

# **MEMS Based Active Control of Macro-Scale Objects**

## *Semiannual Technical Progress Report*

**Covering the Period  
July, 1997 - December, 1997**

**Xerox Palo Alto Research Center  
3333 Coyote Hill Road  
Palo Alto, CA 94304**

**Principal Investigator: Dr. Andrew A. Berlin**

**Co-Investigators: Dr. Patrick Cheung  
Dr. J. Geoffrey Chase  
Dr. Mark H. Yim  
Professor Feng Zhao  
Srinivas Bhashyam  
Rachel Lau**

**Collaborating Researchers: Dr. David Biegelsen  
Dr. Warren Jackson  
Dr. Tad Hogg  
Eric Mao**

**Submitted to:  
Dr. A. Pisano  
Program Manager, MEMS  
Defense Advanced Research Projects Agency**

**Contract number: DABT63-95-C-0025**

**X**

**Title** MEMS-based Active Control of Macro-Scale Objects

**Technical PI** Andrew A. Berlin

**PI Phone** (415) 812-4372

**Organization** Xerox Palo Alto Research Center

**Location** Palo Alto, California

**Agent** USAIC, (602) 538-7500/7613

---

### **Overall Project Goals**

The goal of this project is to develop and demonstrate techniques that enable distributed, MEMS-based arrays of sensors, actuators, and computational elements embedded within materials and on surfaces to enhance and control the behavior of macro-scale systems. We are pursuing system-level research that includes the development of software and architectures for coordinating the actions of large numbers of distributed devices. We are also developing milli-scale hardware components and manufacturing methods to bring MEMS-style batch fabrication to bear on macro-scale objects. We will demonstrate our work through a series of technical demonstrations that address the closely-related applications of active structural enhancement and precision motion control.

### **Recent Accomplishments (July 1997 – December 1997)**

- Developed a novel lamination-based fabrication process for batch manufacture of fluidic valves. This process combines MEMS-style materials deposition and etching with printed-circuit board technology to enable production of large-area arrays of sensors and actuators. An initial fab run of this process is currently under way.
- Completed a feasibility study to explore the potential of using distributed arrays of sensors and actuators to control structural instabilities in stiffened plates, such as aircraft wing skins. Optimal distributed control strategies were developed for this application. Two technical papers are currently in preparation.
- Initiated an effort to apply expertise developed as part of our distributed control strategy development to problems in modular robotics.

### **Milestones (Near and Long-term)**

The milestones in this effort are divided into four technology demonstrations (TDs), as follows:

- **TD1:** To demonstrate the usefulness and feasibility of integrated MEMS technology in solving a macroscale problem (active control of buckling in a composite column).
- **TD2:** Develop distributed control strategies that scale to large numbers of sensors and actuators, as well as analysis tools for predicting the operating range of actively controlled systems. Demonstrate these tools using a prototype “Programmable Structure”.
- **TD3:** To demonstrate components that use MEMS devices to interact with macro-scale objects, in order to show the progress in the development of intelligent surfaces that affect the dynamics of nearby objects.
- **TD4:** To demonstrate distributed local control of MEMS components arrays for object manipulation and motion control (MEMS-based active surface/material demonstration).

