Optomechatronics with Adaptive Optics

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Optomechatronics

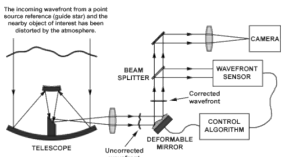
Integrated design, optimization, and control of automation systems involving active optical, mechanical and electronic components.

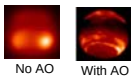
Adaptive Optics (AO): Devices that can change wavefront in real-time, in response to environmental or operating conditions.

- Examples:
  - Deformable mirror (DM)
  - Liquid crystal spatial light modulator (SLM)
  - Fast steering mirror
  - Liquid lens
  - Segmented micro-mirrors
  - Digital micromirror device (DMD)

Existing Applications of AO

Atmospheric aberration compensation

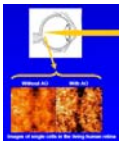




Keck Telescope (Laird Close, Arizona, 2002)

Vision Science (Retina Imaging)

David Williams (Rochester, 1997, 2004)



New Emerging Opportunities for AO

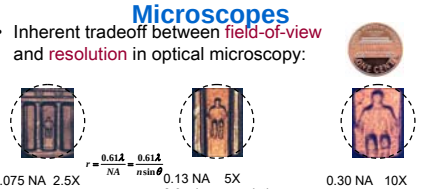
- Microscopy: Correct for intrinsic optical aberrations to enhance resolution.
- Telescope: Correct for atmospheric disturbance as well as astigmatism from off-axis imaging
- Laser beam shaping: Modify Gaussian irradiance profile to flat top hat with different shapes

Challenges:
- Small stroke for MEMS deformable mirrors (few μm)
- One way actuation of electrostatic MEMS mirrors

Optomechatronics required for integrated design!

Fundamental Limitation of Microscopes

- Inherent tradeoff between field-of-view and resolution in optical microscopy:



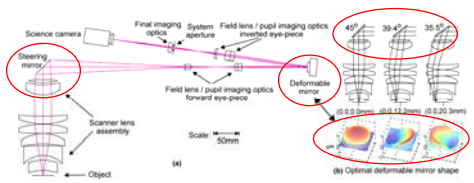
$$r = \frac{0.61\lambda}{NA} = \frac{0.61\lambda}{n\sin\theta}$$

0.075 NA 2.5X	0.13 NA 5X	0.30 NA 10X
4.5 micron resolution	2.6 micron resolution	1.1 micron resolution
4.8 mm field diameter	2.4 mm field diameter	1.2 mm field diameter

Common Solution: Moving stage, multiple parfocal objectives, multiple microscopes, zoom lens

➔ **Slow – unsuitable for dynamic events, disturbance of specimen, difficult to add additional instruments**

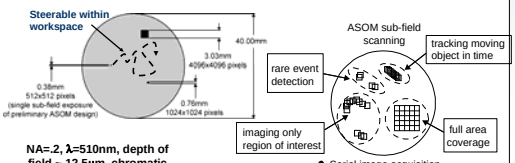
Adaptive Scanning Optical Microscope



- **Post-objective image field scanning (not a point)**
  - **Faster than a moving stage**
  - **No agitation to the specimen**
- **Deformable mirror aberration correction**
  - **Two order of magnitude larger field area**
  - **Simplified scan lens design**

Potsaid, Bellouard, Wen, Optics Express, 2005

ASOM Field of View and Scan Time



NA=.2, λ=510nm, depth of field ~ 12.5μm, chromatic performance: [490,530]nm

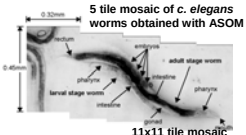
- Serial image acquisition
- Fast dynamic speed
- Medium field of view

★Excels for imaging dynamic and/or low fill factor objects.

ASOM Camera	Scan Movements for full coverage	Estimated time to scan (100 moves/sec)	
		40mm DIA	10mm DIA
512x512	8737	87.4 sec.	5.5 sec.
1024x1024	2184	21.8 sec.	1.4 sec.
2048x2048	546	5.5 sec.	0.3 sec.
4096x4096	136	1.4 sec.	0.09 sec.

