Recent Progress in Controlling Single Surface Thin Shell Apertures

Eric M. Flint

President

Mevicon Inc.

2534 W. Middlefield Rd

Mountain View, CA 94043

(650) 969-2675

www.mevicon.com

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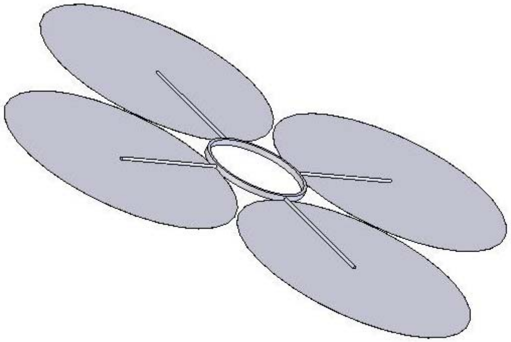
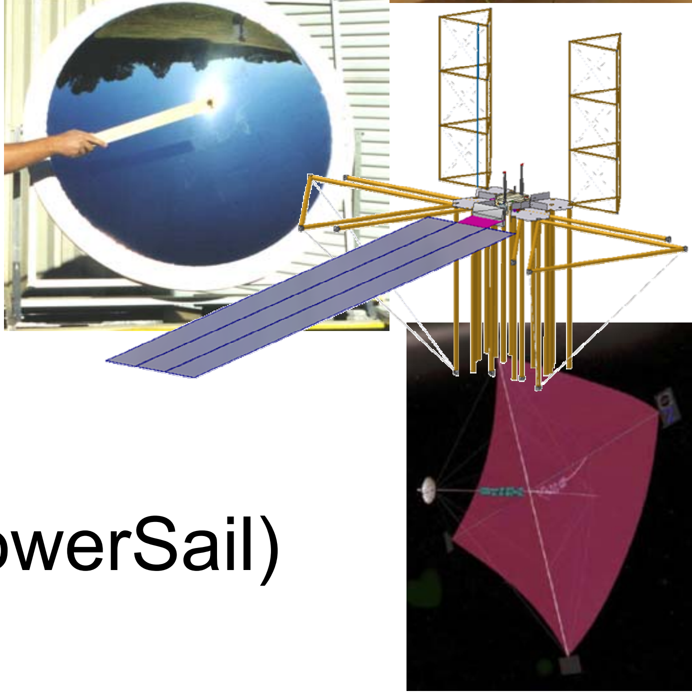
Presentation Outline

- Motivation
  - Gossamer/membrane structure potential
  - Advantages of single surface shells
  - New actuation approached needed though
- Design code overview
- Example applications of code to actuation studies
  - Single to multiple arbitrary actuation region combinations
  - Commanding zernike modes
  - Actuation approach comparison
  - Actuation region quantity trades
- Conclusions/Acknowledgements

Quick Intro to Mevicon Inc.





- Technical Focus Areas
  - Membrane
  - Vibration
  - Characterization
  - Control
- Application Focus Areas
  - Precision Surfaces/Apertures
  - Solar Concentrators
  - Solar Sails
  - Deployable Structures (DSX/PowerSail)

Motivation

Ongoing Trends in Optics Primary Apertures

- Historically, trends in desired scientific return versus mission cost and packaging constraints, are driving space optics designs to packagable, lower areal density primaries
- Gossamer or membrane structures such as
  - Pressurized lenticulars
  - Systems of tensioned flats approximating a curve
  - Tensioned singly curved troughs,
  - . . .

  offer strong advantages in realizing <u>large</u> deployable apertures with projected extremely low areal densities
- Challenges remain though
  - Reaction structures required
  - Downstream correction/clean up often baselined
- However, over the last few years a variety of approaches to realize, <u>self supporting</u> optical or near optical grade <u>single surface</u> doubly curved thin film shells have been demonstrated:
  - UAT, SRS, JPL, AFRL, ISAS, . . .

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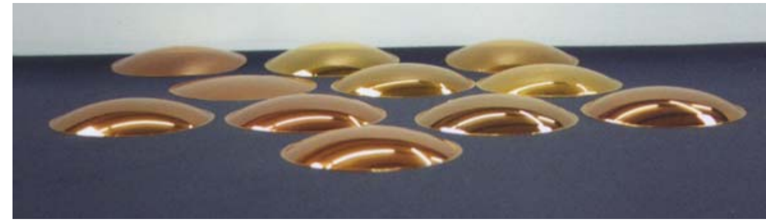
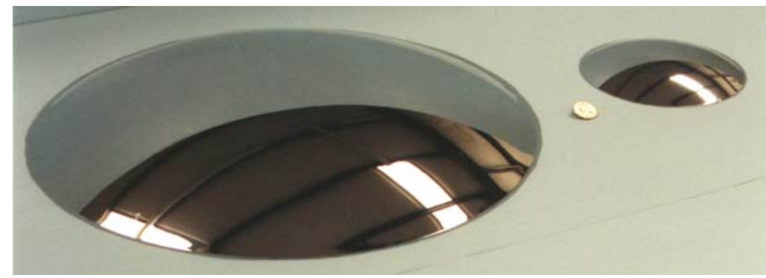
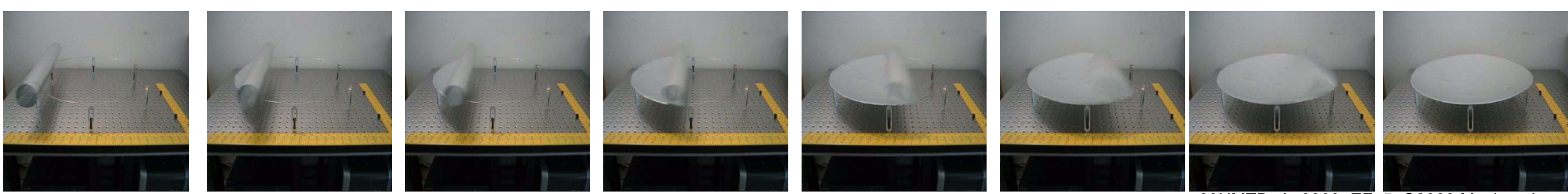
Single Surface Shells



