Bio-mimetic optical sensor for real-time measurement of aircraft wing deflection

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Outline

- Innovation
- Technical approach
- Impact of the innovation
- Results of Seedling effort to date
- Distribution/Dissemination
- Next steps

Collaborators at University of Wyoming

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Prof. Steven F. Barrett Mr. Md. Arif Khan

Mr. Robert W. Streeter

The Innovation

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Front view of sensor head with U.S. dime for comparison

Bio-mimetic sensor takes advantage of desirable aspects of vision system of *Musca domestica*, the common house fly

- Motion hyperacuity, e.g., ability to track motion at extremely small increments
- Fast processing speed
- Low power requirements
- Lightweight
- Small form-factor

Motivation

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Need measurement of wing deformation for next generation energy efficient aircraft configurations[1]

Current solutions: Strain gauges, fiber optic strain sensors, accelerometers, GPS, traditional cameras

[1] http://www.aeronautics.nasa.gov/ [Accessed 1/27/2014]

An Enabling Technology

Aerovironment's Helios[1]

"The [Mishap Investigation] board determined that the mishap resulted from the inability to predict, using available analysis methods, the aircraft's increased sensitivity to atmospheric disturbances such as turbulence, following vehicle configuration changes [...]."[1]

[1] http://www.nasa.gov/centers/dryden/news/ResearchUpdate/Helios/ [Accessed 2/10/2014]

Traditional Cameras

- Single-aperture design (based on anatomy of the human eye)
- High resolution, large pixel array
  - Charge coupled device (CCD)
  - Complementary metal oxide semiconductor (CMOS) array
- Lens (or lenses) used for focusing image onto array
- Large data transfer required
- Detection usually requires significant data processing
- Target movement cannot be measured across a pixel

Musca domestica

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- Scanning electron microscope image of *Musca domestica*
- Depiction of associated first layer neural "wiring"
- Neural superposition

Image courtesy of Alex Wild
www.alexanderwild.com

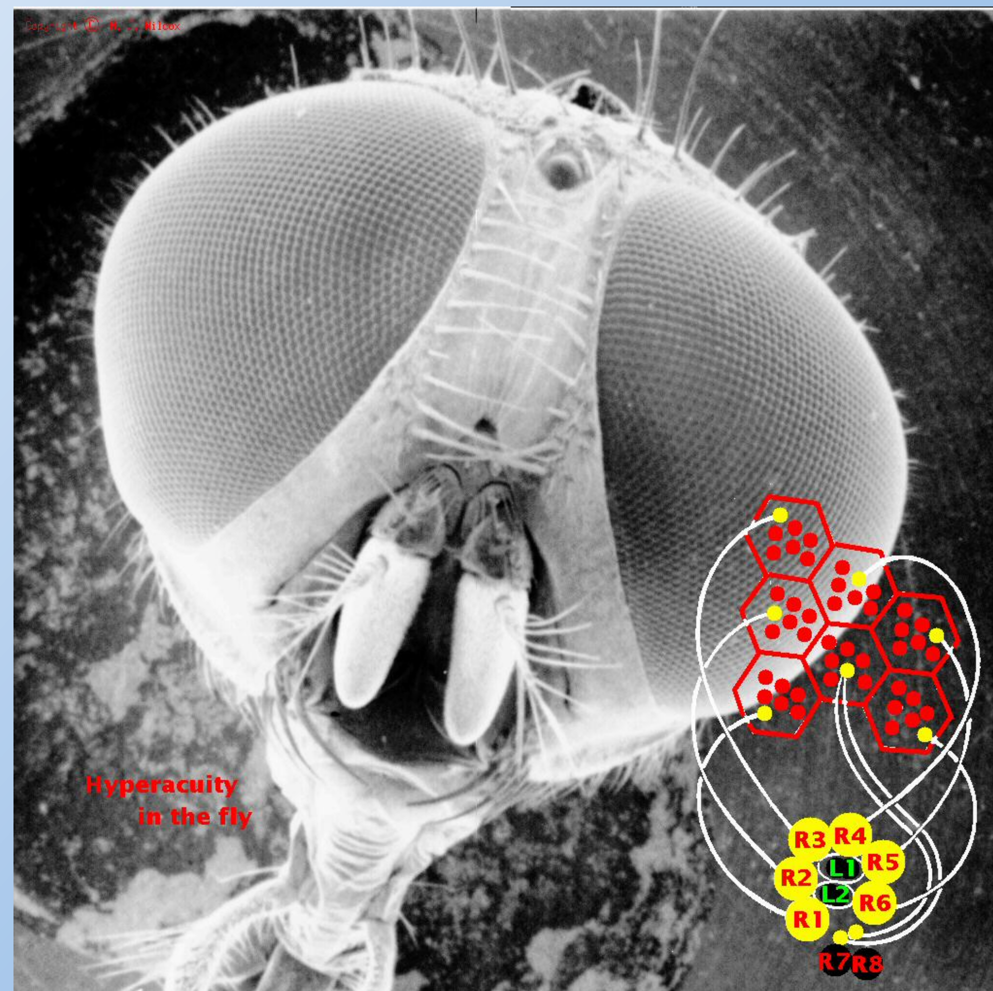
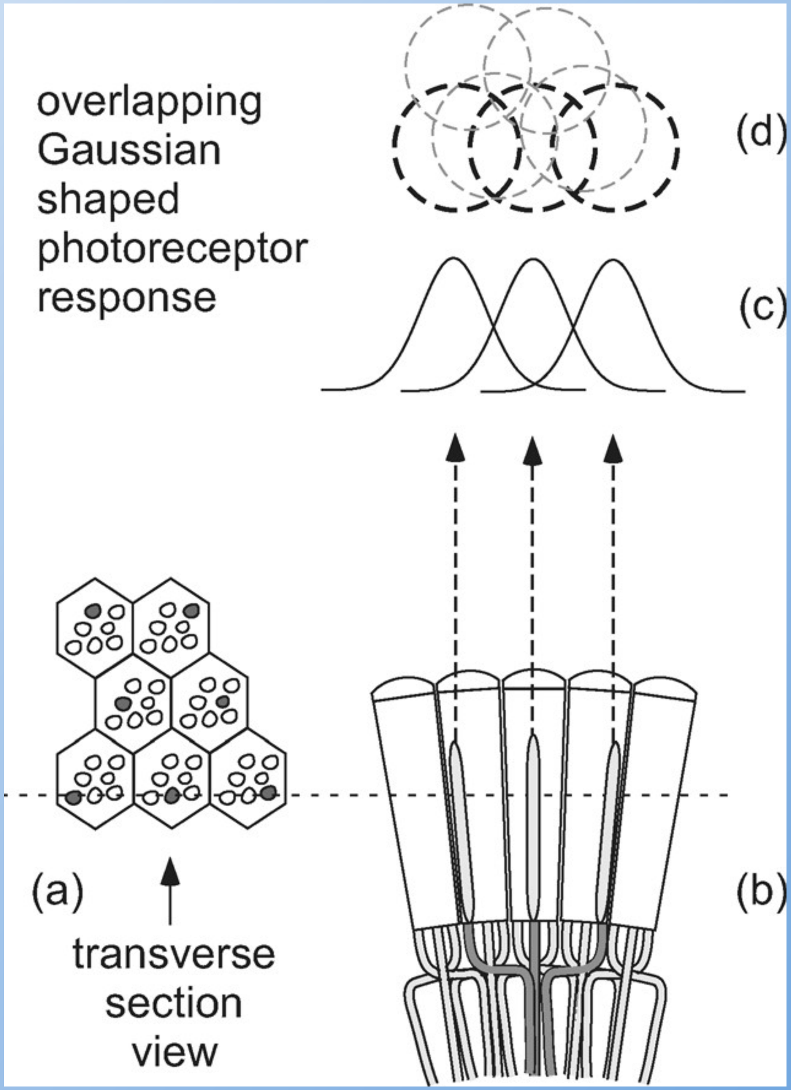


