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The Application of Controlled Structures Technology to Adaptive Optics

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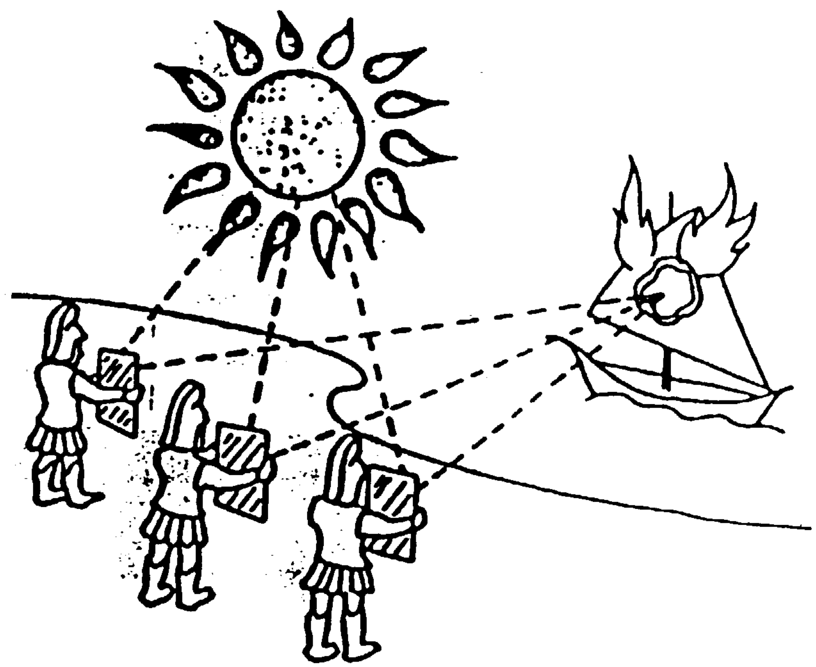
Historical Note

- Archimedes (287-212 BC)
  - Roman warships burned during siege of Syracuse (open to historical debate)



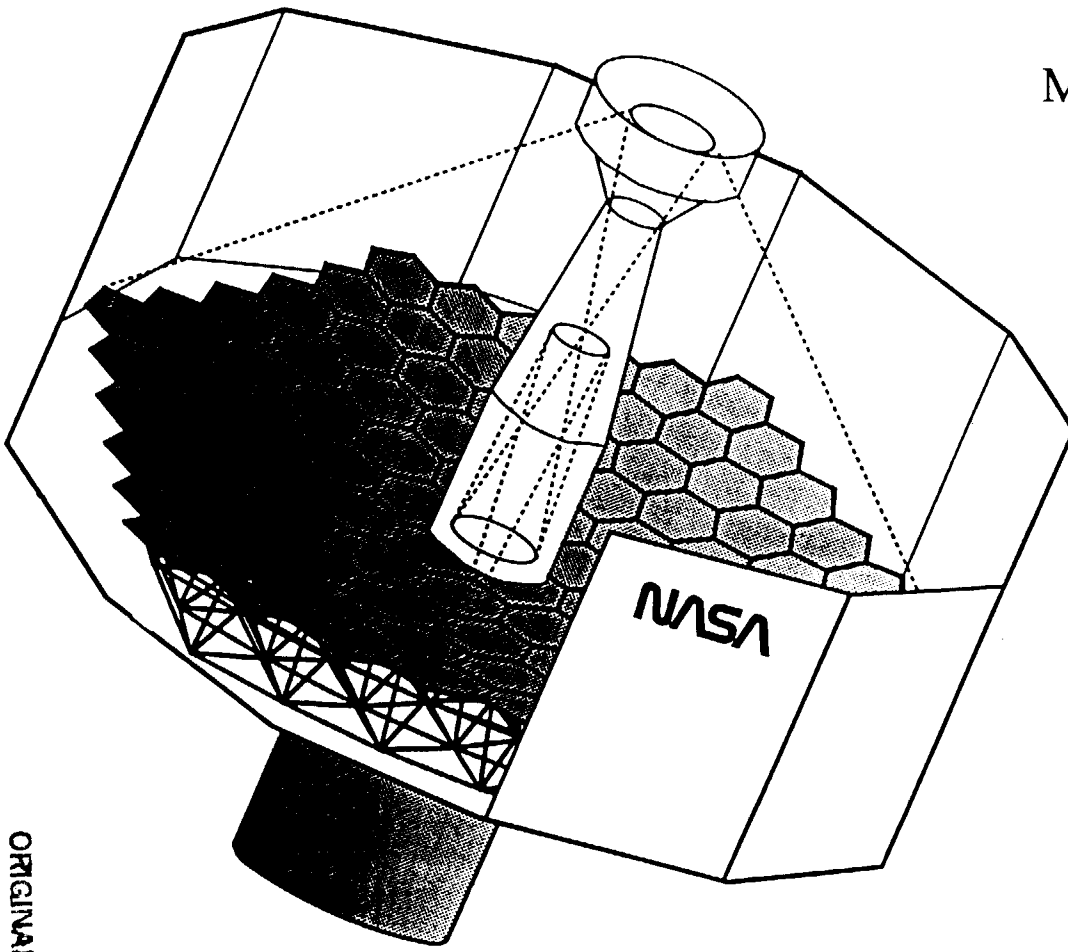
Outline

- Objectives
- Review of current approaches to optics
- Constraints on weight and performance imposed by control-structure interaction (CSI)
- Potential benefits of CST methodology
- Testbeds for demonstration of approach
- Experimental results from a simple testbed
- Open issues and conclusions