- **Advantages for Optics**
  - "Easy" to make deep
  - Single surface
    - No diffraction due to segment edges, etc.
    - No potential scatter from passing through canopies)



- **Advantages for Space**
  - Very lightweight (80g/m^2 or better)
  - Self supporting (in 1-G)
  - Dynamically stiff
  - Compact stowage approaches
    - No folding needed
    - No discrete hinge mechanisms
  - Self rigidizing
  - Deterministic self deployment process



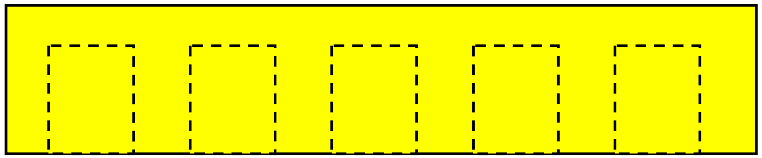
Motivation

Ongoing Trends in Optics Primary Apertures

- Extending traditional terrestrial or deformable optics approach (i.e. bed of normal actuators and reaction structure) is Limited in the Extreme
  - **Challenge #1**: As reflector substrate grows thinner, individual actuator influence function areal authority diminishes (i.e. dimpling or pin cushion effect)
    - → More actuators required
    - → Architecture robustness dwindles (especially for stiff mounts)
  - **Challenge #2:** Reaction structure also required
  - **Challenge #3:** Both # of actuators and reaction structure size (and hence non reflective mass) scale at least a D^2 phenomena
  - Note: General trends hold true for Contactive (PZT/PMN Stack, . . .) and Non-Contactive (electrostatic, electromagnetic, . . .)
- Tools to efficiently evaluate and perform trades on alternatives actuation approaches are needed

Primary Mirror Evolution

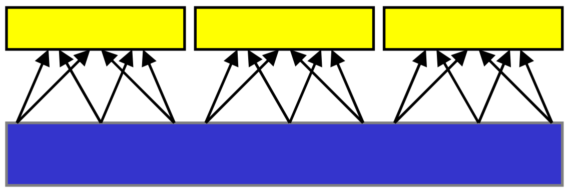
Lightweighted Monolithic (Palomar, LBT, HST)



0 to 8 m dia.

~250+ Kg/m^2

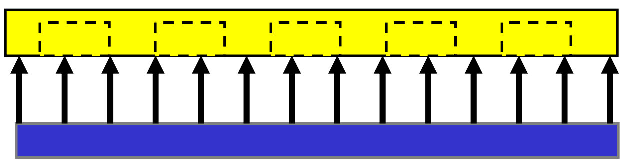
Segmented (Keck, …)



6 to 10+ m dia.

~ 150+ Kg/m^2

Powered Lightweighted Mirror (ESO VLT, AMSD SOA)



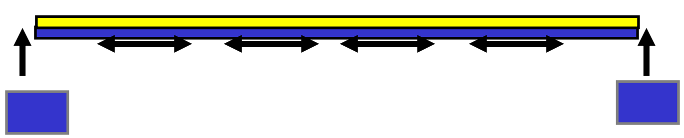
0 to 2 m dia

~ 25+ Kg/m^2

(1/2 mass is actuators and reaction structure)

Lightweighted Glass SOA

Smart Monolithic Mirror (Future)



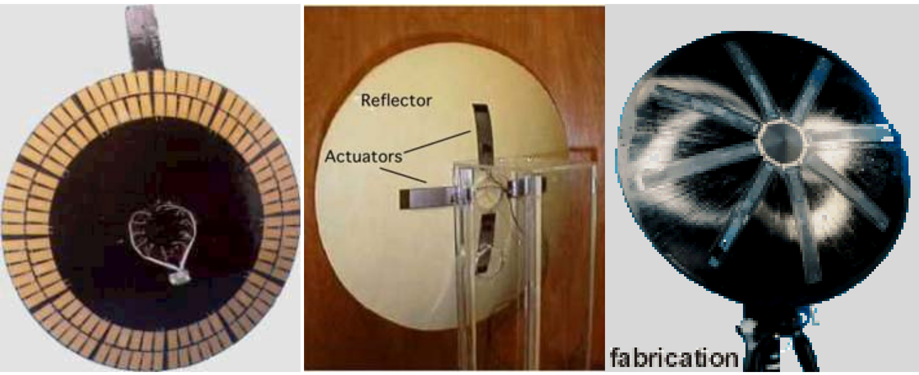
10m+ diameter

1.5 Kg/m2

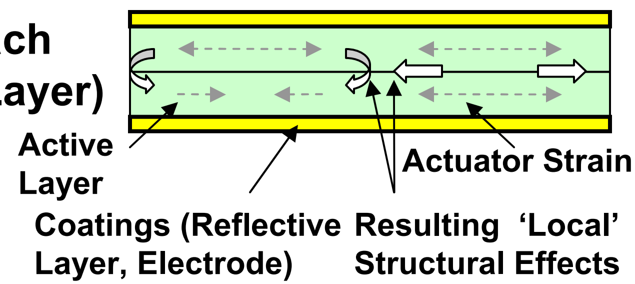
Would Drop Hubble Primary from ~2000 lb to ~15lb (or 27m)

Thin Film Shell
Potential Control Strategies

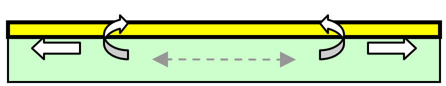
Embedded Shape Control



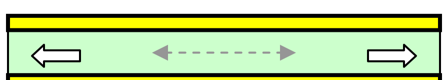
Bimorph Approach
(Double Active Layer)