Image courtesy of M. Wilcox

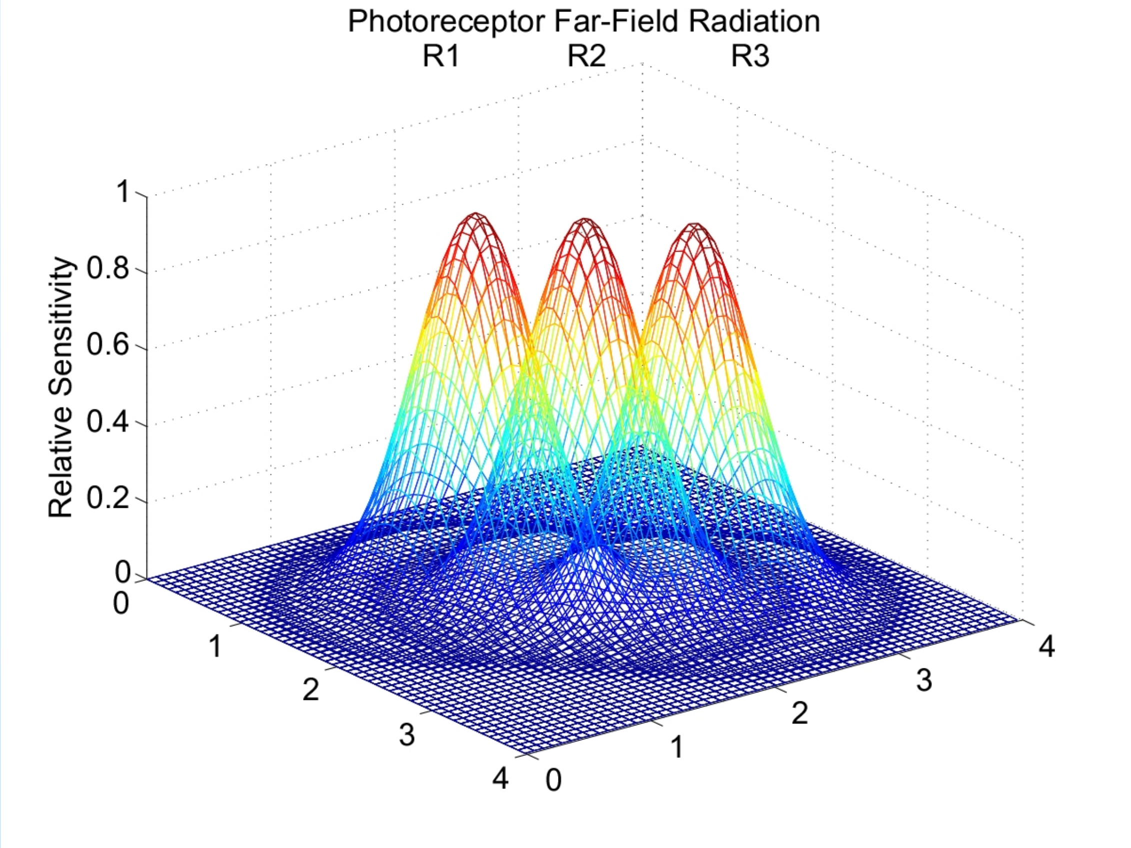
How does the fly eye work?

Simplified diagram showing Gaussian overlapping photo-receptor response and neural superposition; each hexagonal shape in (a) delineates the cross section of a structure called an ommatidium.



Overlapping Gaussian Response

Overlapping Gaussian response similar to that exhibited by compound eye of common house fly

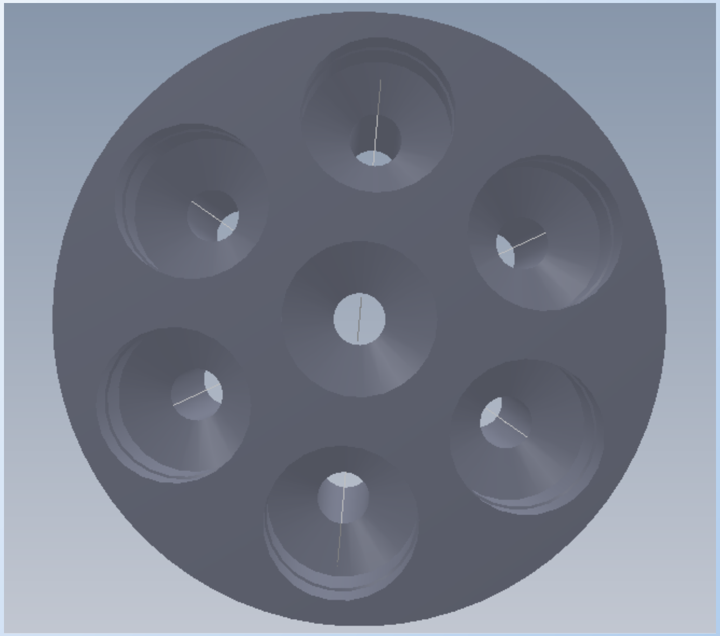


Sensor Head

Sensor head with lenses and fibers attached

- Machine milled aluminum
- Outer diameter is 12 mm
- Head height is 9 mm
- 7 photodarlington detectors (IF-D91)
- 1 mm multi-modal, single-fiber optical light guides
- 3 mm lenses

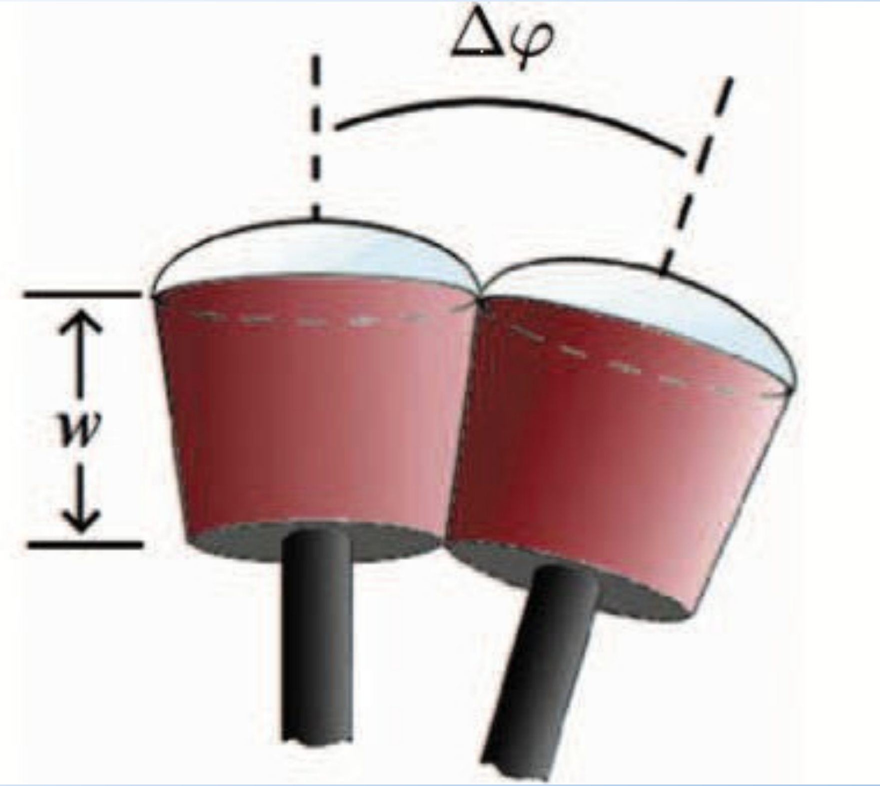
Sensor Head Housing



Sensor head housing (SolidWorks™ drawing)

