Technology Trends

- Sensors, actuators, computers
  - » will get cheaper
  - » use less power
  - » become smaller
  - » become prevalent in everyday equipment

(Appendix I)

Reason

- Cheaper, more flexible to use electrons
- Why?
  - » continuing evolution of silicon manufacturing
  - » cheap programmable controllers
  - » cheaper sensors and actuators
- So to predict the future
  - » understand underlying technology trends

(Appendix I)

Hardware Trends

- There are 4 key areas:
  - » energy
    - – power the system
  - » sensors
    - – monitor environment
  - » actuators
    - – influence environment
  - » electronics
    - – communication, digital processing

(Appendix I)

Energy

- Battery
  - » 1 J/mm^3
  - » technology improves slowly
- Solar cells
  - » 10-100 μAmps/mm^2 [1 J/day]
  - » near physical limit
- Gasoline
  - » miniature turbine (Epstein, MIT)
  - » potential of 10 J/mm^3 of fuel + turbine

(Appendix I)

MEMS Sensors

	Now	5 Years	Long Term
Volume mm^3	10 - 100	1 - 10	< 1
Power mW	1 - 10	0.1 - 1	0.001 - 1
Availability	preliminary	rapid, common	boring

(Appendix I)

MEMS Actuators

	Now	5 Years	Long Term
Power/ Volume $\mu J/mm^3$	0.1 - 1	1 - 100	1000
efficiency	generally < 1%	1 - 50 %	50 + %
Availability	minimal	preliminary	??

(Appendix I)

Electronics

- RF
  - » transmit
    - – 60 % efficiency
  - » receive
    - – mW when on [NF]
    - – duty cycle control to μW
  - » unlikely to see dramatic improvement
- Digital
  - » dramatic improvement
    - – 0.5 μ today (α = 0.7)
    - – shrink by α every 3 years
  - » energy * delay
    - – scales as α^3 - α^4
  - » processors
    - – 3000 SPEC²/W @ 0.5 μ
    - – 10 SPEC, 4 mW in 2001

Memory: 50 features², 80 K/mm² today

(Appendix I)

Appendix II

Application Overviews

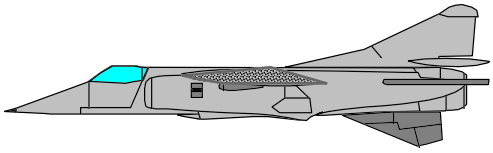
Envisioned Applications

Active surfaces

- Active camouflage/stealth
- Reduce fatigue
- Increase maneuverability
- Reduce drag

Ultra-safe Equipment

Warning: Insufficient pressure detected on left engine mount fastener



Condition-based Maintenance

Fatigue crack detected in wing section C, 3mm below surface

Strength on Demand

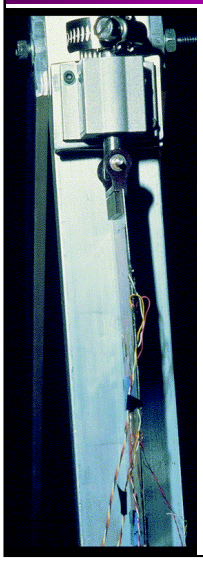
Active landing struts
Ultralightweight
Extra margin of safety

(Envisionment)

(Appendix II)

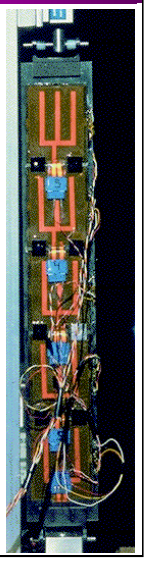
(Photo courtesy of Dr. Andrew Berlin, Xerox PARC)

Structural Enhancement



- Adjust dynamics to prevent buckling of compressive members
- Strength on demand
- Reduce fatigue

What is the operating range of a structure that includes computation as a mechanical property?

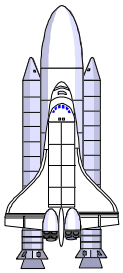


(Appendix II)

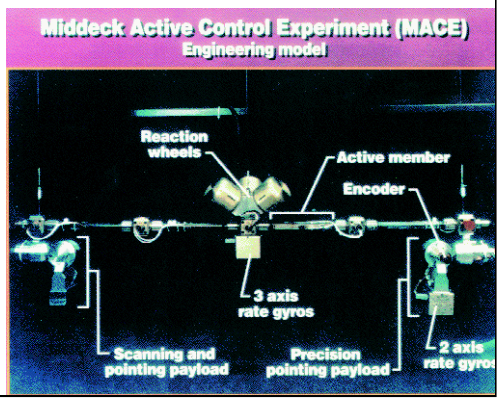
(Photo courtesy of Professor Jonathan How, Stanford University)

Precision Pointing/Alignment

MACE Experiment:
Precision Pointing/Targeting in Space



"Achieving robust adaptive control of MACE involved 2 years of manual control strategy optimization"



Message: Today's control strategies do not scale well to large numbers of sensors and actuators.