Unimorph Approach
(1 Active Layer,
offset from neutral axis)

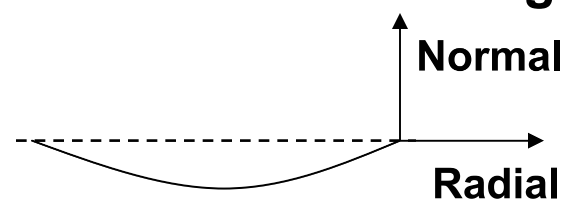


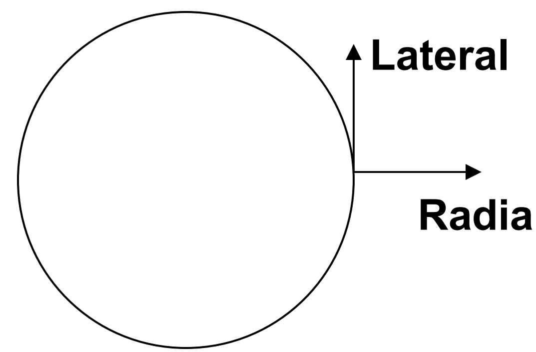
Pure In-Plane Force
(Balanced Coatings)



Boundary Control

- Wide range of actuation options available.
- Proper choice is application specific and driven by mix of performance and cost targets





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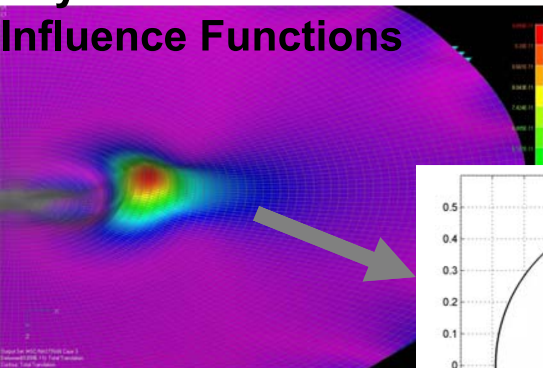
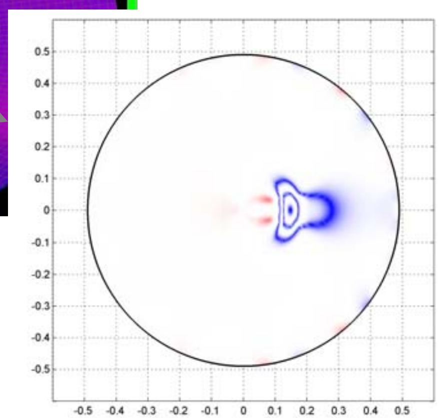
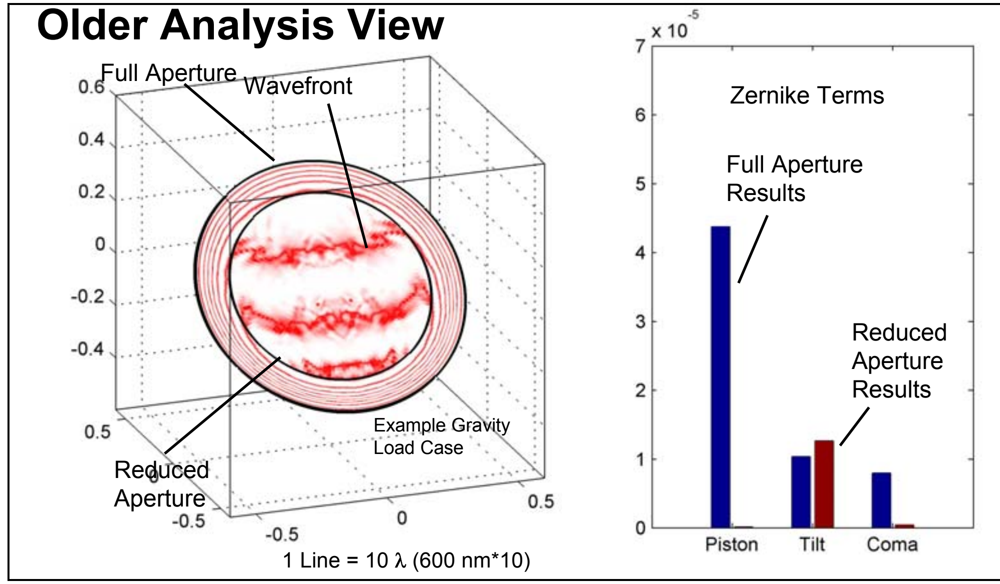
Design Tool Overview

