mar's rover 3D camera

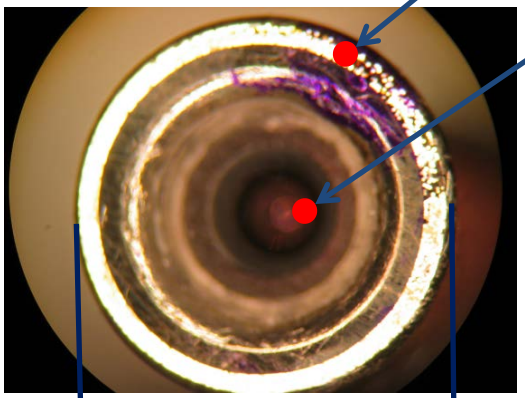


Typical arrangement of a 3D camera

Objectives

- Miniaturize a stereo imaging system into a size fit in a 3-mm diameter.
  - Skull-base minimally invasive surgery
  - Other surgical instruments built around the diameter

SBI_vid1.mp4



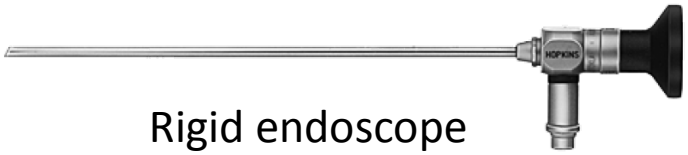
Frontal view of Stryker's 4-mm Dia. monocular rigid endoscope

Why stereo endoscope?

- Better-assist remote tasks
  - Transformation of image to 3D coordinate
  - Helps prehension
- More efficient visuomotor task
  - Shorter task time
  - Fewer error

Stereo endoscopes

- Rigid endoscope
- Fiberoptic endoscope
- Video endoscope (Chip-on-the-stick)



Rigid endoscope

Fiberoptic endoscope

Chip-on-a-stick

3D endoscope by Intuitive surgical Inc.

Engineering

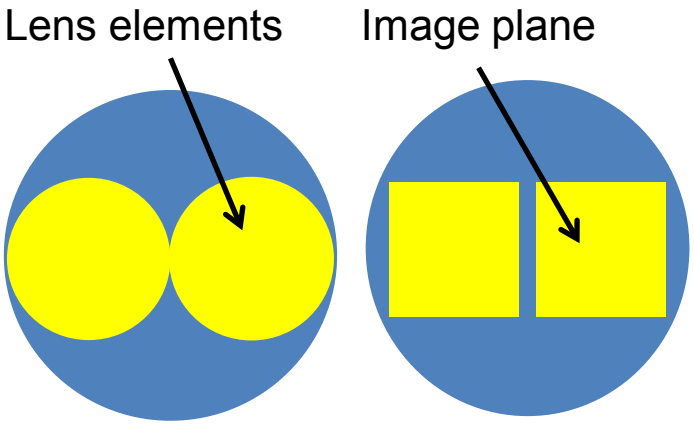
- Can it provide a sufficient stereoscopic depth effect?
- Can a prototype be built with current engineering?

SDE comparison

$$SDE = M \cdot SB \cdot FD_o$$

	Activity	FD	SDE
Human stereoscopic vision	Eating	35 cm	0.09
	Surgical op.	70 cm	0.0022
Dual lens stereo endoscope (1 mm)	Closer op.	1 cm	0.01
	Far op.	3 cm	0.003