- Sensor housing designed to:
  - Incorporate multi-aperture nature of *Musca domestica* eye
  - Facilitate stable packaging of sensors on a spherical surface
  - Be small and rugged
- Sensor housing optimized for:
  - Response
  - Motion acuity
  - Scalability for commercial production

Photo Receptors Alignment



Detail of two photo receptors in sensor head

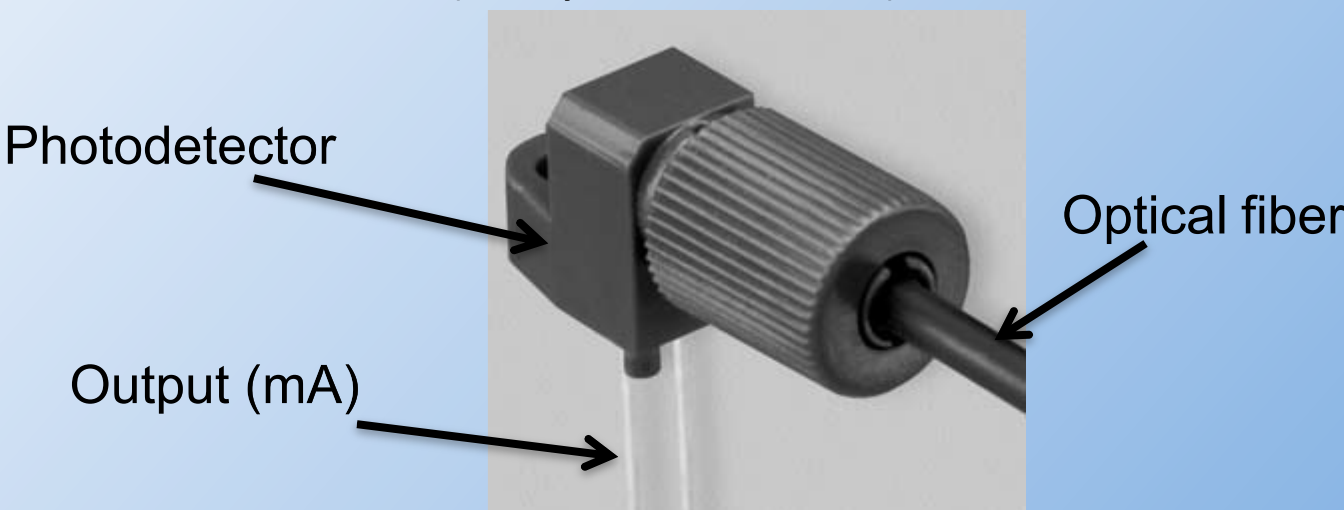
$w \equiv$ distance between lens and image plane (2.4 mm for pre-blurring)

$\Delta\varphi \equiv$ angle between two lenses (7.5 deg for 50% overlap)

Detectors

Photodarlington detectors (IF-D91) :

- Semiconductive devices
- Output a current proportional to number of photons impinging on element
- Current is small (0.1 µA to 10 mA)



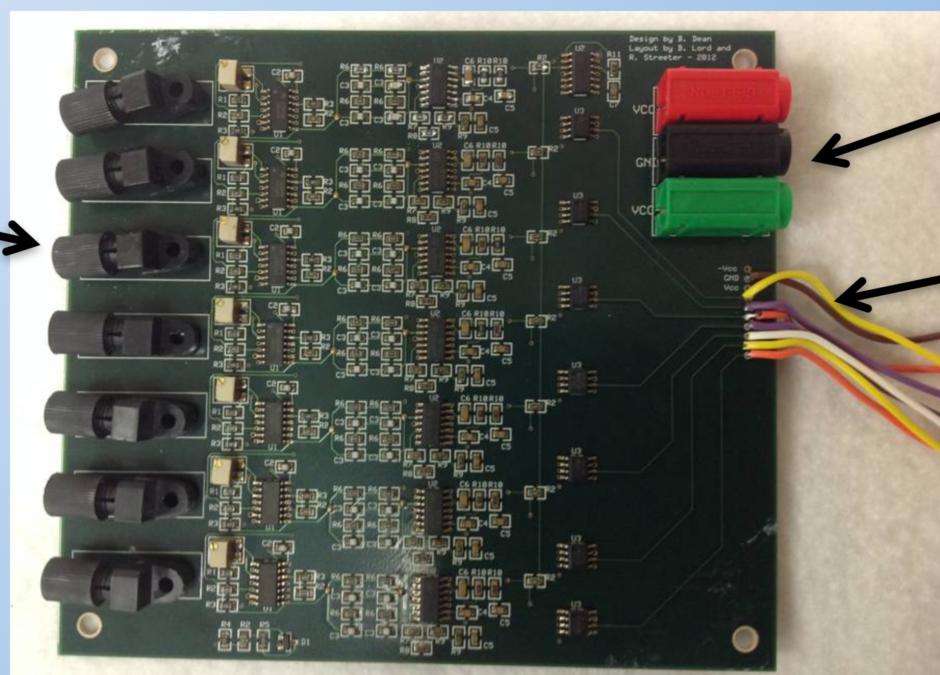
IF-D91 Fiber optic detector
www.i-fiberoptics.com

Sensor Functionality

Block diagram of sensor functionality through a single channel

($i \equiv$ current, $v \equiv$ voltage)

Sensor PCB

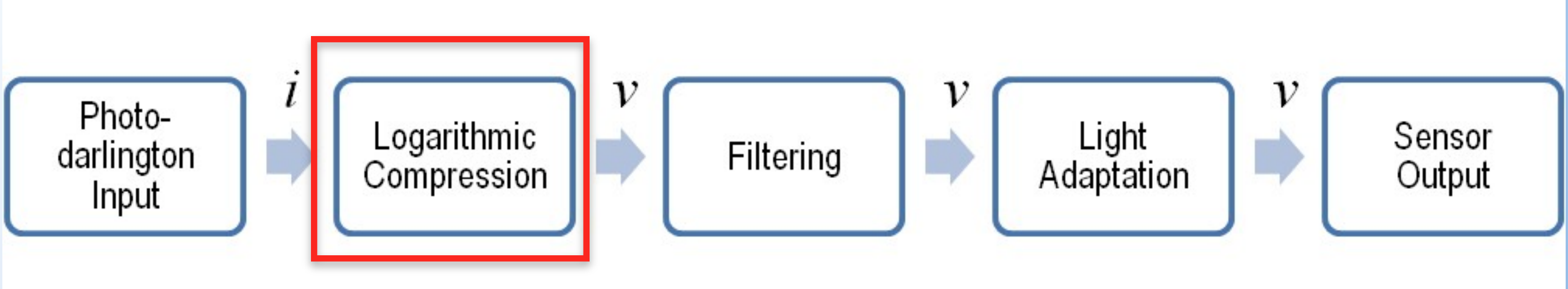


Photodarlington Input

Power (±15 VDC)

Analog Outputs (VDC)

Logarithmic Compression



Logarithmic Compression Circuit:

- Current-to-voltage conversion
- Logarithmic amplification to achieve increased dynamic range
    - Enables use of sensor in wide variety of ambient lighting conditions (e.g., from dim light to extremely bright conditions)
    - Ensures adequate image contrast for detection purposes