Physics Driven Actuator Influence Functions

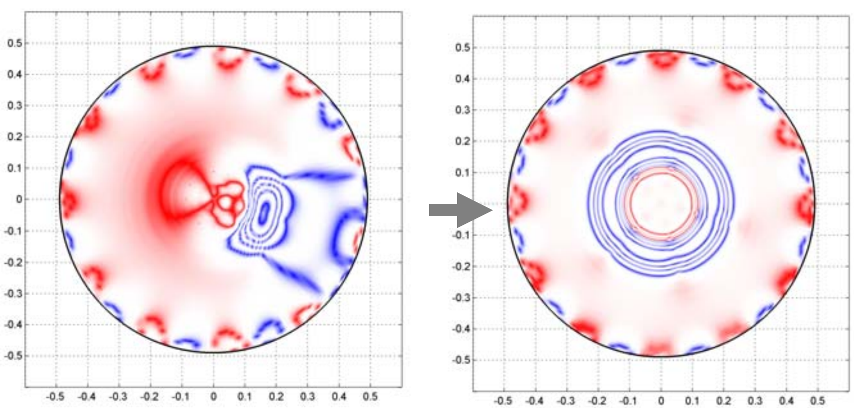




Example Single Patch FE Results Translated to Code



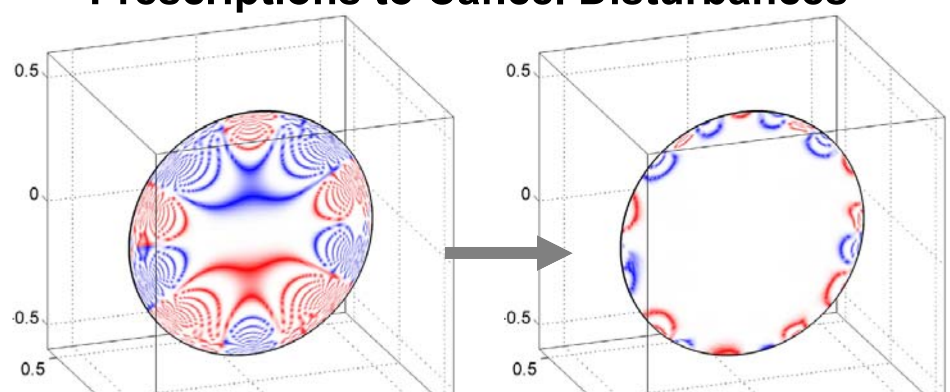
Study of Arbitrary Combinations of Actuation Approaches



4 Neighboring Patches

2 Rings

Automated Calculation of Actuator Prescriptions to Cancel Disturbances

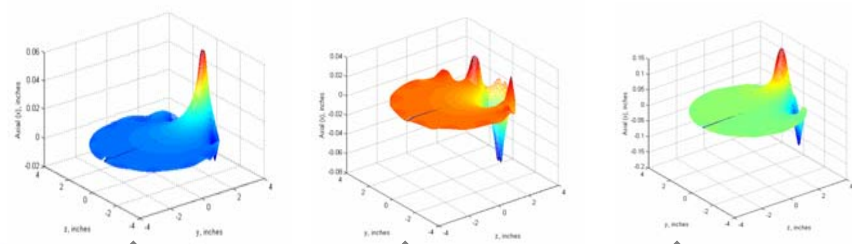


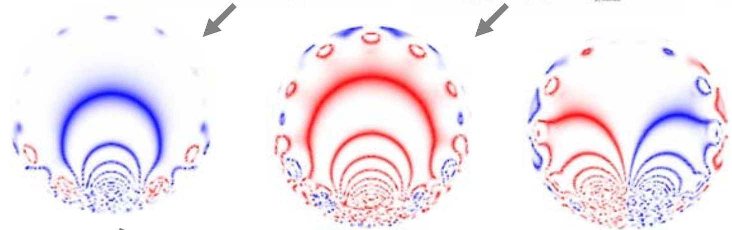
Effect of Gravity on Partially Clamped Membrane

Resulting Corrected Surface

Corrective Prescriptions Calculated in Reduced Order "Zernike Space"

- Start with limited # of physics based model large dof inputs
- Actuator and uncorrected wavefronts filtered into Zernike terms
- Resulting actuator vectors assembled into an influence matrix
- Solving matrices with pseudo-inverse yields optimal (in LMS sense) actuator prescription

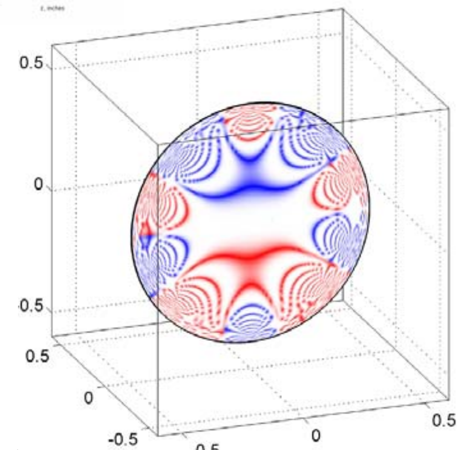




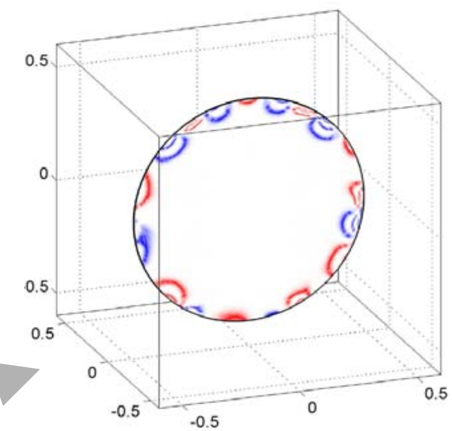
$$\begin{bmatrix} \begin{Bmatrix} Z_{N1}\\ Z_{N2}\\ Z_{N..}\\ Z_{Nn}\end{Bmatrix} & \begin{Bmatrix} Z_{R1}\\ Z_{R2}\\ Z_{R..}\\ Z_{Rn}\end{Bmatrix} & \begin{Bmatrix} Z_{L1}\\ Z_{L2}\\ Z_{L..}\\ Z_{Ln}\end{Bmatrix} \end{bmatrix} \begin{Bmatrix} F_N\\ F_R\\ F_L\end{Bmatrix} = -\begin{Bmatrix} Z_{E1}\\ Z_{E2}\\ Z_{E..}\\ Z_{En}\end{Bmatrix}$$

$$-\begin{bmatrix} \begin{Bmatrix} Z_{N1}\\ Z_{N2}\\ Z_{N..}\\ Z_{Nn}\end{Bmatrix} & \begin{Bmatrix} Z_{R1}\\ Z_{R2}\\ Z_{R..}\\ Z_{Rn}\end{Bmatrix} & \begin{Bmatrix} Z_{L1}\\ Z_{L2}\\ Z_{L..}\\ Z_{Ln}\end{Bmatrix} \end{bmatrix}^{+} \begin{Bmatrix} Z_{E1}\\ Z_{E2}\\ Z_{E..}\\ Z_{En}\end{Bmatrix} = \begin{Bmatrix} F_N\\ F_R\\ F_L\end{Bmatrix}$$