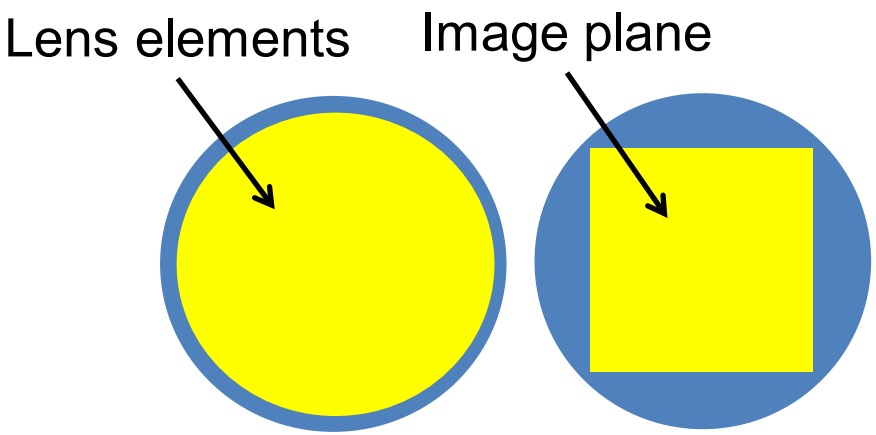
Engineering of dual lens scheme



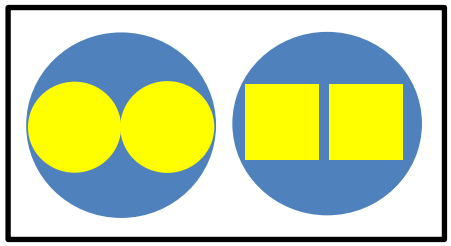
Dual lens scheme

- Two duplicate sets of lens systems and detector array
- 1.5 mm lens elements

Dual aperture scheme

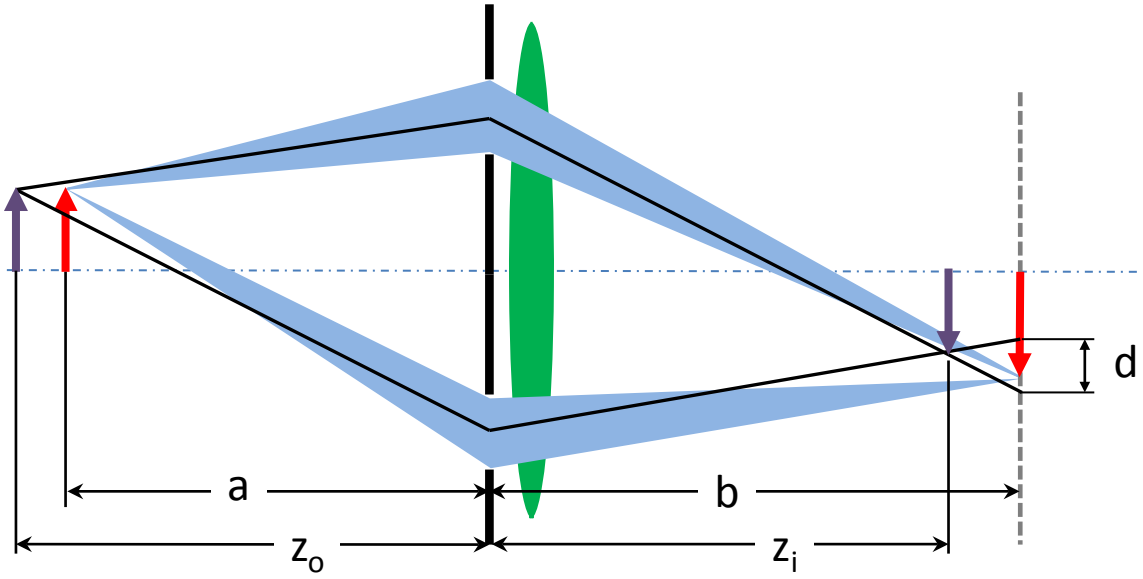


Dual aperture scheme



	Dual aperture	Dual lens
Lens	Single set	Two duplicate sets
Element's diameter	3 mm	1.5 mm
Image plane	1 (Alternating)	2 (Simultaneous)
Pixel size for HD	~2 microns	~1 microns