Filtering

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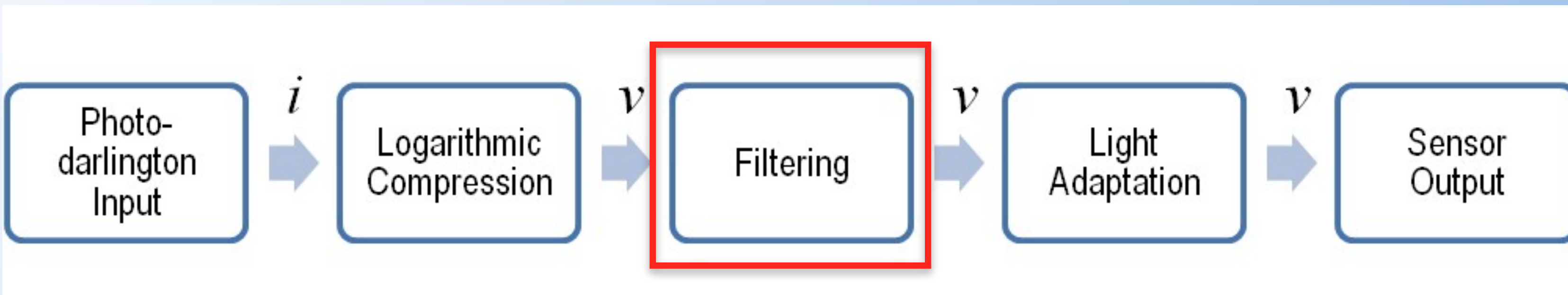

Filtering Circuit:

- Active filters for noise removal, including flicker from interior lighting
- 4th-order Butterworth low-pass filter with a 50 Hz cutoff frequency
- Notch filter centered at 60 Hz
- Inexpensive
- Small number of components

Light Adaptation

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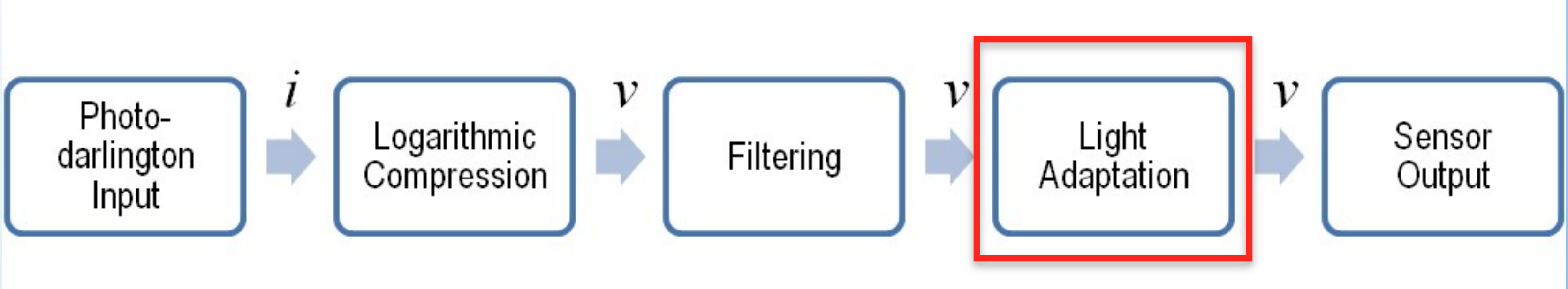


Light Adaptation Circuit:

- Sensor can adapt to different levels of ambient lighting
- Makes use of average value of ambient lighting
- Computed average is filtered to near DC using active filter, reducing oscillations caused by detected motion
- Average is subtracted from each of the 7 signals independently
- Delay is added so light adaptation circuit does not react instantaneously (sample and hold circuit with a timer)

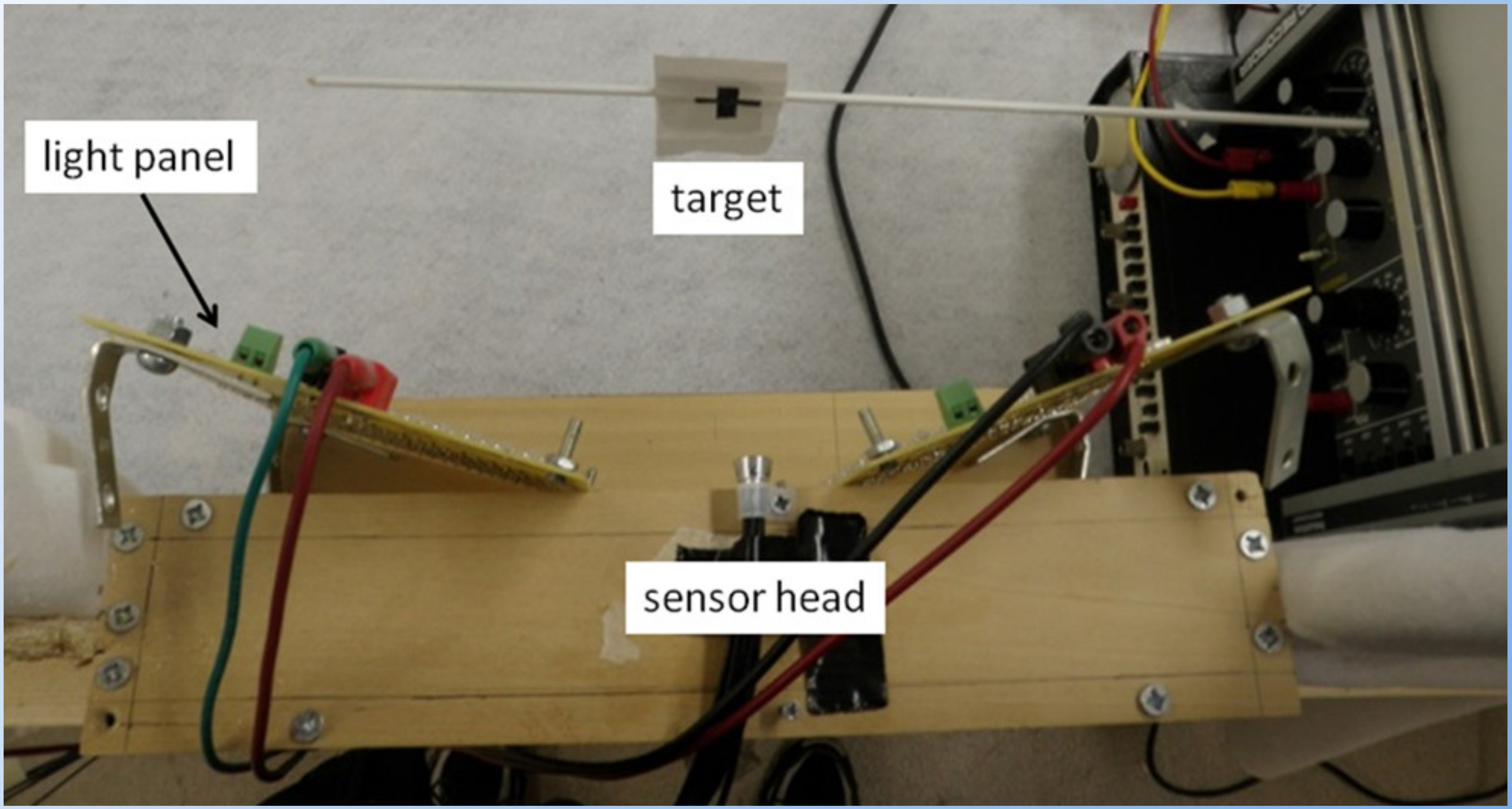
Sensor Summary

Benefits:

- Small form factor, light weight
- Very low power requirements
- Hyperacuity to motion
- Extremely fast response
- Excellent signal to noise
- Ambient light adaptation
- Adjustable bandwidth depending on application

Parameter	Min	Typical	Max
Output [V]	~0.0	0.49	0.72
Operating Range [cm]		25.4	~130-150
Weight (sensor, PCB, cables) [g]		135	
Input Illuminance [lx]	1	520	36,000
Power Consumption [W]		3.3	