Objectives

- Understand current approaches in optics
- Investigate potential limitations imposed by flexibility in existing and planned optical systems
- Determine and demonstrate benefits of designing large optical systems within the Control Structures Technology (CST) framework.
  - Deformable surfaces
  - Flexible support structures

A Typical Large Optical System (LDR)



Major components:

- Primary
- Secondary/other optics
- Support structure

Overview of Current Optical Programs

- Current design methodologies
  - mirror and support structure designed to avoid interaction of flexible modes with disturbances
  - controller bandwidth limited to avoid any interaction with flexible modes

- Note on terminology
  - Adaptive control
  - Active and adaptive structures
  - Active and adaptive optics

Current Approaches

- Passive devices
  - designed for mechanical and thermal stability
  - typically heavy, thick, very stiff (high natural frequency)
  - not directly designed to perform active or adaptive optics
  - possible gravity sag in secondary support structure
  - recent advance: large lightweight mirror (borosilicate and thin meniscus)

  - Example: Hale Observatory/Mt. Palomar (1949)

Current Approaches, cont.

- Active devices
  - quasistatic shape correction
  - demonstrated benefits over passive devices:
    - improved performance with wind disturbances.
    - requires smaller blanks and less stringent polishing
  - backplane stiffness (weight) major issue for monolithic mirrors (depends on actuator type)
  - control has proved effective for segmented mirrors (Keck), but CSI limits bandwidth and performance
  - employ thin meniscus mirrors (40:1)

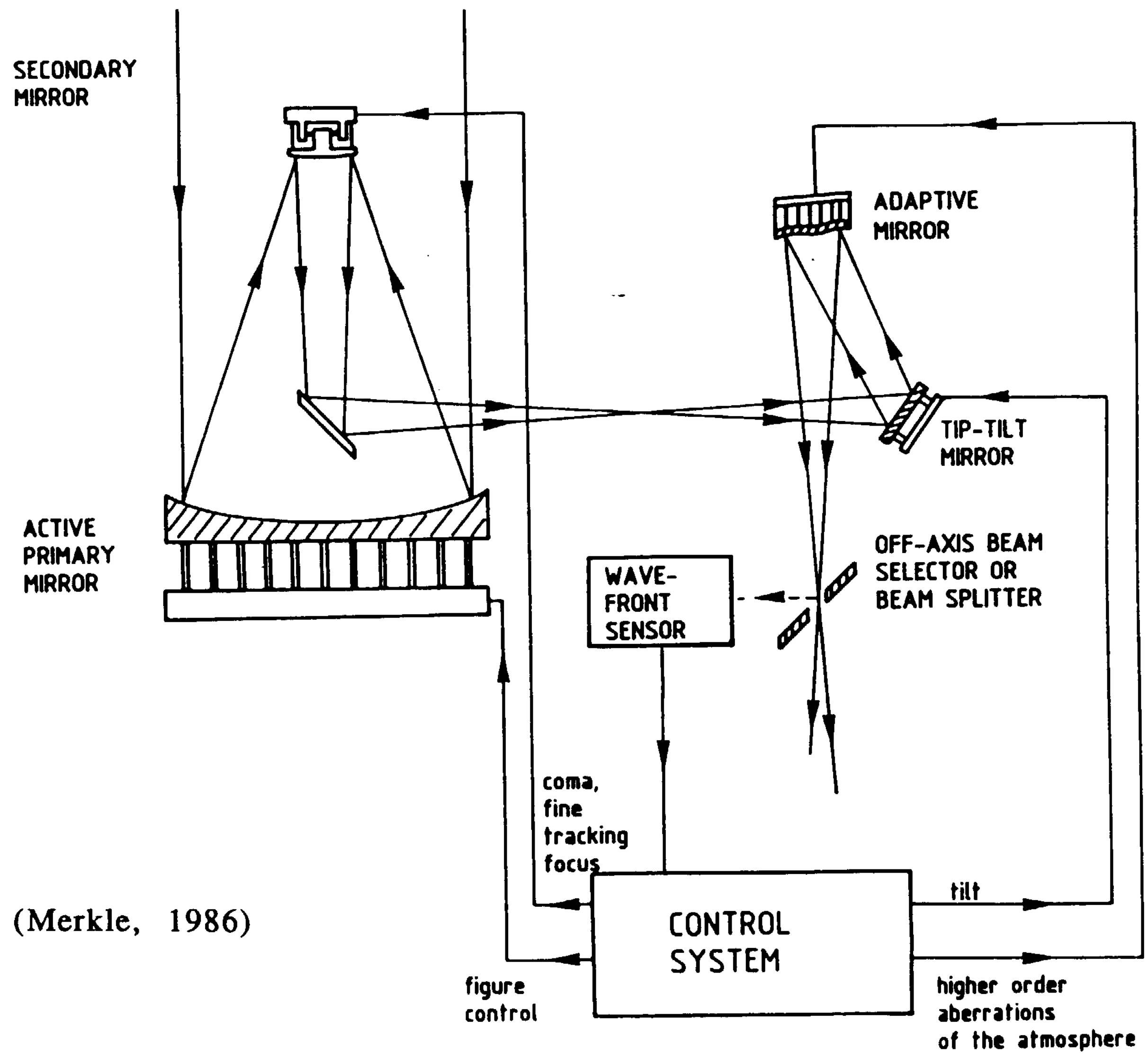
  - Examples: HST, Keck, New Technology Telescope (NTT)

Current Approaches, cont.