Dual aperture scheme



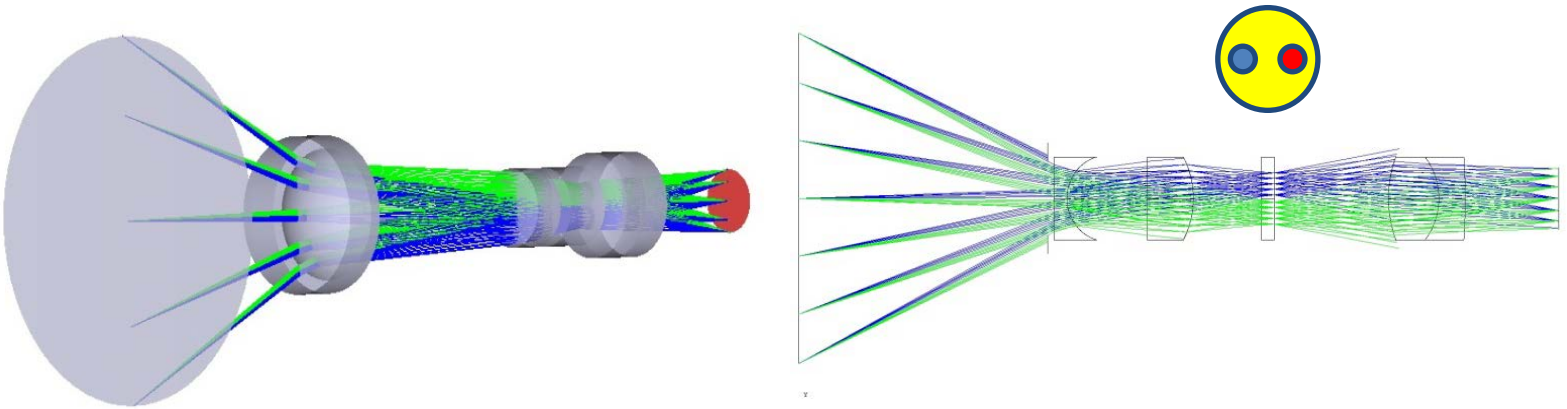
$$d = SB \cdot M \cdot \left(1 - \frac{a}{z_o}\right)$$

$$SDE = M*SB/FD_o$$

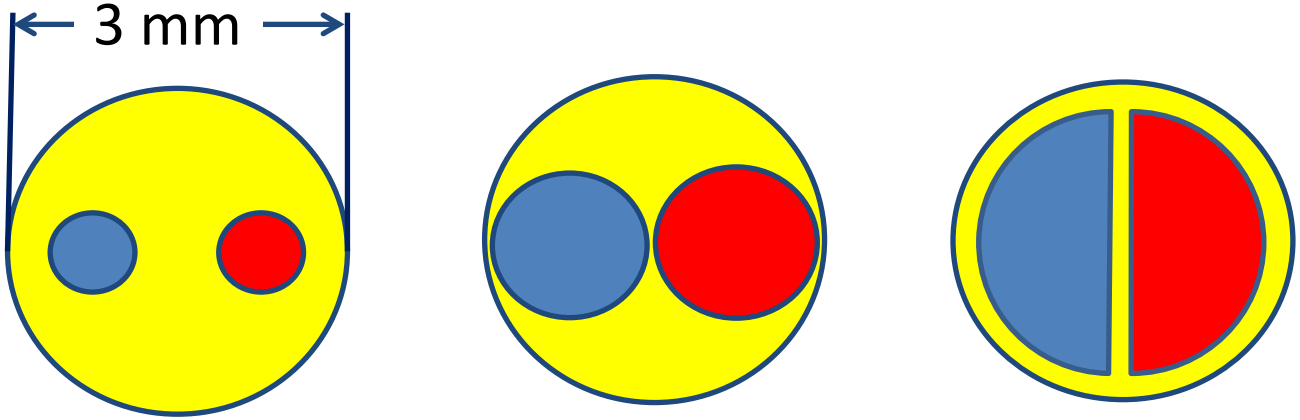
The equation of SDE is the same as dual lens scheme

Stereo Baseline of the Dual Aperture

- Affected by the lens system
  - Defined at the pupil
  - The larger the FOV, smaller the stereo baseline.
- Needs only to be 1 mm