(Appendix II)

Active Surfaces

Examples:

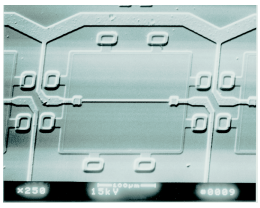
- Microflaps
- Arrays of cilia
- Arrays of airjets
- Arrays of cylindrically micromachined fibers

Location in design space:

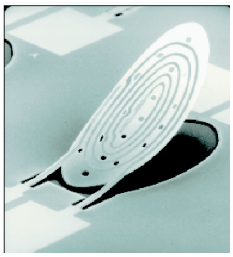
- Fixed topology
- Behavior driven by dynamics of object (or fluid) being manipulated
- Require spatial and temporal coordination at both the regional and local levels

(Appendix II)

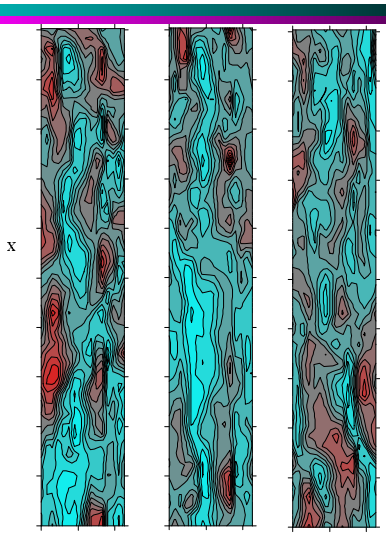
Active Aircraft Wing



Shear Stress Sensor



Micro-Actuator Array

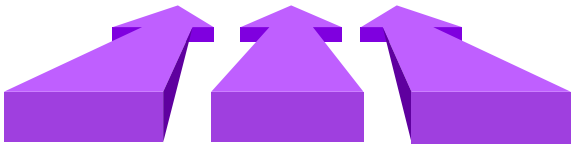


Vortex motion over wing surface

Photos courtesy of UCLA/Caltech

(Appendix II)

New Roles for Information Technology



Factory-installed:

- Aircraft, ships, …
- Clothing
- Weapons systems
- Small parts/fasteners
- Consumer products
- Machinery

Field-deployable MEMS:

- Battlefields
- Access to denied areas
- Hazardous waste sites
- Security perimeters
- Upgrading existing infrastructure
  - smart patches/paint

(Appendix II)

Appendix III

Factors Influencing Computational Requirements of MEMS Systems

Application Requirements Taxonomy I

- **Static—Dynamic**
  - Physical organization (e.g. wing control vs. floating dust)
  - Logical organization (e.g. perimeter detection vs. smart soup)
  - Static calibration and/or dynamic compensation (e.g. laser trim vs. real-time drift compensation)
  - Incremental modifications (e.g. repair)
- **Local—Global**
  - Degree of local interaction & feedback
  - 'Need to Know' (local spanning to global)
  - 'Need to Tell' (e.g. need for an external global perspective)

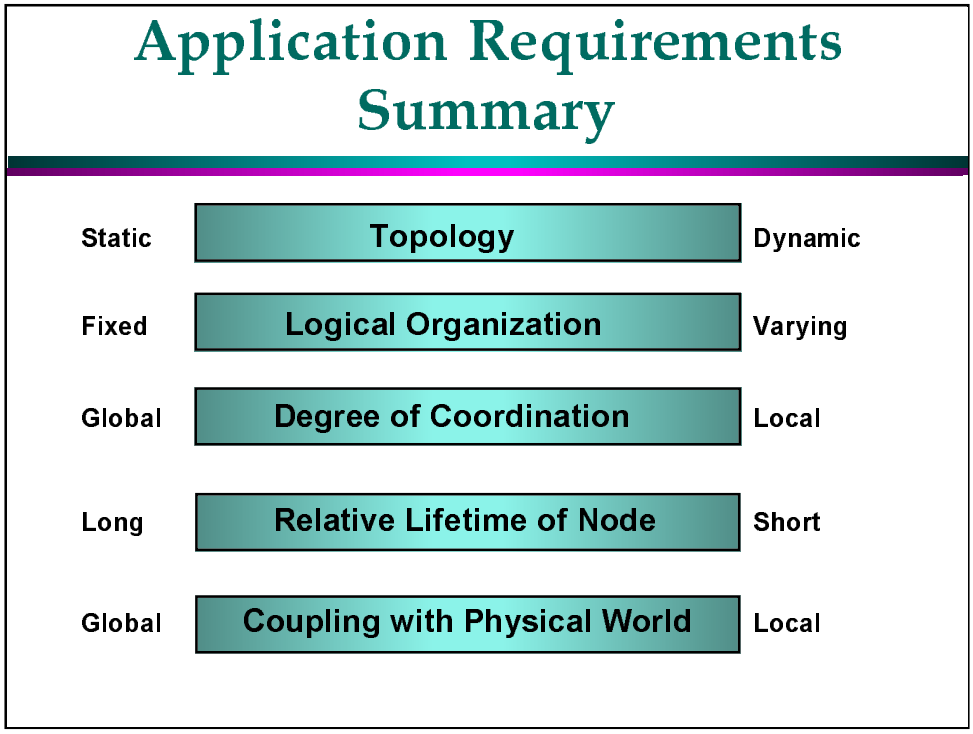
(Appendix III)

Application Requirements Taxonomy II

- **Nodes**
  - » Capability (e.g. sensors, actuators, computation) and role (e.g. 'managers' and 'workers') of nodes.
  - » Communication requirements (bandwidth, lifetime)
  - » Energy requirements
  - » Manufacturing costs
- **Configuration**
  - » Spatial scale and organization (relative or absolute positions of elements)
  - » Temporal synchronization
  - » Alignment precision (spatial and temporal)
  - » Yield (i.e. defect tolerance)
  - » Number and mix of nodes

(Appendix III)

Application Requirements Summary



(Appendix III)