- Adaptive devices
  - atmospheric compensation requires very high frequency control.
  - current design methodology results in structures with natural frequencies of kHz.
  - leads to size and weight restrictions
  - pixel processing limit exists as well
  - recent innovation: laser guide star beacon (Starfire)

  - Examples: SDI,Very Large Telescope (VLT)

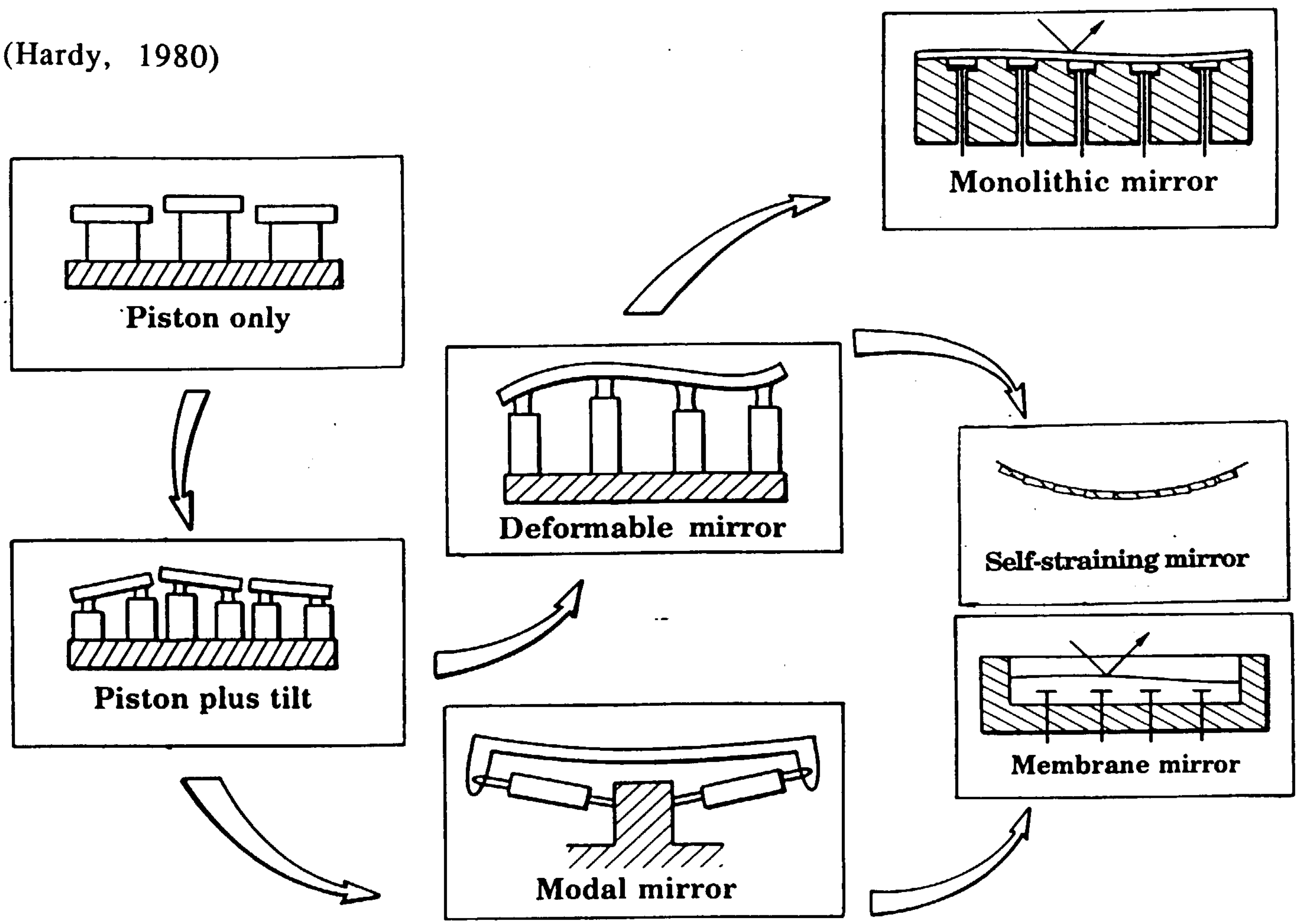
Typical Adaptive Optics System



(Merkle, 1986)

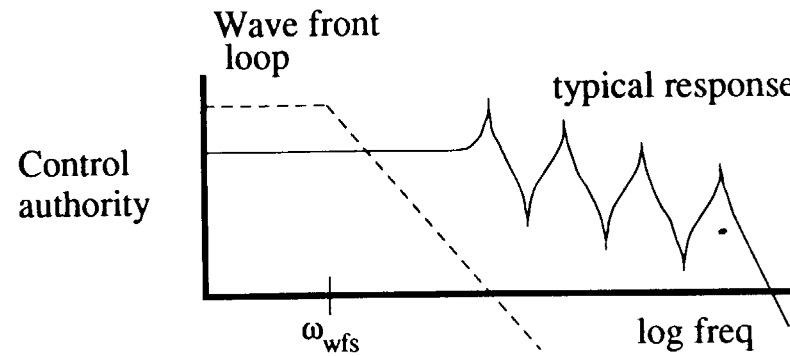
Actuation Approaches for Deforming a Mirror

(Hardy, 1980)