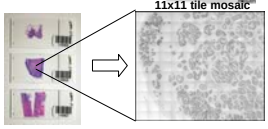
Bio-imaging Applications

- Multiscale and Longitudinal biological imaging of live organisms
  - Simultaneous observation of single cells, organisms, animals and populations with limited phototoxicity
  - Individual organisms tracked throughout their lives with behavior correlated to genetic makeup



5 tile mosaic of *c. elegans* worms obtained with ASOM

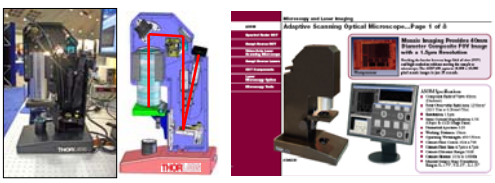
- High throughput Screening
  - Scanning performed only at areas of interest
  - Typical biopsy has low fill ratio



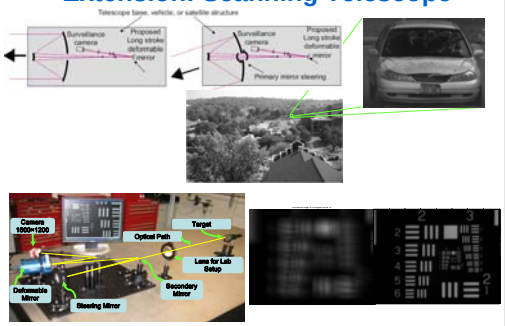
11x11 tile mosaic

Licensing and Commercialization

- First ASOM prototype built at RPI CATS based on NSF and CATS funding. RPI licensed to Thorlabs in 2006.
- Close collaboration for Photonics West 1/07 live demo
- Thorlabs ASOM won Laser Focus World Product of the Year Award in CLEO May 2007
- ASOM sold through Thorlabs catalog (8-page spread) July 2007

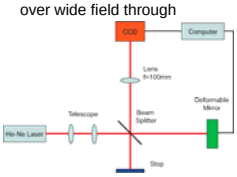


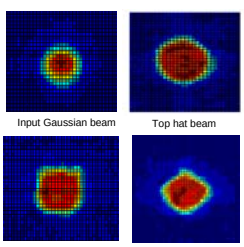
Extension: Scanning Telescope



Extension: Laser Beam Shaping

- Uniform energy distribution important for laser processing (cutting, drilling, marking) and communication
- Deformable mirror based beam shaping allows flexible energy distribution specification and shaping over wide field through



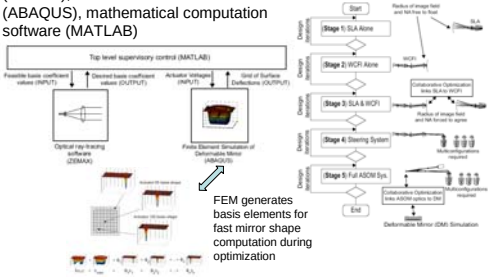


Input Gaussian beam | Top hat beam | Square top hat beam | Rotated square beam

Design Tool

Integrated design optimization environment coordinating optical simulation software (ZEMAX), finite element simulation (ABAQUS), mathematical computation software (MATLAB)

ASOM optimization using the AO design tool



FEM generates basis elements for fast mirror shape computation during optimization

Summary

- **Opto-Mechatronic System design** considers interactions between optical, mechanical, electrical, and computer components at the earliest stages of device conceptio
  - ➔ Result: **Considerable performance gains**
  - ASOM: particularly suitable for challenging biotech, MEMS, and microrobotic applications:
    - Dynamic observations
    - Low fill factor
    - Low Lighting
    - High Throughput
  - ASOM extension: subsurface imaging, LED illumination
  - New AO devices (ready for commercialization in a few years):
    - Scanning telescope
    - Wide field laser beam shaping

Acknowledgements:

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