Acceleration Cancellation Case



Distorted



Corrected

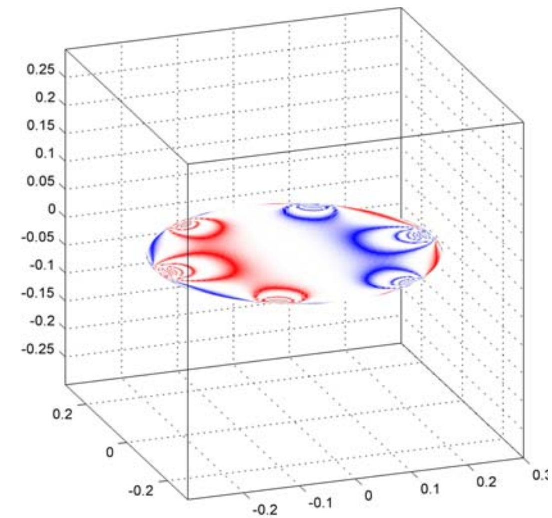
What's It All Good For?
Design, Trade Studies, and Visualization

Trade Study Tool

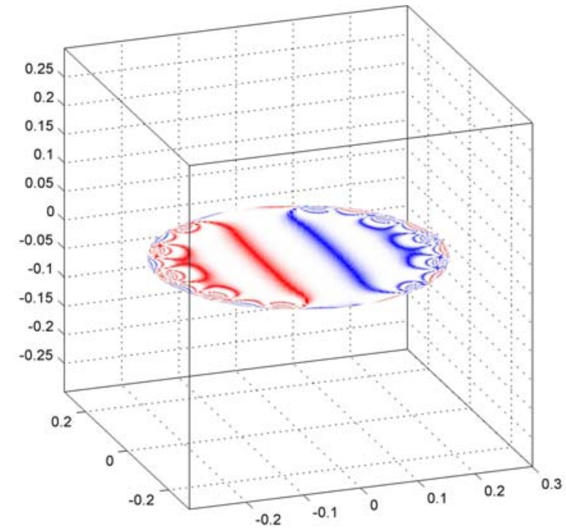
- Compare different actuation approaches (global, boundary)
- # of actuators
- Trends versus aperture parameters
  - Diameter
  - F#
- Actuator architecture robustness

Design/Concept Evaluation Method

- Top Down: For given level of disturbances can predict required actuation authority
- Bottom Up: For given level of actuation authority, can predict achievable disturbance rejection



6 Normal Actuators



12 Normal Actuators

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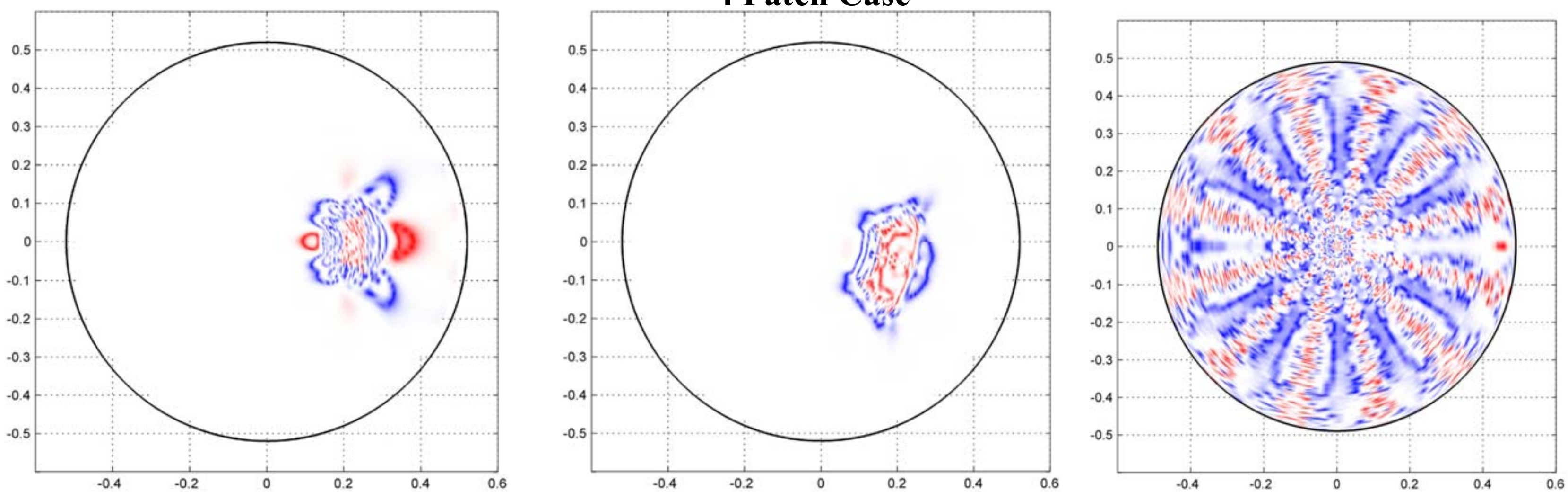
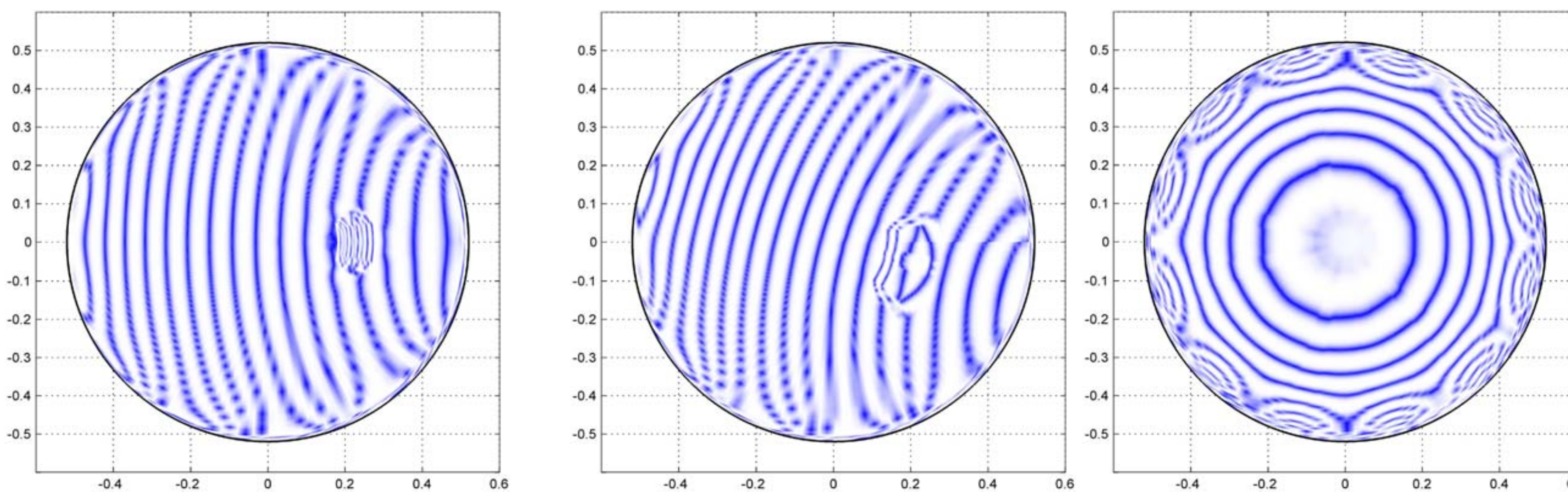
Global Actuation Type (Trade Study)