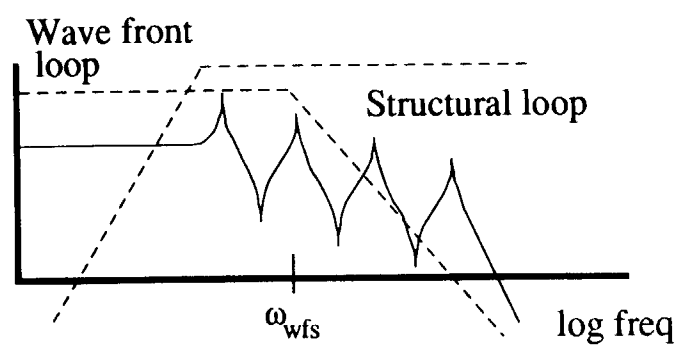
Control Approach Comparison

- Current design:
  - stiff structure
  - static displacement feedback



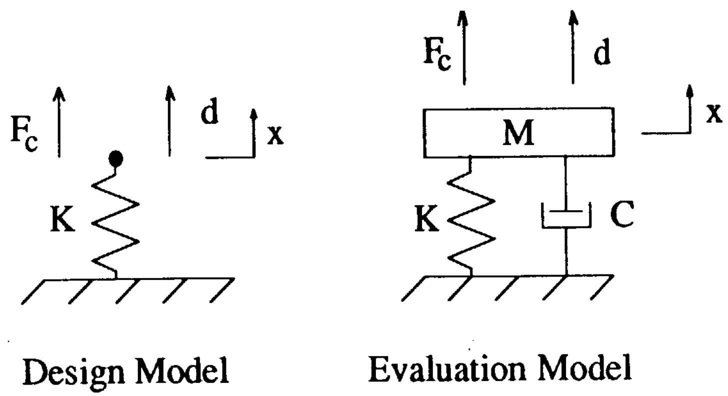
- CST approach:
  - performance demands lead to higher bandwidths
  - weight limitations lower natural frequency

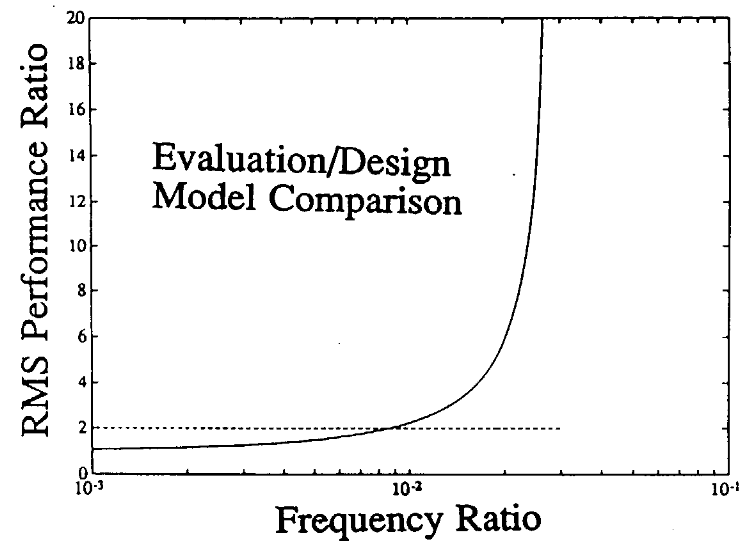
  - design structural loop to augment WFS, using passive and active feedback



CSI Control Bandwidth Limitations

- Simple models [Hardy 1977], [Robertson 1970] can predict CSI instability from displacement feedback.





- In this case, can increase control bandwidth by including rate feedback and/or passive damping [Pearson and Hansen].

- CST design methodology provides unified approach to control design for significantly more complex structures

==> potential performance improvements.