Dual aperture plate



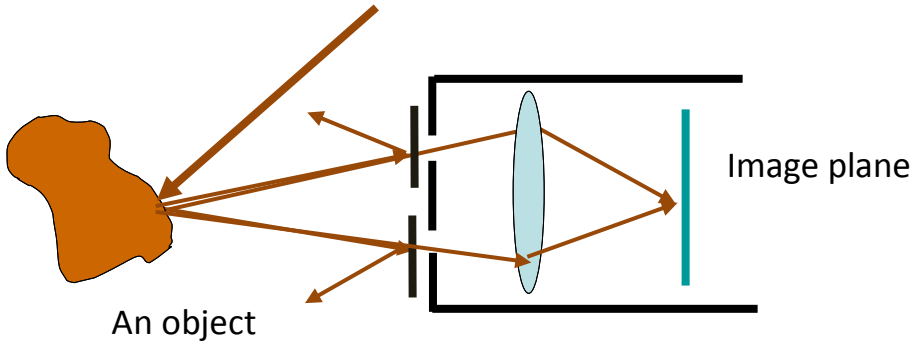
Small aperture/large baseline

Large aperture/small baseline

- 600-micron apertures, 900-micron apart.
- That yielding 0.9 mm stereo baseline

Dual aperture scheme

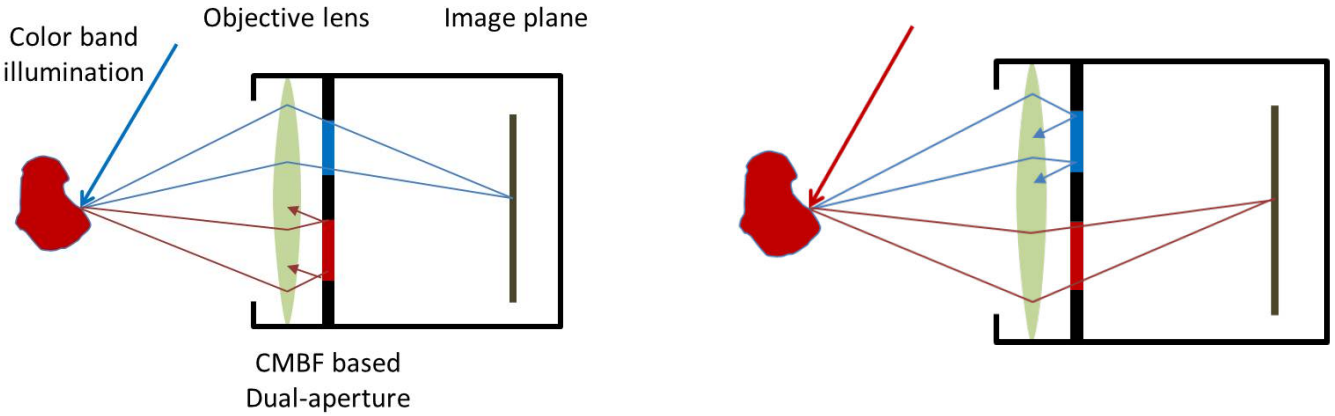
- Projects images from both aperture overlapped
- Requires a means to open apertures one at a time
- Has only a 3-mm space