Test Set-up



Sensor head mounted in test box with target and light panel

Target Motion

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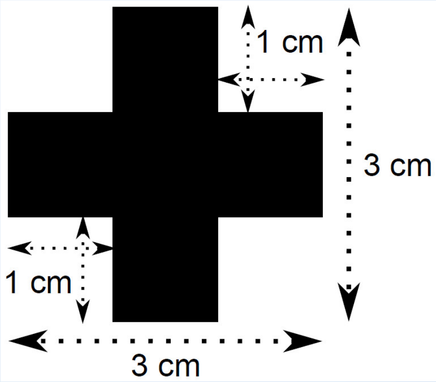
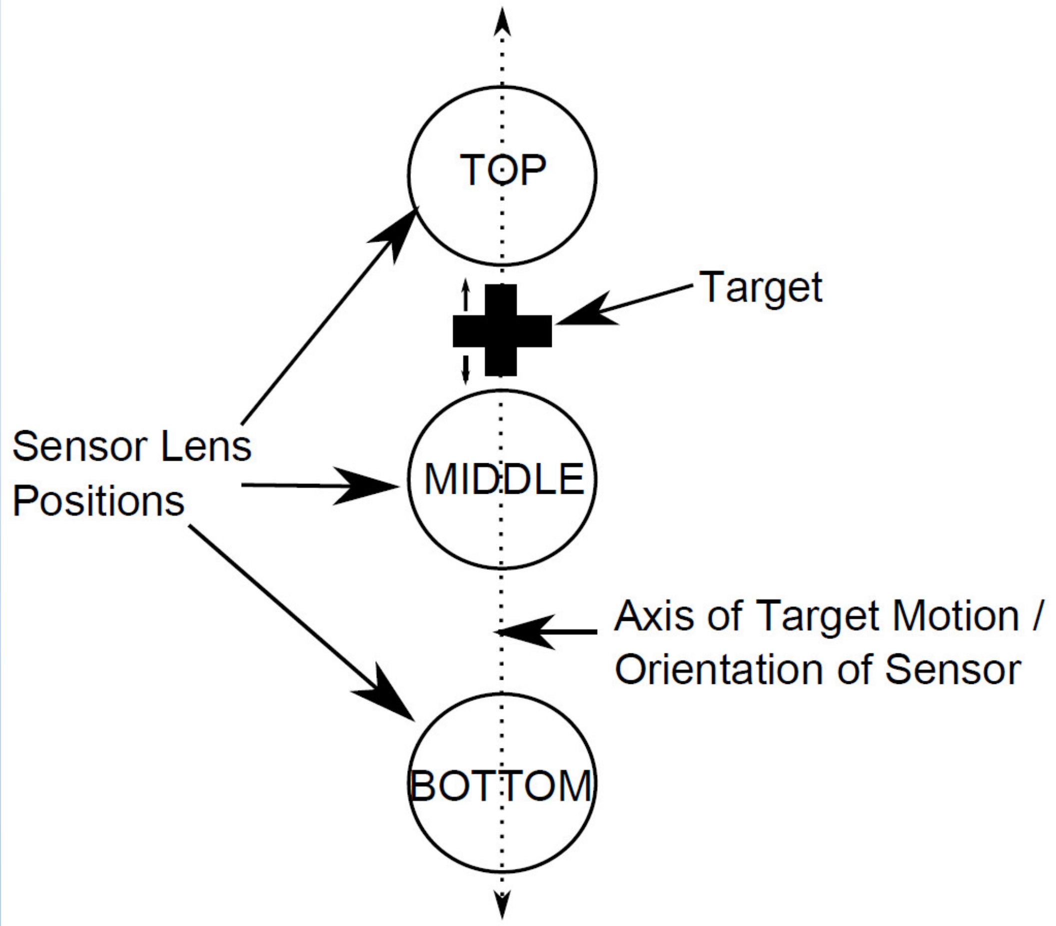


Image of target used for testing



Alignment of sensor's primary axis and motion axis of target (Target not to scale)

Noise Removal

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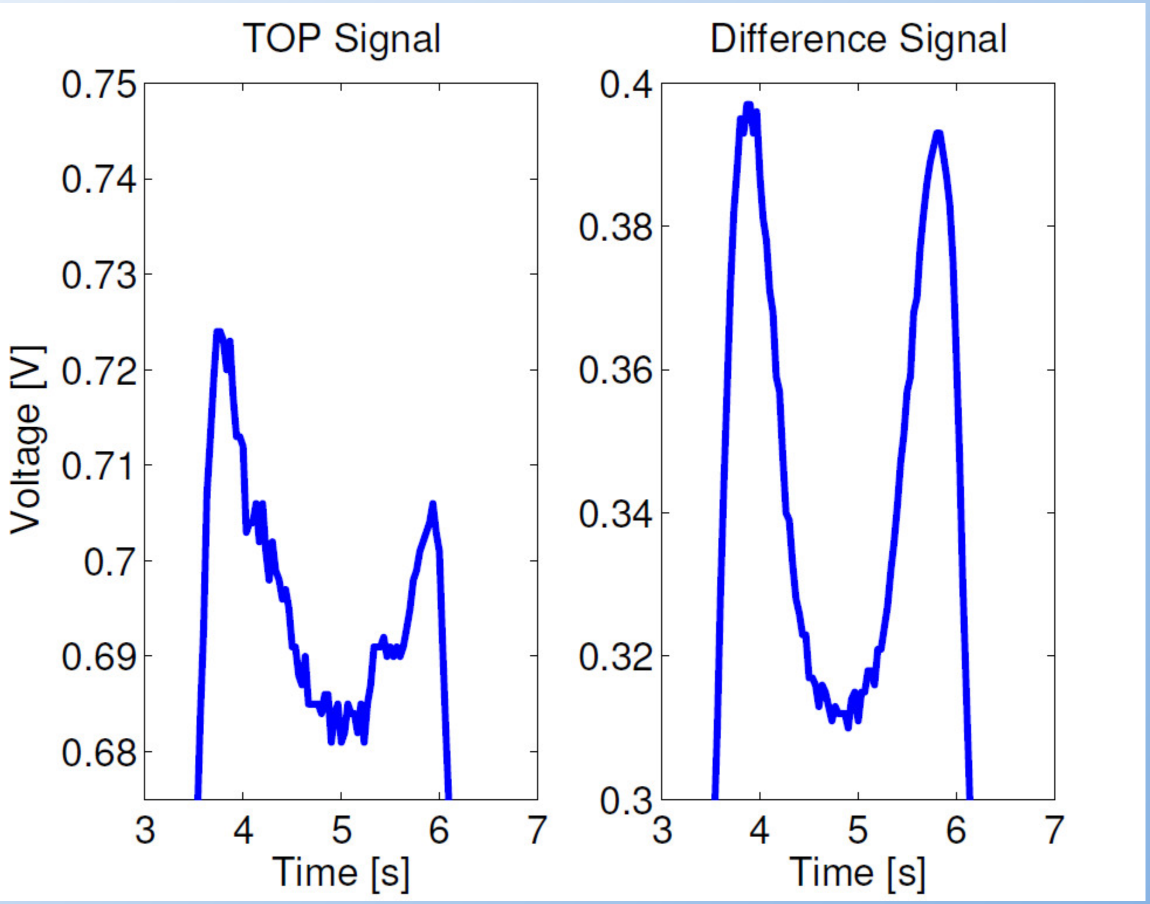

Quantitative noise comparison of scaled TOP signal and difference signal (TOP minus BOTTOM)