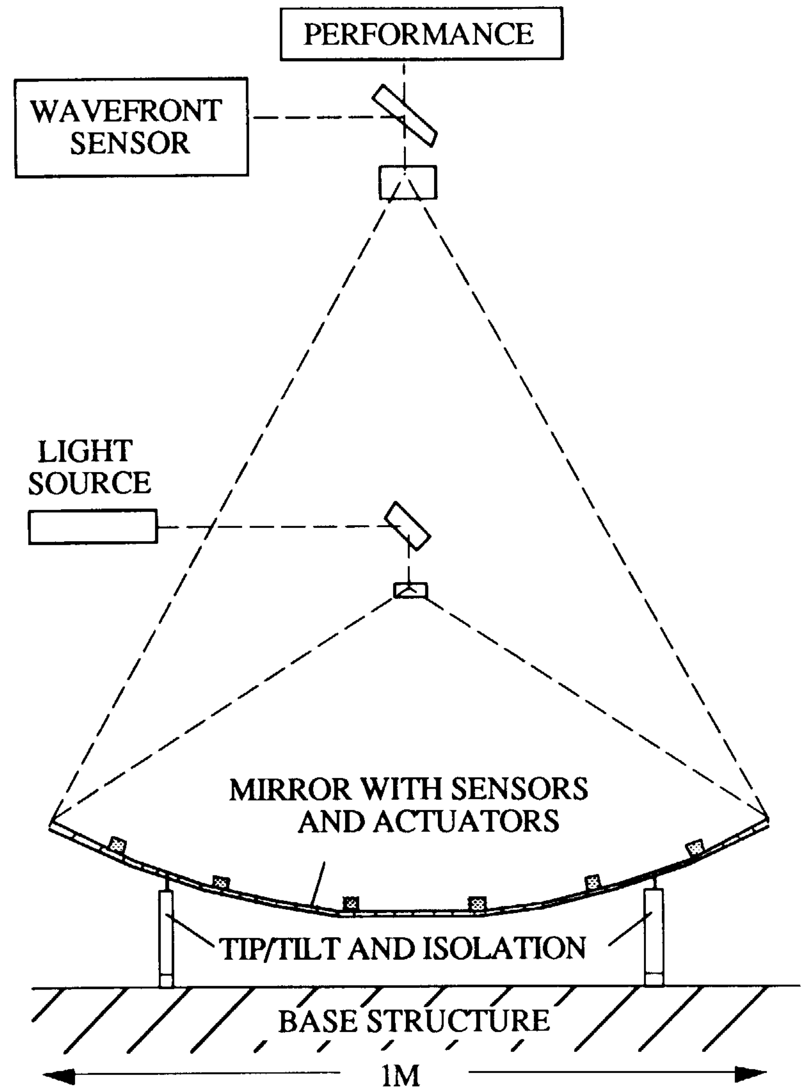
Applications of CST Concepts to Optics

- Examples from literature:
  - Pearson and Hansen [1977] - viscous damping oil extends control bandwidth beyond first mode
  - Greene and Pope [1980] discuss importance of flexible modes on optical performance
  - Perkin Elmer JOSE proposal - truss control bandwidth includes natural frequency of primary mirror
  - segmented mirror designs with active elements in support structure [Chen et al., 1989]
  - ASCIE - closed loop verification of CST on a segmented precision optical device
  - Combined CST/optics modelling (Redding)

- Emphasis of previous CST work has been on support structure
- Application to flexible mirror surface control not fully explored.

Deformable Mirror Testbed Concept

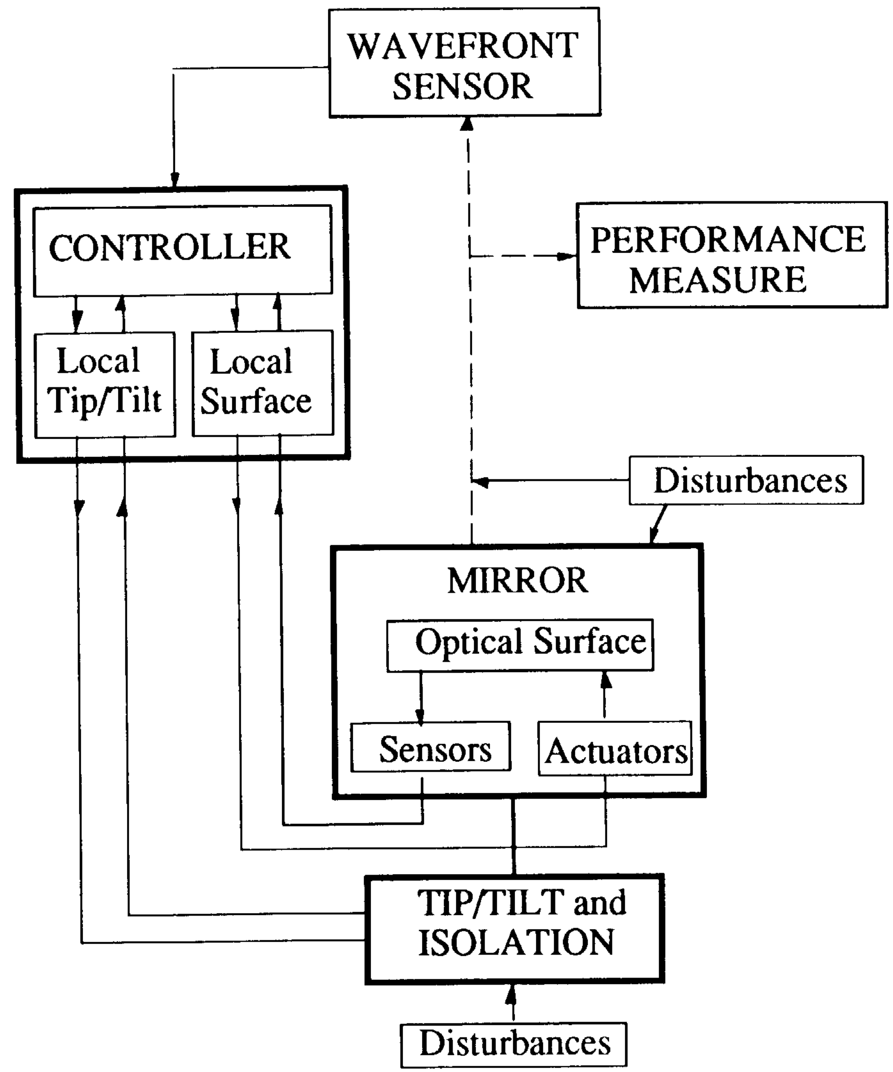
- Main features:
  - self-straining lightweight mirror surface, no backplane
  - elliptical shape for nearby source and sensor (or use distrib. point retroreflectors)
  - 1D testbed captures some relevant science and dynamics.
  - tip/tilt and isolation from supporting truss structure (not shown)