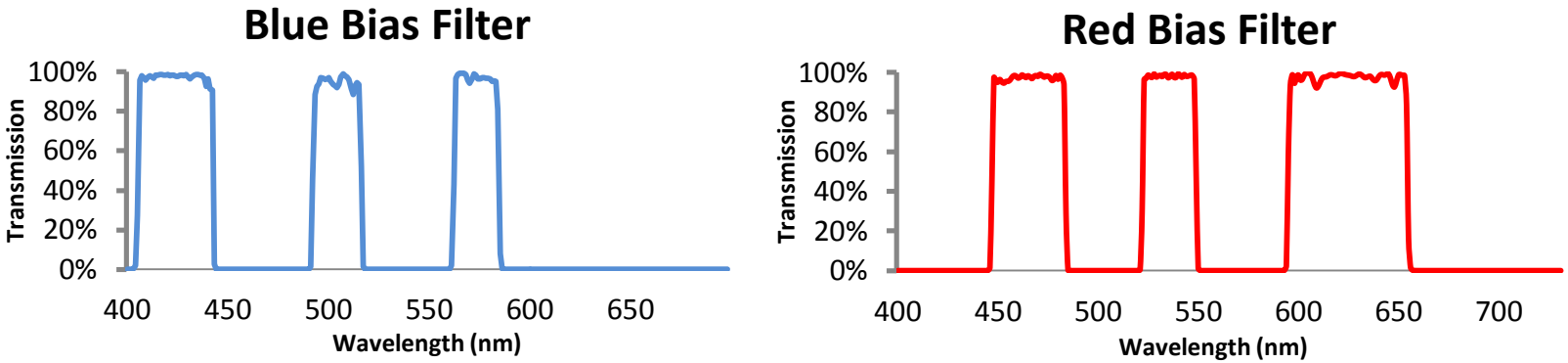


Shutter means

CMBF

(Complementary Multi-band bandpass filters)





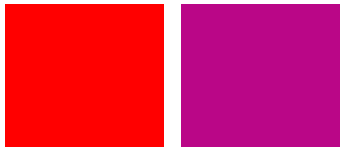
Transmission of the complementary filters

Color difference

- Caused by passing different halves of light bands
- May color rivalry if the difference is large.

Example, image pair from CMBF

- Color fusion[1,2,3]
  - Color rivalry, ΔE>10
  - Color diff. ΔE <10



~ΔE 50

~ΔE 10

[1]JK Hovis, Optometry and Vision Science (1989)
[2]YI Jung, Optics Espress (2011)
[3]M Ikeda, J. of the Optical Society of America (1979)

Mitigation

- Digital Image processing
- Color Transformation
  - Chromatic Adaptation Transformation
  - Least Square Fit

Right raw image

$$\times \begin{bmatrix} Transformation \\ Matrix\ for \\ the\ right\ viewpoint \end{bmatrix}$$

Left raw image

$$\times \begin{bmatrix} Transformation \\ Matrix\ for \\ the\ left\ viewpoint \end{bmatrix}$$

$$=$$

Simulation results

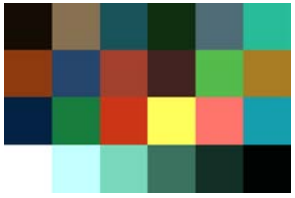
Complementary filter pairs	ΔE raw	ΔE after transformation
Dual-band	57	24
Triple-band	79	21
Quadruple-band	40	6

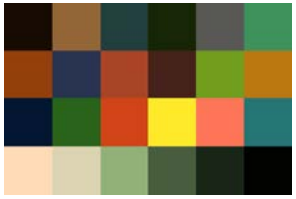
* More the passbands that each filter has, smaller the color difference between the two stereo images