Position Reconstruction

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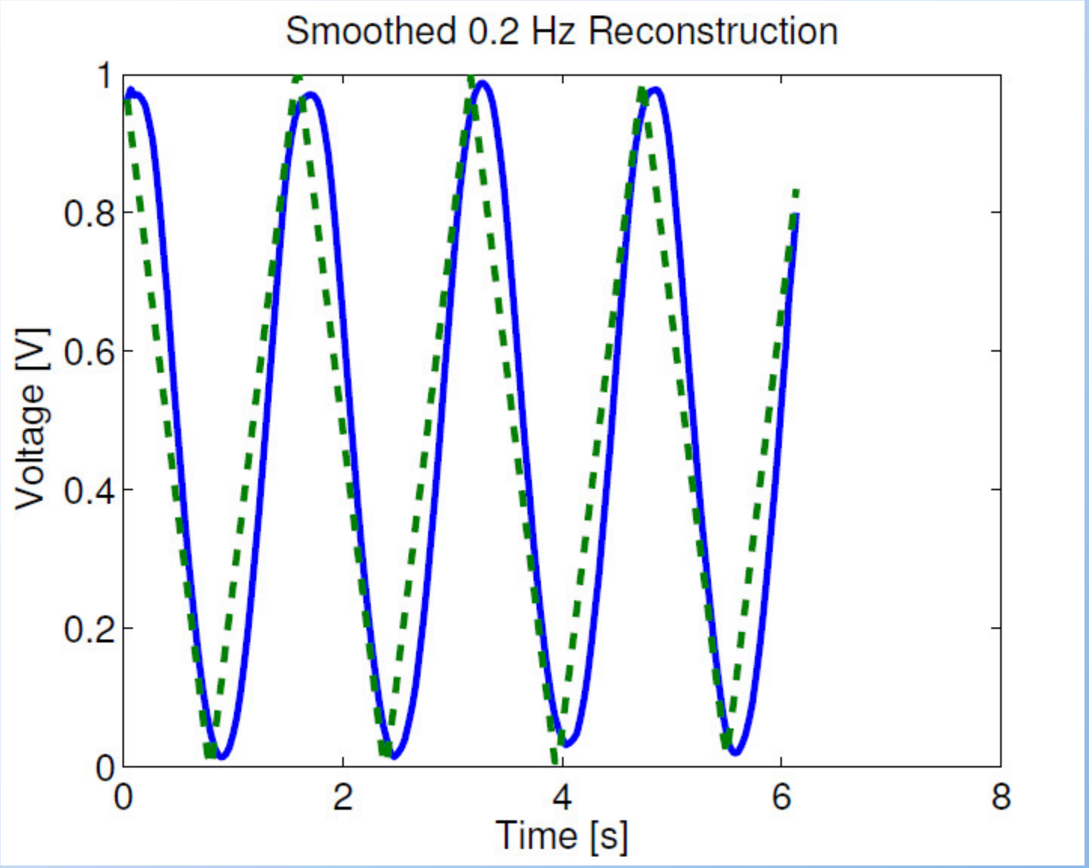

Position reconstruction with smoothing for target oscillating at 0.2 Hz (solid line) and position truth (dashed line)

No Smoothing

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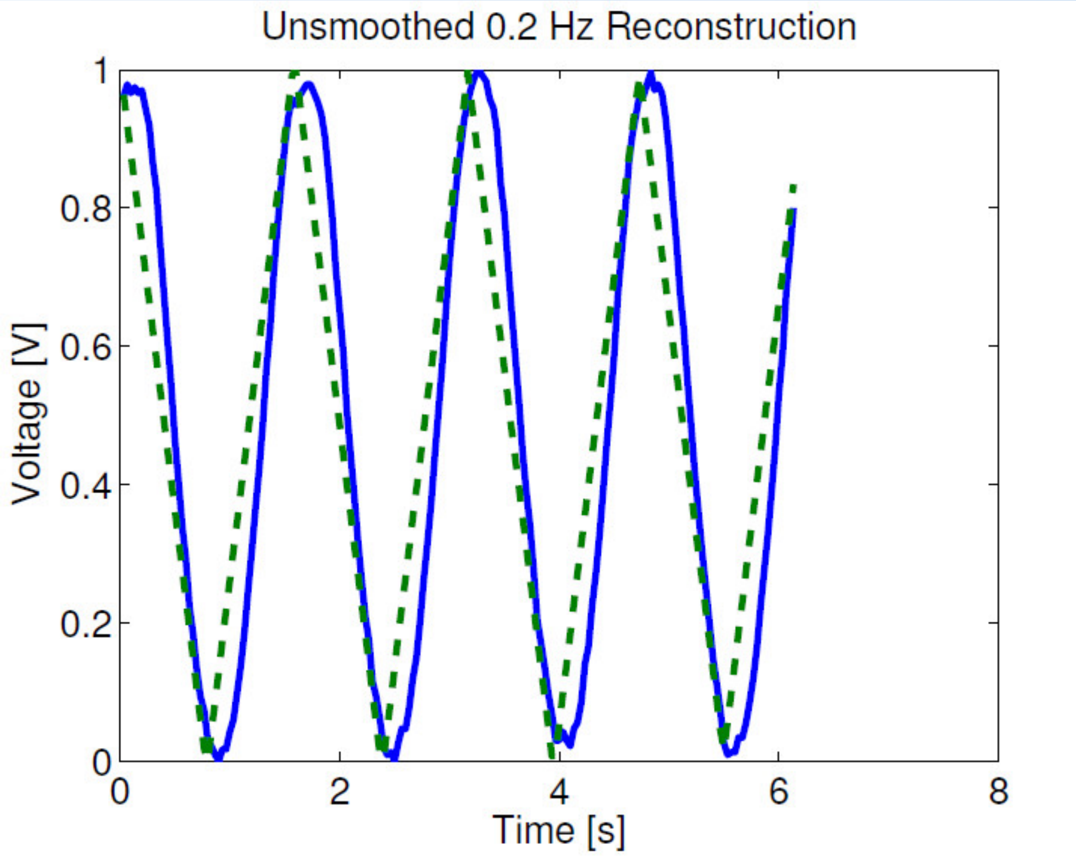
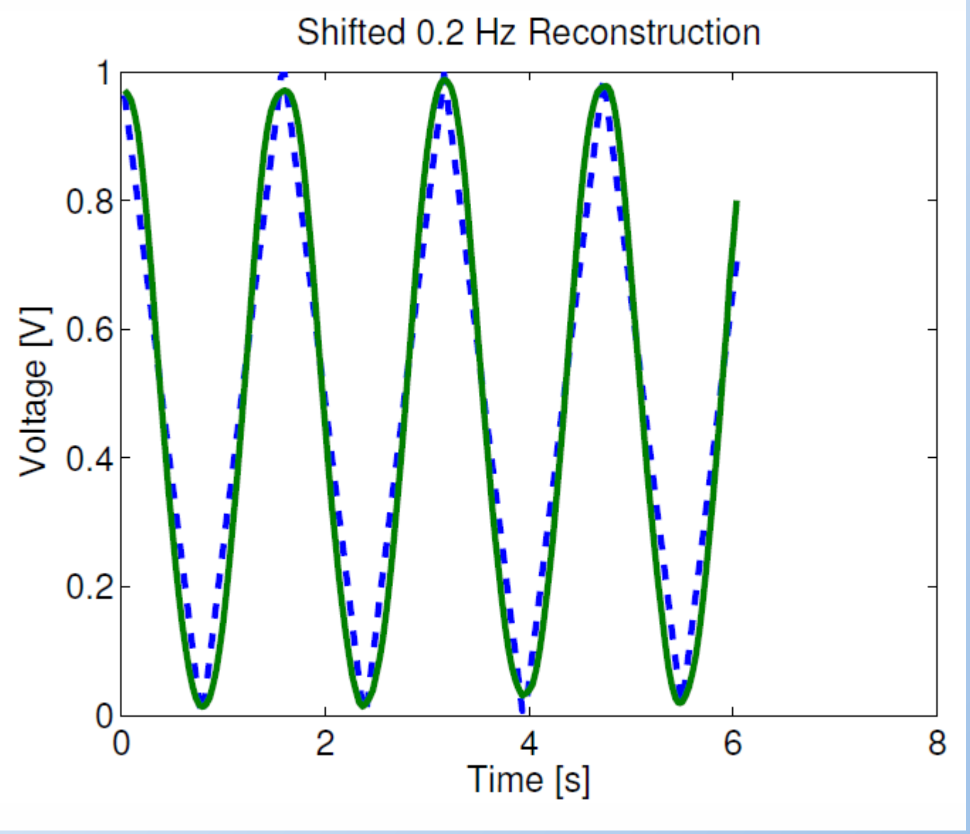