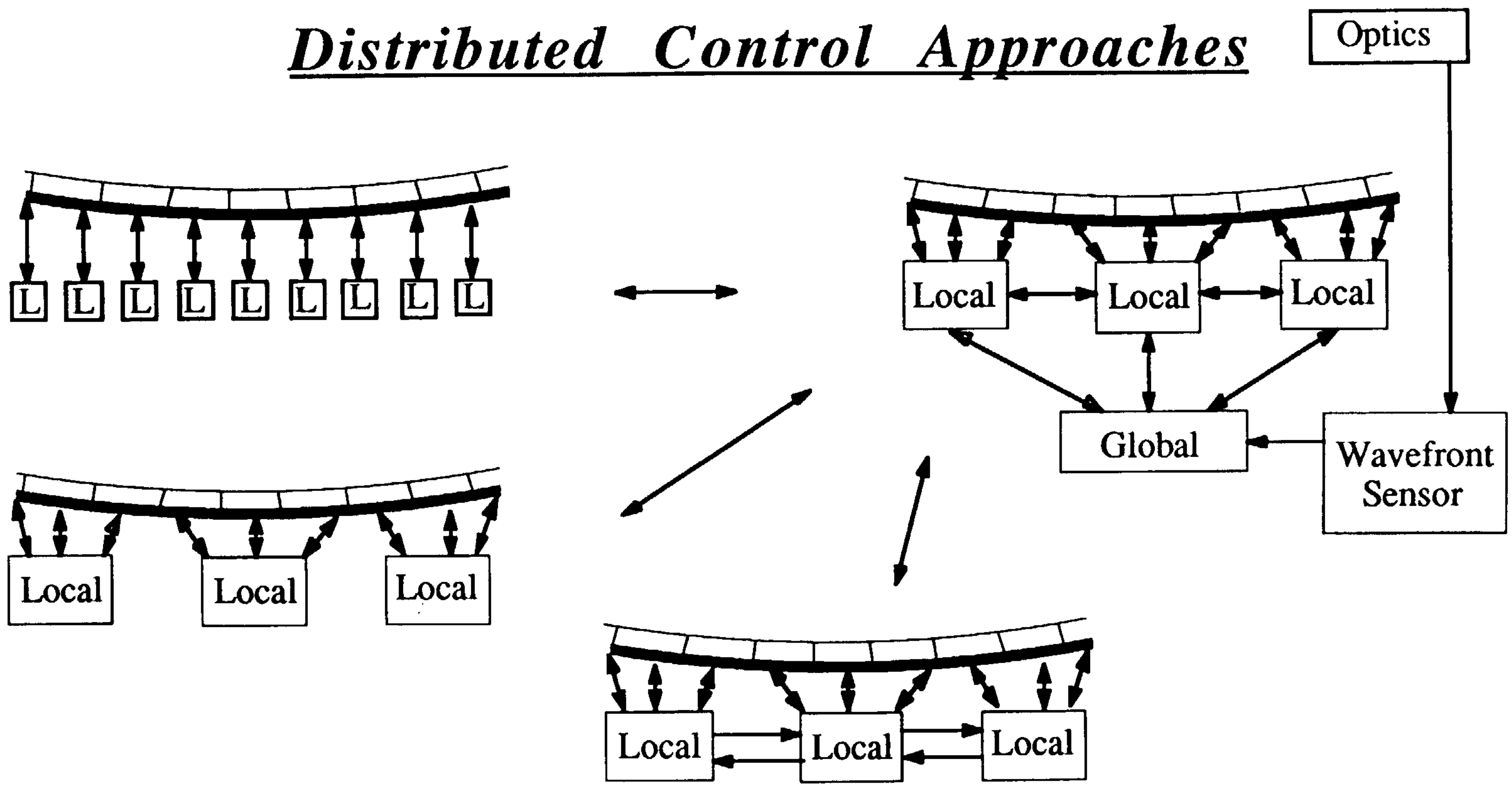
Testbed Functional Block Diagram

- Main components:
  - mirror (actuators/sensors)
  - isolation and controller
  - optical measurement and performance evaluation

- For design flexibility, disturbances enter acoustically, mechanically, and optically.