Results

(c) Under Xe lamp light

(f) Under D65 light





(d) Remapped

(g) Remapped

(a) Under the blue bias filter

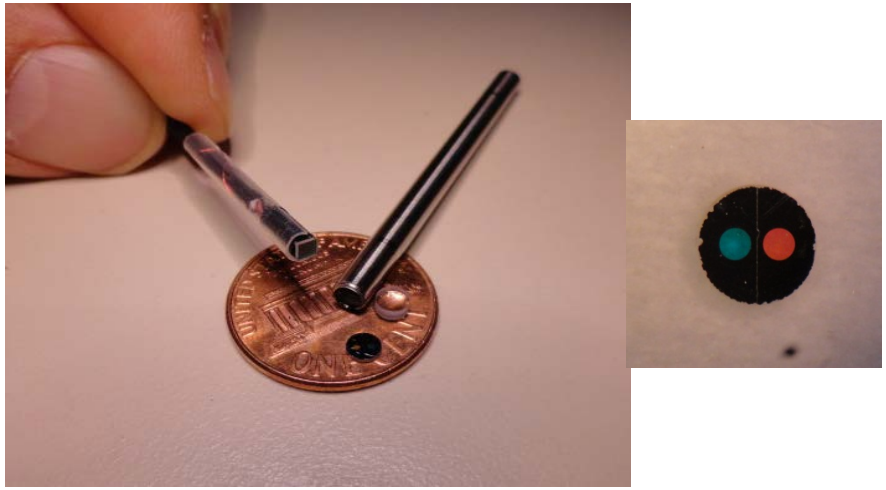
(e) Remapped

(h) Remapped

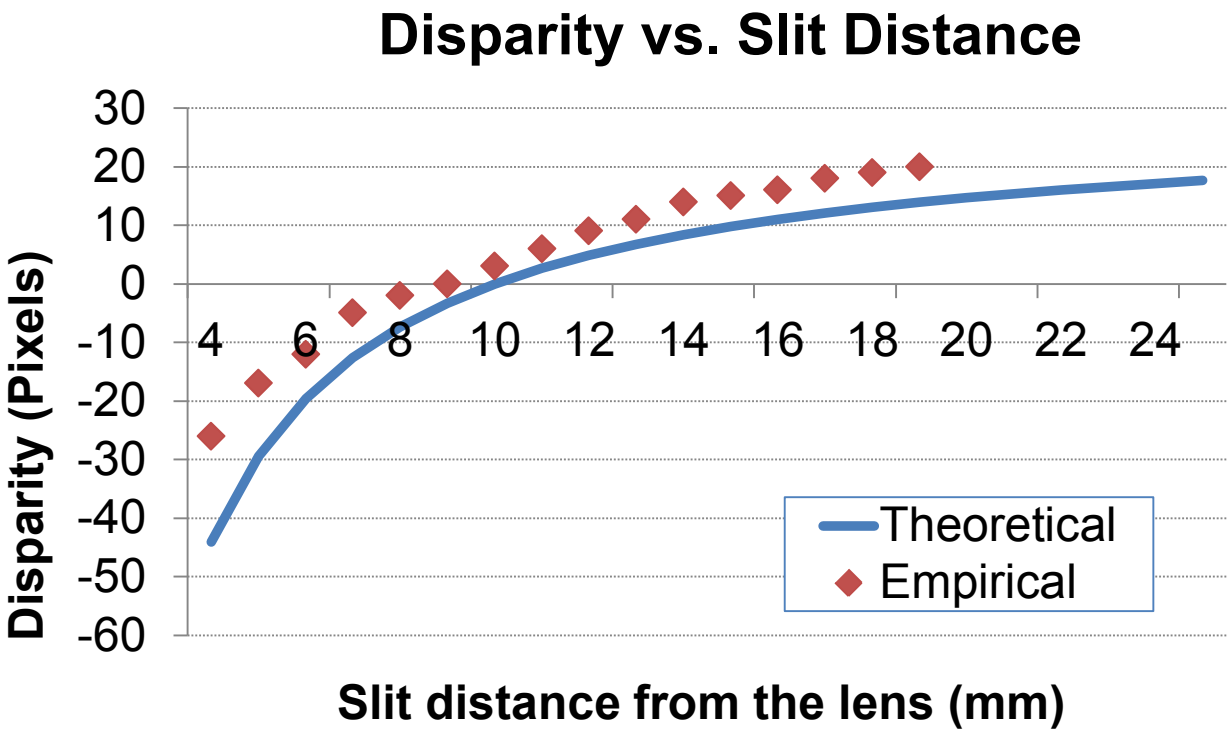
(b) Under the red bias filter

Prototyping

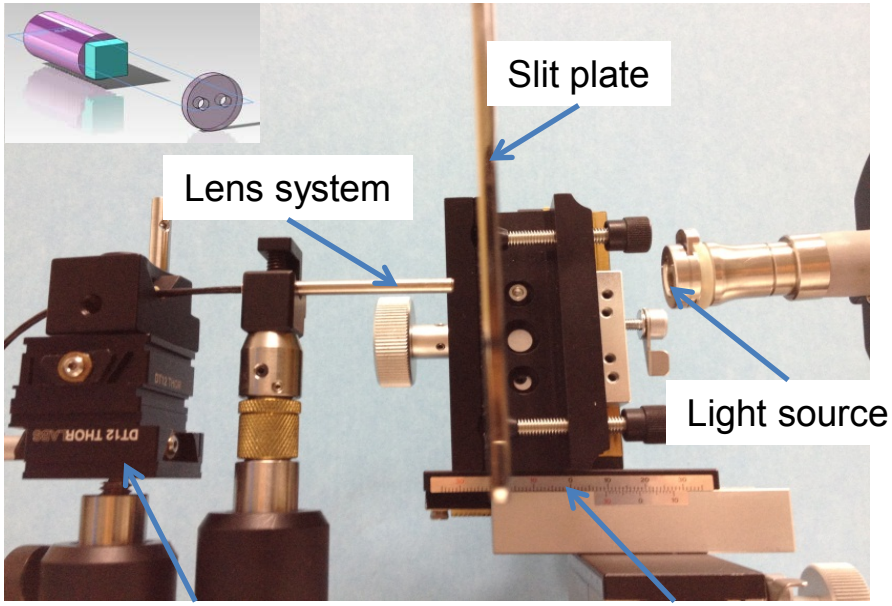
- Lens system: F/16, 52-degree FOV, CMBF
- Detector array: 400 x 400 pixels
- Packaging: 3-mm metal tube
- Image processing: Matlab

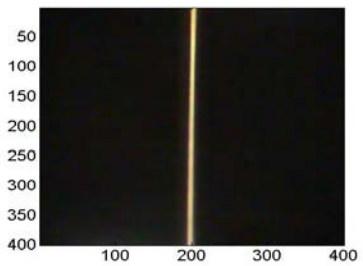


Stereo Depth Effect

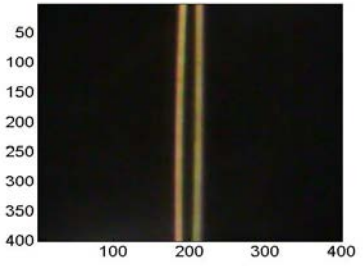


Stereo Depth Effect Experiment





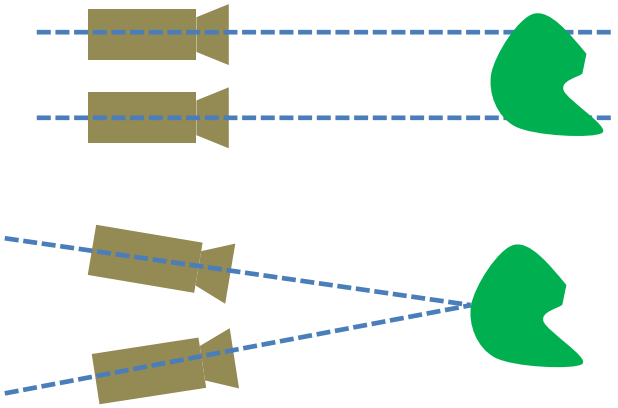
No disparity



Disparity

Convergence and focusing

- Convergence with focusing alone
  - Complete overlap of stereo image
  - The stereo images are more natural to human vision than that of dual lens



Convergence of dual lens

Conclusions

- Prototype fabricated using:
  - Commercially-off-the-shelf 3-mm lens elements
  - Complementary multiband bandpass filters
  - Matlab to produce 6 fps image-speed

- Prototype producing:
  - Color images
  - SDE 1 to 2.5 cm

Conclusion

- The prototype can yield stereo depth effect sufficient for skull-base minimally invasive surgery.
- The dual aperture scheme can be applied to build a stereo camera.
- The engineering demonstrated simplicity in the fabrication and feasibility in miniaturization.

Acknowledgement

- Professor Monbouquette
- Dr. Harish Manohara
- Ronald Korniski
- SBI/NASA