Position reconstruction with no smoothing for target oscillating at 0.2 Hz (solid line) and position truth (dashed line)

Shifted Reconstruction



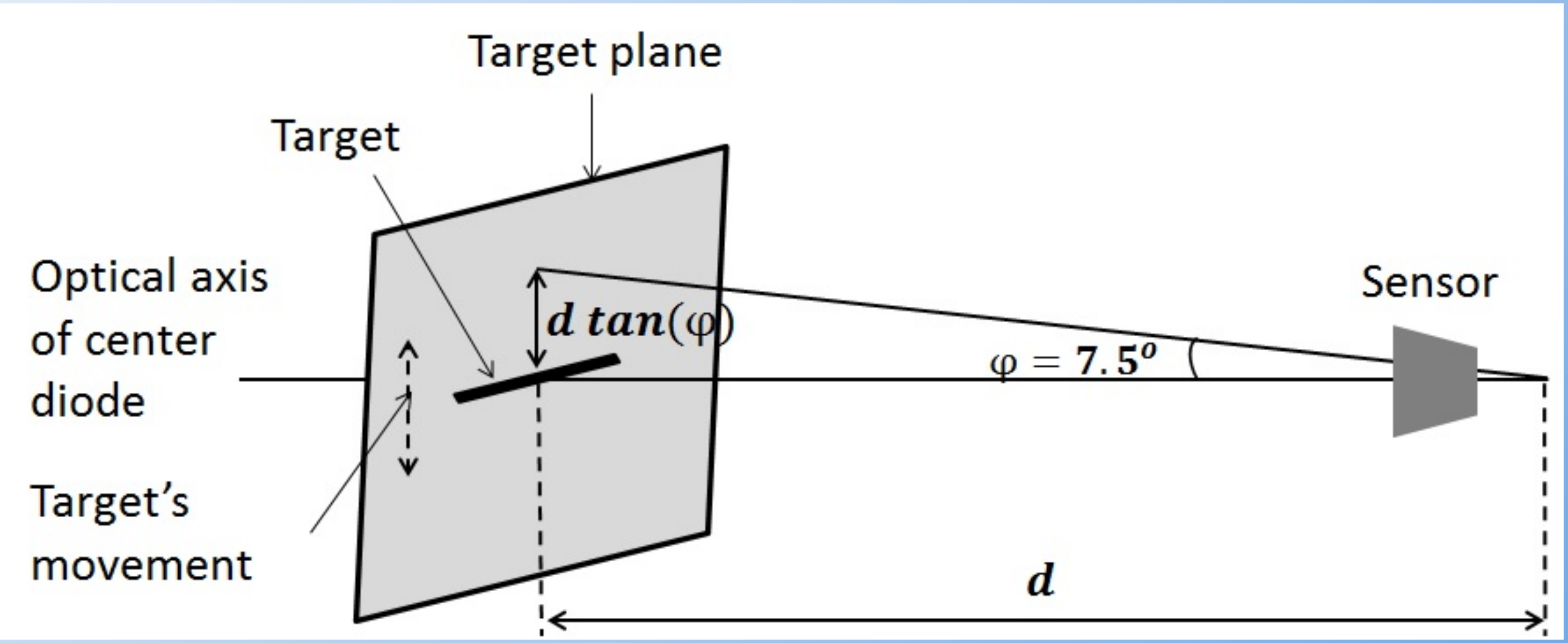
Shifted and smoothed position reconstruction for target oscillating at 0.2 Hz (solid line) and position truth (dashed line)

Parameter	**Value**
Mean squared error	0.0049
Root mean squared error	0.0697
Maximum error	0.1161
Average error	0.0624

Sensor Simulation

Matlab™ simulation of sensor was developed

- Target shape and size can be modified
- Target movement can be controlled
- Target-background contrast can be changed



Simulated Sensor Response

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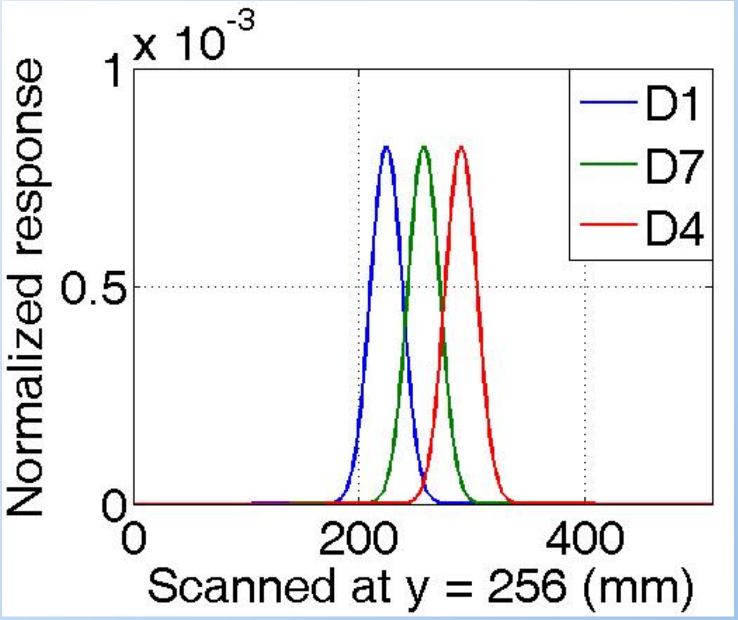
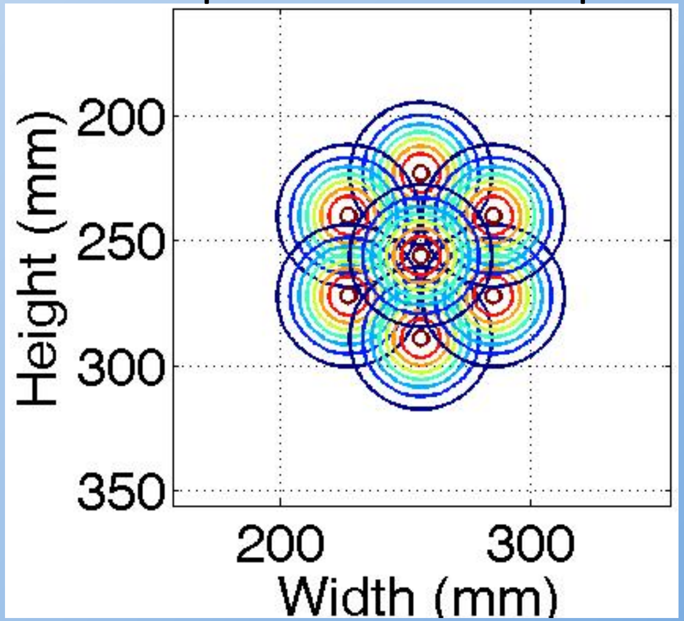
Target position