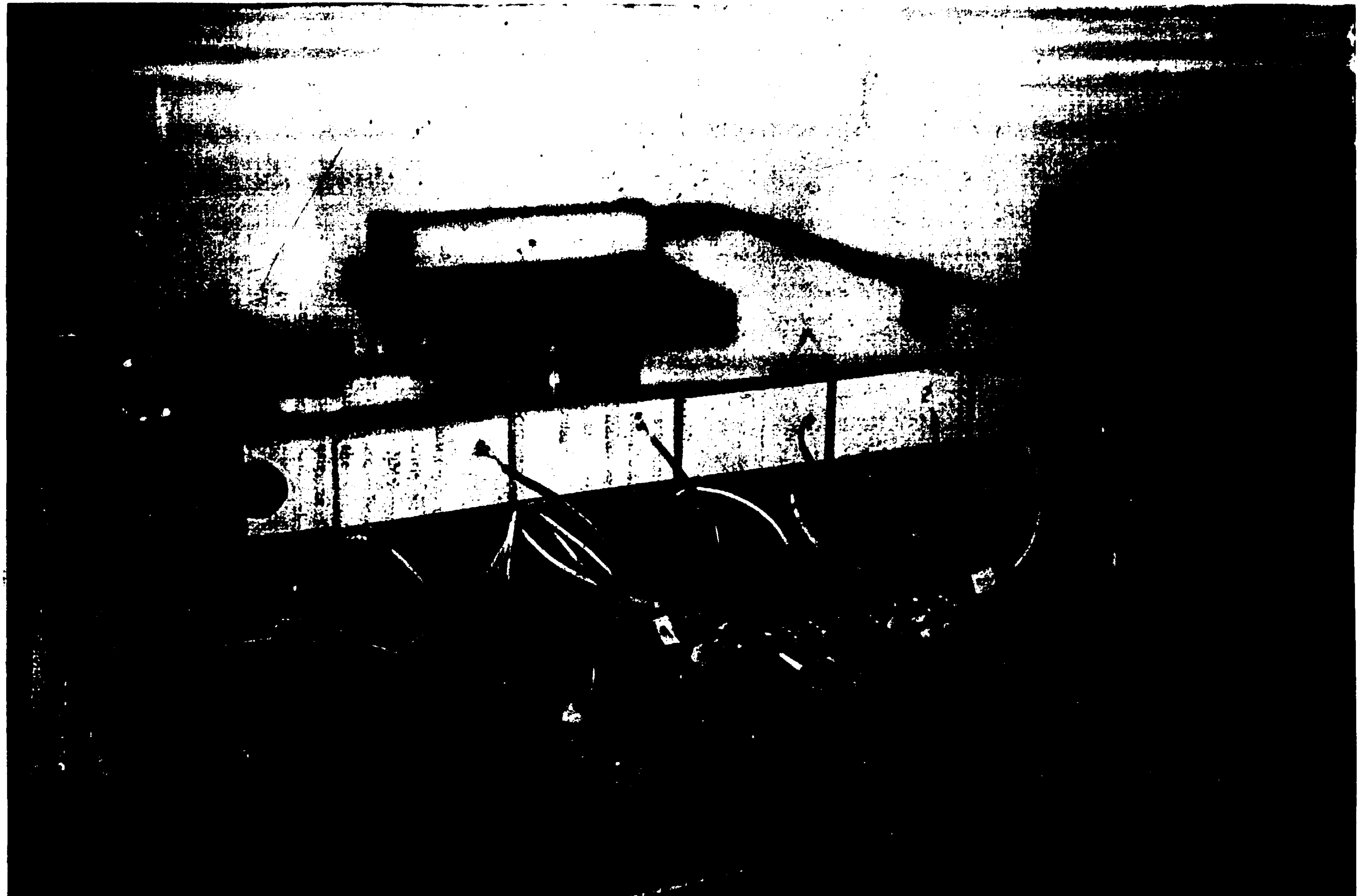
Distributed Control Approaches



- Distribute control to complement dynamic behavior of structure.
- Efficiency and performance of multi-level architecture required to handle large number of sensors and actuators.
- Low authority controllers designed for stability robustness and local performance.

Available Testbeds

- Phase 0 deformable mirror testbed
  - Initial step towards more comprehensive testbed
  - Self-straining (PZT actuators)
  - Optical and structural (PVDF) measurements
- Interferometer multi-point alignment testbed



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DEFORMABLE MIRROR TESTBED

Results from the DMT

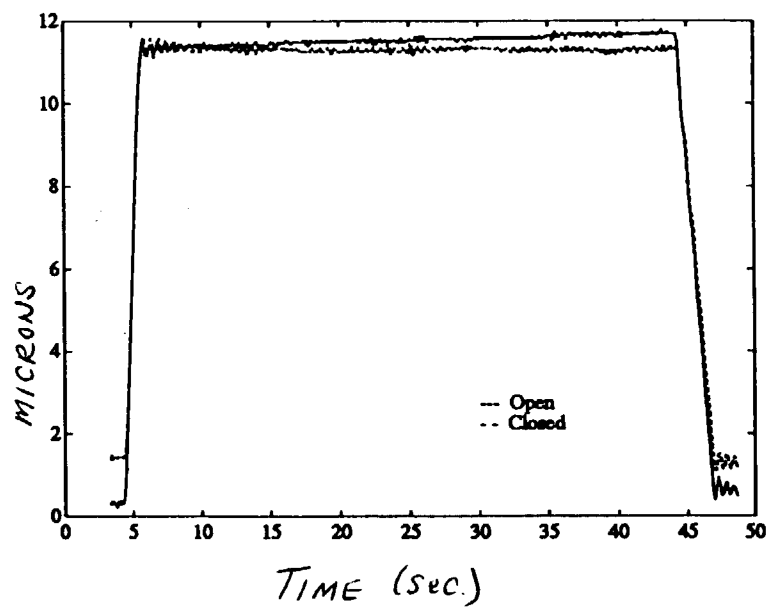
- Static and quasistatic considerations
- Noncollocated transfer functions and non-minimum phase zeros (Fleming, Spector and Flashner)
- Overall approach to dynamic control
  - Passive damping (resistive shunting)
  - Low authority control (collocated strain rate feedback)
  - High authority control (reduced order LQG, noncollocated optical measurement, low bandwidth)
- RMS performance

Test	Description	Tip RMS (microns)	Perf. Ratio
A	Open Loop	23.0	1.0
B	Shunt	21.9	.95
C	CRF(1,2)	19.9	.86
D	CRF(1,2), HAC(2)	16.8	.73
E	CRF(1), HAC(1,2)	11.8	.51

Table 1: **Test summary. Numbers in correspond to sensor/actuator pairs for collocated rate feedback (CRF), or the actuator used for high authority control (HAC).**

Quasistatic Error Correction

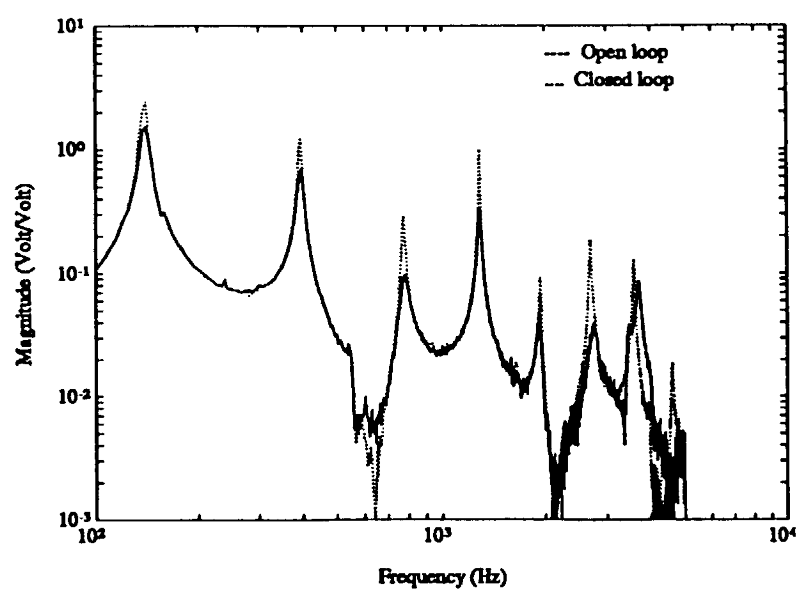
- Sources of error: initially wrong shape; thermal distortion; actuator material nonlinearities
- Solutions: alternative actuators; charge control; linearizing feedback