Moments

1 Patch Case | 4 Patch Case | All On Case



In-Plane Force



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Global Shape Control

Zernike Mode Actuation Trade Studies

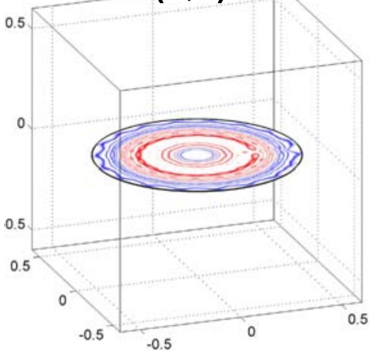
Conclusions

- Good authority over higher order modes (i.e. those with center motion)
- Some authority over symmetric (n=m) modes

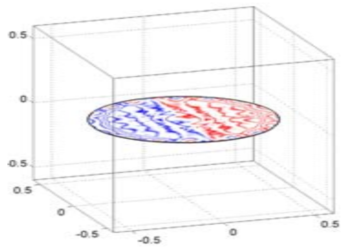
Assumptions

- 15 radial patch areas
- 18 x 20 degree arcs
- In-plane force mode
- Inner and outer 3 patch regions not used
- Fitted over 80% radius

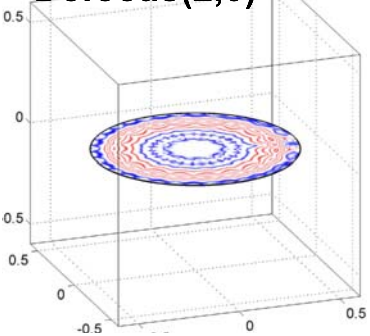
Piston(0,0)



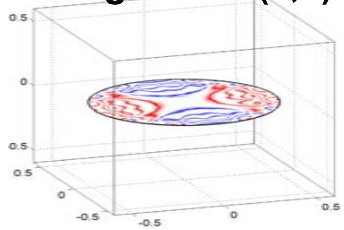
Tilt(1,1)



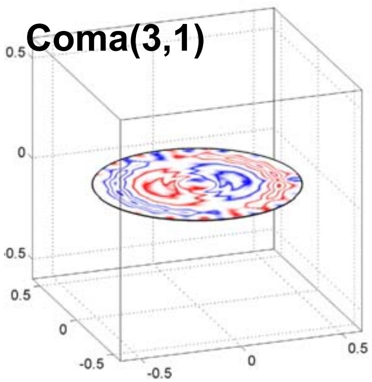
Defocus(2,0)



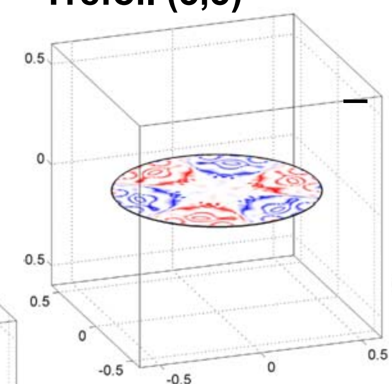
Astigmatism(2,2)



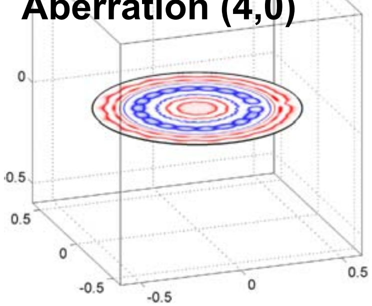
Coma(3,1)



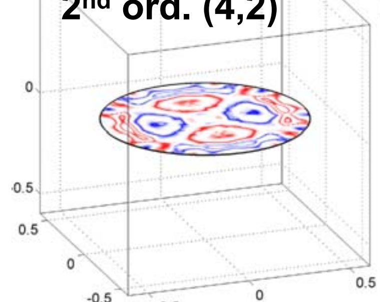
Trefoil (3,3)