Sensor diodes

Response of adjacent pixels when a vertical line is scanned



Contour plot of sensor response



Simulation Studies

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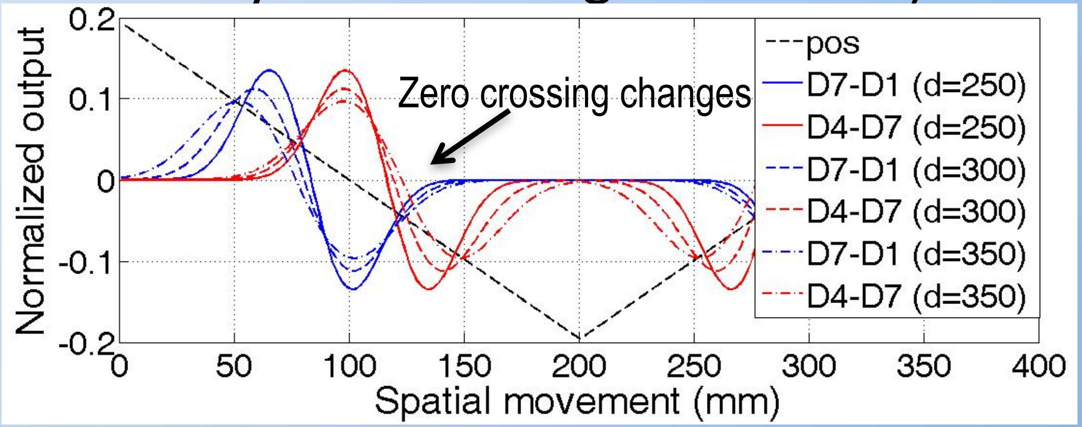
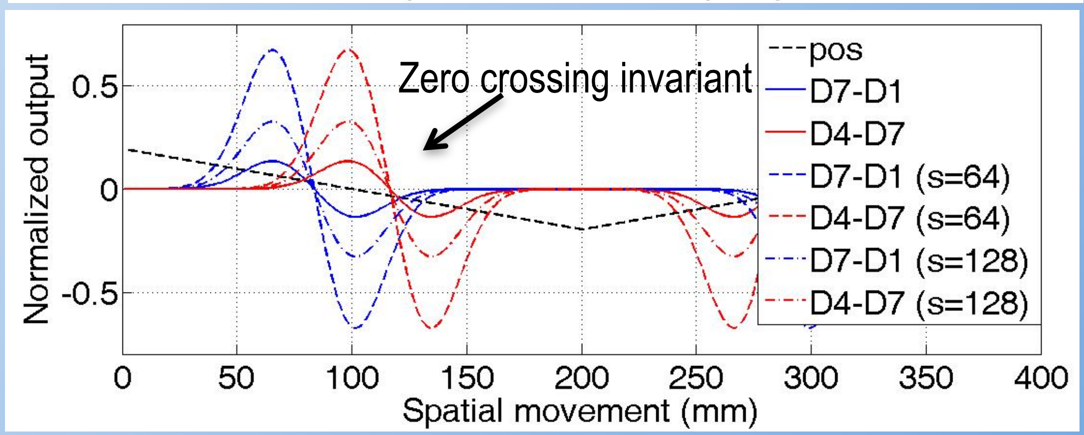
- Edge localization is independent of target-background contrast
- Investigation of zero crossing of difference between two adjacent pixels (commonly used for edge detection)

Target located at different distances (d=250, 300, 350 mm) from sensor



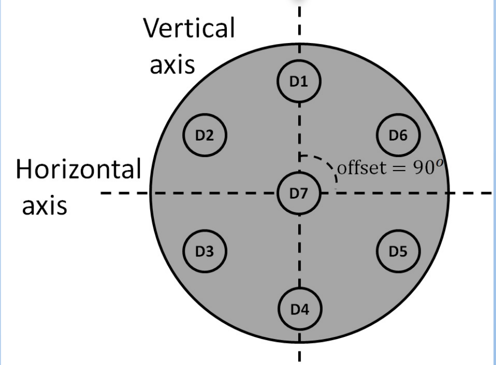
Target shifted to right by different distances (s=0, 64, 128 mm)



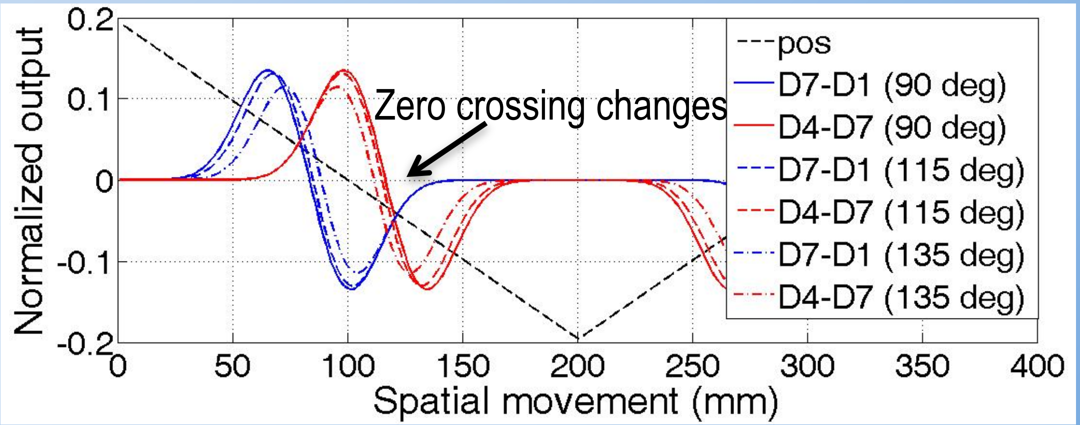
Simulated Target Motion

Zero crossing is affected by change in direction of target motion

Target direction of travel
(offset = 90 deg)



Target located at different offset angles from horizontal axis (offset=90, 115, 135 deg)



Results of Seedling Effort

- 2 Sensors designed, built, tested, and operational
- Algorithms developed for real-time target tracking
- Sensor simulation developed and verified
- Testbed constructed
- Provisional U.S. Patent Application filed 02/25/14
- Publications
  - *SPIE Smart Structures/NDE Conference*, San Diego, CA, March 2014, 1 paper.
  - *Rocky Mountain Bioengineering Symposium,* Denver, CO, April 2014, 3 papers.
  - M.S. Thesis successfully defended, University of Wyoming, Dept. of Electrical and Computer Engineering

Distribution/Dissemination

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- Frost, S.A., Wright, C.H.G, Streeter, R.W., Barrett, S.F., and Khan, M.A., "Bio-mimetic optical sensor for structural deflection measurement," to appear *SPIE Smart Structures/NDE Conference*, San Diego, CA, March 2014.
- Khan, M.A., Streeter, R.W., Wright, C.H.G, Barrett, S.F., and Frost, S.A., "Localization of a Moving Target using a Fly Eye Sensor," *to appear Rocky Mountain Bioengineering Symposium,* Denver, CO, April 2014.
- Khan, M.A., Streeter, R.W., Wright, C.H.G, Barrett, S.F., and Frost, S.A., "Effect of Sensor-Target-Background Distance on Target Tracking using a Fly Eye Sensor," *to appear Rocky Mountain Bioengineering Symposium,* Denver, CO, April 2014.
- Streeter, R.W., Khan, M.A., Barrett, S.F., Wright, C.H.G, Frost, S.A., "Results of Target Tracking with a *Musca domestica* Inspired Sensor," *to appear Rocky Mountain Bioengineering Symposium,* Denver, CO, April 2014.
- Streeter, R.W., "Target tracking with a *Musca domestica* based sensor platform," M.S. thesis, University of Wyoming, 2013.

Next steps

- Phase 2 Proposal
- Build test environment that enables target tracking in 3 dimensions
- Develop FPGA sensor board for real-time implementation
- Improve target tracking algorithms
- Integrate sensor on UAV
- Perform flight test on UAV
- Investigate use of active targets (LED)

Questions?

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Prof. Cameron H.G. Wright Prof. Steven F. Barrett

Mr. Robert W. Streeter Mr. Md. Arif Khan