proportional feedback / actuator 3

Low Authority Control (LAC)

- Measuring strain rate with PVDF
- Rolloff issues
- Implemented at locations 1 and 2
- Target 3rd and 4th modes (400 Hz, 780 Hz)
- Disturbance at actuator 3

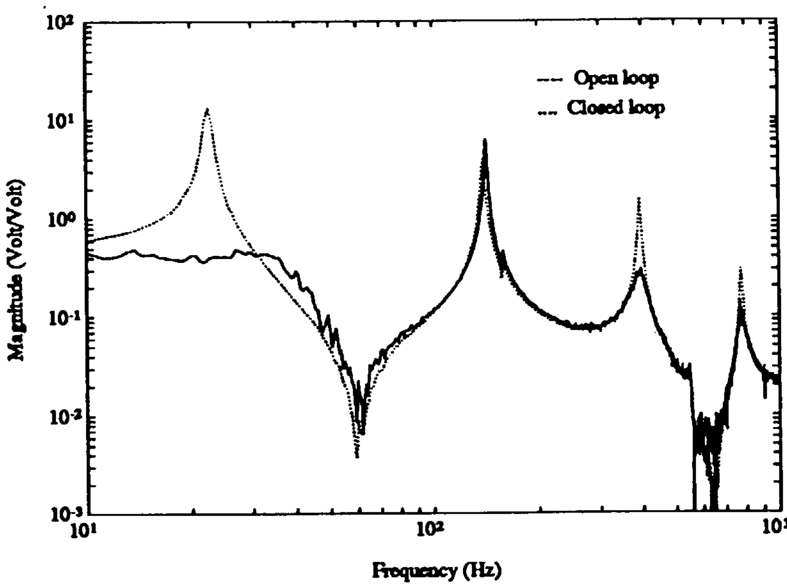


High Authority Control (HAC) Design Methodology

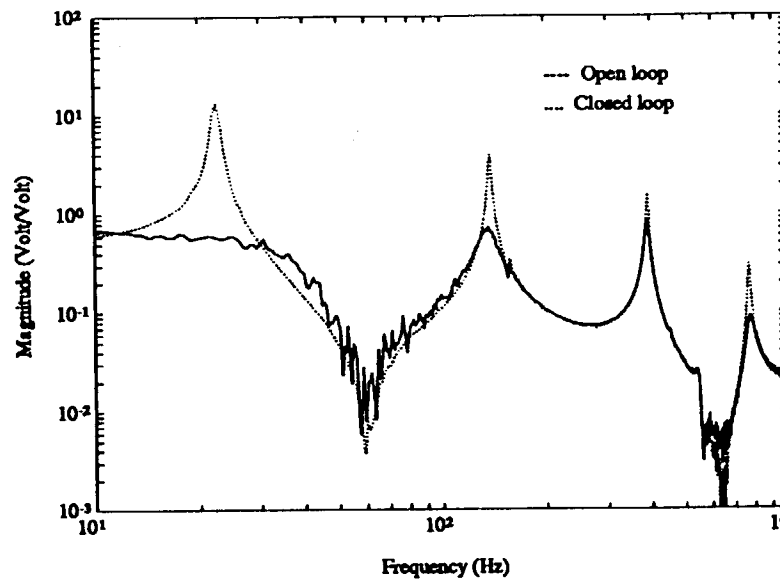
- Designed for first 2 modes (freq.-weighted rms performance)
- 10th order design model based on measured data
- Reduced order LQG
  - Technique developed by Mercadal
  - Possible robustness improvement
  - 2nd and 4th order compensators
- Disturbance at actuator 3

Results of HAC

- Implemented on "stealth" real-time control computer at 4 kHz



HAC: actuator 2
CRF: locations 1,2



HAC: actuators 1,2
CRF: location 1

Open Issues

- Must demonstrate concepts on a realistic optical system
  - 2-D mirror
  - wavefront sensor
  - disturbances
    - aircraft borne, atmospheric, wind, thermal, gravity gradient
- Structural sensor options
  - number, location, size, shape
  - fiber optics, strain gauges, piezo-polymers (PVDF), piezo-accelerometers
  - resolution for small surface deflections
  - benefits of "ganging"
- Actuator options
  - number, location, size, shape
  - amplifier power consumption and potential of charge storage devices.
  - membrane mirrors/electrostatic actuation

Open Issues

- Control
  - efficient architecture for numerous sensors
  - implementation: digital/digital vs. digital/analog
  - integration of WFS information into control loop

Conclusions

- Deformable mirrors built to date have been constrained by flexibility.
- Optical systems/deformable mirrors can benefit immediately from application of CST.
- Both weight reduction and performance improvement are possible.
- Application to surface control complements multi-point alignment goal