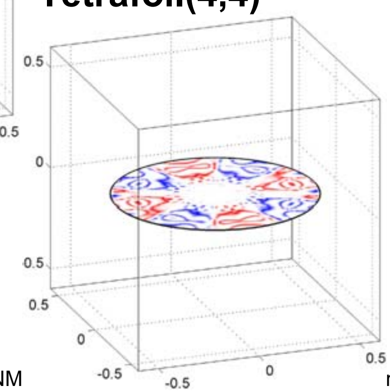
Spherical Aberration (4,0)



Astigmatism 2nd ord. (4,2)



Tetrafoil(4,4)



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Boundary Control Actuation Effectiveness by Zernike Mode

Conclusions

– Symmetric (n=m) modes ‘easy’ with BC,

– Controllable order limited to # Actuators/2, 3 is better

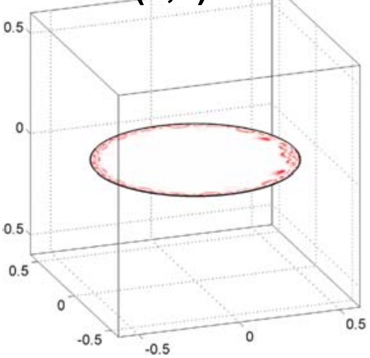
– Center actuation or could improve higher order modes (m<n)

Model Assumptions

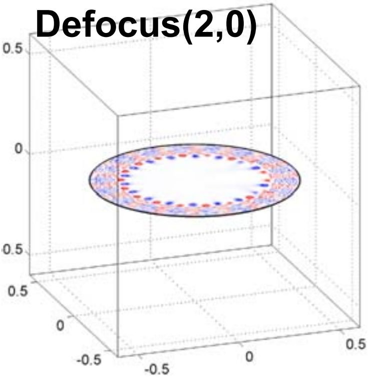
– 1m membrane clamped at 18 x 3 deg wide locations

– 18 x Radial, Normal and moment actuators enabled

Piston(0,0)



Defocus(2,0)



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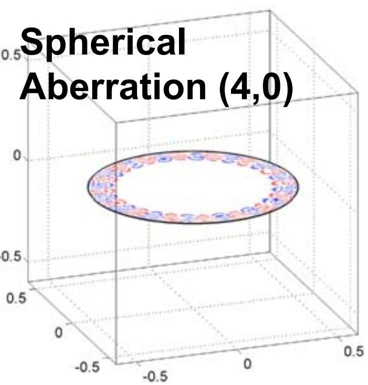

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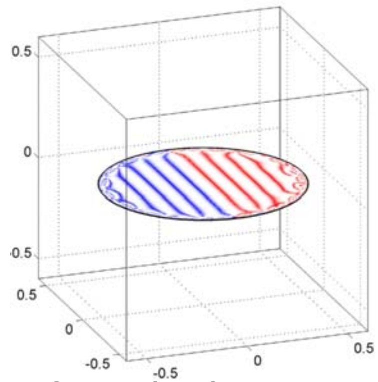
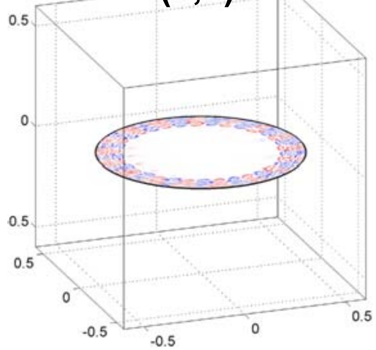
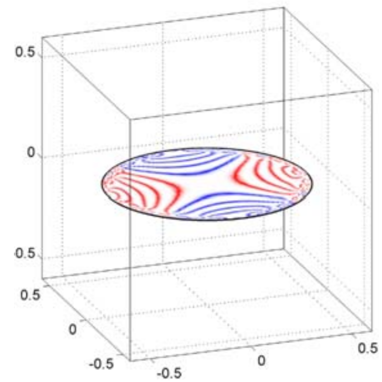


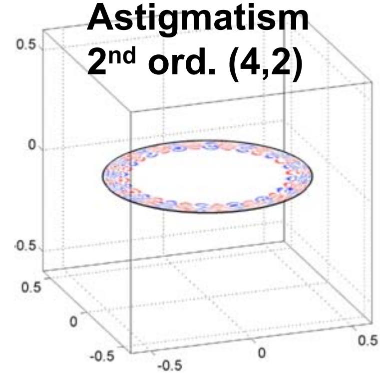
Coma(3,1)



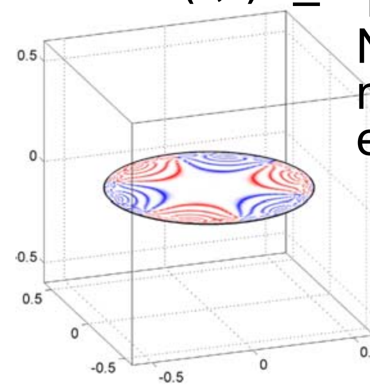
Astigmatism(2,2)



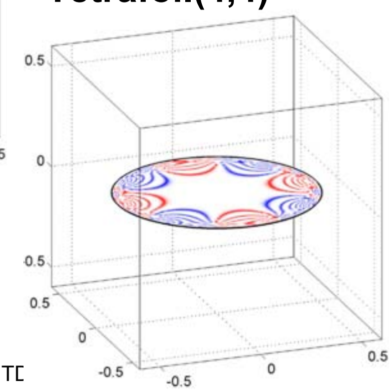
Astigmatism 2nd ord. (4,2)



Trefoil (3,3)



Tetrafoil(4,4)



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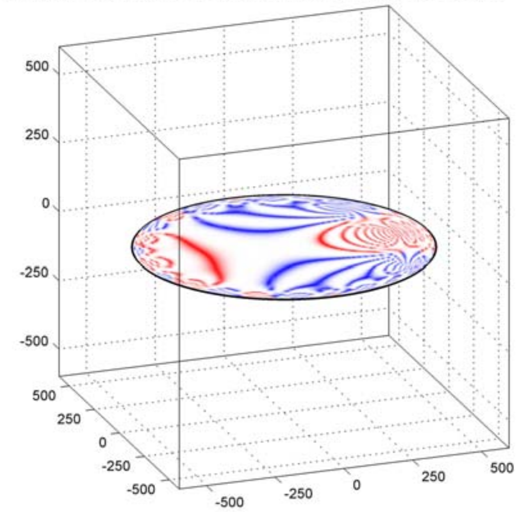
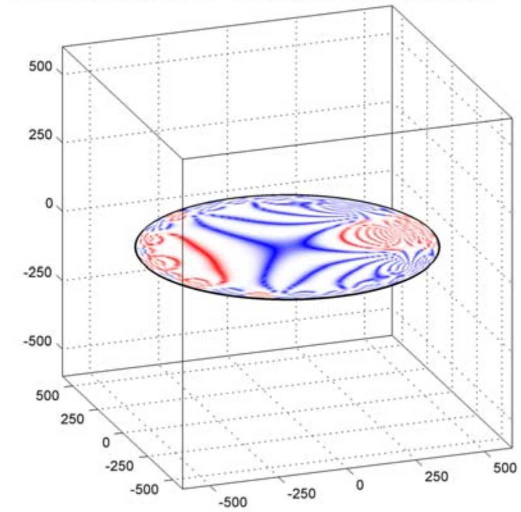
Non Linear Effects

- Preliminary results show that geometric non-linearities are relatively benign
- Geometric and material non-linearities can be captured in physics based models of AIF’s and disturbances
- Note: After initial shape capture and phasing, most operations around that point are likely small displacement (i.e. linear) in nature

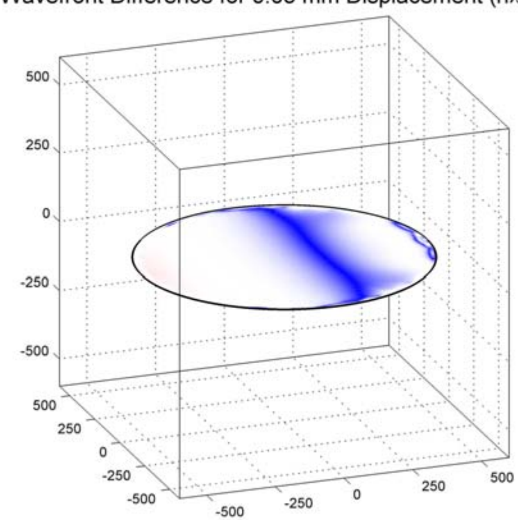
Nonlinear Analysis for 0.05 mm Displacement ($n\lambda$ = 10)



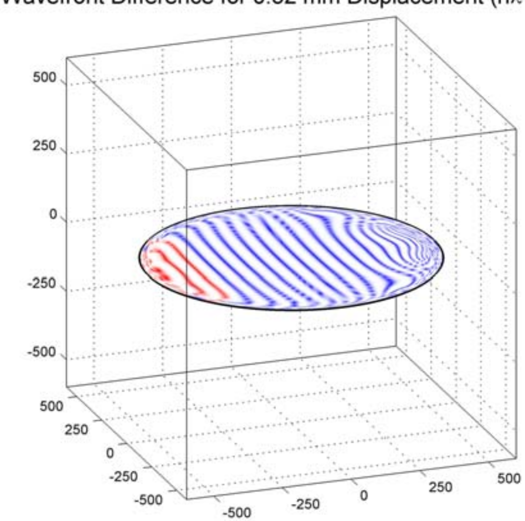
Nonlinear Analysis for 0.52 mm Displacement ($n\lambda$ = 100)



Wavefront Difference for 0.05 mm Displacement ($n\lambda$ = 1)



Wavefront Difference for 0.52 mm Displacement ($n\lambda$ = 10)



Conclusions

- Major topics discussed
  - Motivation for research: Confluence of
    - Historical optical aperture design trends
    - Recent advances in available membrane materials/structures
    - Knowledge of active control approaches
  - Reviewed general principal/approach for design code
  - Provided representative trade study results of use of code
    - Global shape control
    - Boundary control

- Key Results
  - Global shape control appears worthy of additional study for maintaining membrane aperture shape prescriptions, but material development issues will likely drive work in the short term
  - Boundary control is also promising but as studied lacks authority over non-symmetric Zernike terms, therefore currently limiting its use as a full figure control approach
  - Robust flexible design methodology exists to rapidly evaluate alternatives design approaches/concepts

Acknowledgements

- Air Force Research Laboratory:
  - Mike Holmes (PR)
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  - Russell Partch (VSE)
  - Greg Spanjers (VSSV)
  - Brett DeBlonk (VSSV)
- NASA JPL:
  - Houfei Fang, Mike Lou,
  - Mark Dragovan, Eri Cohen
- DAPRA
  - Ephriam Garcia
  - John Main
- UAT
  - Rodney Bradford
  - Larry Bradford
- CSA Engineering:
  - Jason Lindler
  - Roger Glaese
  - Keith Denoyer
- Rhombus Consulting Group:
  - Marc Reggelbrugge

Relevant Publications

Control of Single Surface Thin Shell Control

- “Boundary Actuation Shape Control Strategies For Thin Film Single Surface Shells”, 2004, Abstract Submitted to 5th Gossamer Spacecraft Forum, Palm Spring, California, April, 2004.
- “Approach for Efficiently Evaluating Internally Reacted Global Shape Control Actuation Strategies for Apertures”, 2003, Paper # AIAA-2003-1738, 4th Gossamer Spacecraft Forum, Norfolk, Virginia, April 8-10.
- “Actively Controlled Thin-Skin Space Optics”, 2003, Paper # 5054-31, SPIE 10th Annual International Symposium on Smart Structures and Materials, Conference 5054: Industrial and Commercial Applications of Smart Structure Technology, San Diego, March 3-5.
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