## Introduction

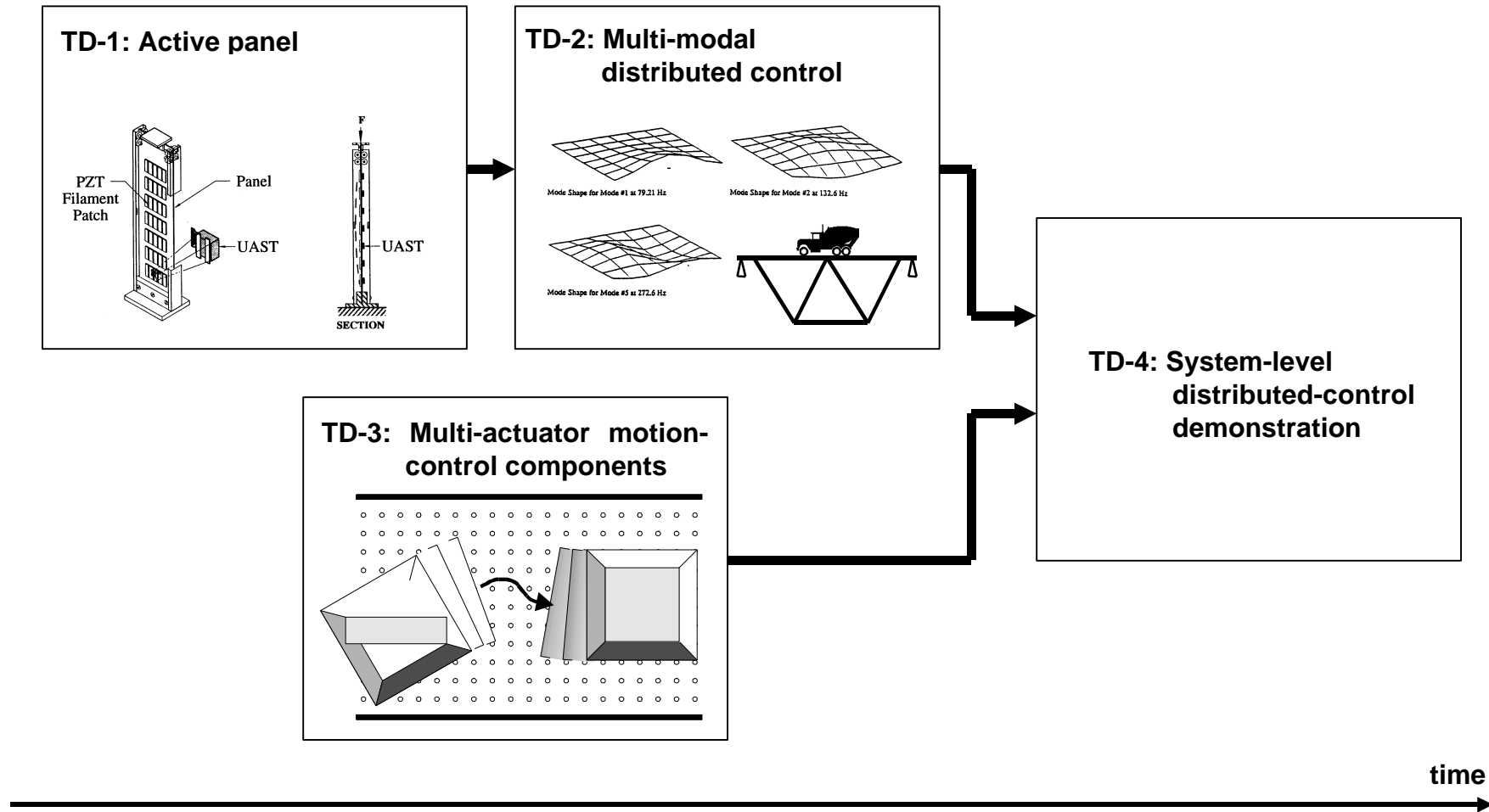
Imagine how different the world would be if matter were programmable, so that fundamental properties such as shape, stiffness, color, reflectivity of light and sound, and even load-bearing strength could be dynamically adjusted on demand. Although today's structure and product designers have many materials with varied properties to choose from, once a particular material is selected and cut to size, its properties remain fixed -- individual parts are unable to adapt to changing conditions. Making the dynamic behavior of matter programmable has the potential to enable "control-centric" products and processes that actively adapt to changing conditions, achieving strength and precision operation through intelligent adjustment of their dynamic behavior.

We are developing techniques that combine micromachining with a variety of other technologies to allow MEMS-based arrays of distributed sensors, actuators, and computational elements to interact with and control the behavior of macro-scale systems. We will demonstrate the techniques we develop using two closely-related applications: **active structural enhancement**, in which actuators are embedded within materials to modify the dynamics of an object, and **precision motion control**, in which control forces are applied to an object remotely. Achieving these goals will require the development of software technology and architectures for effectively coordinating the actions of large numbers of devices interacting with the physical world. It will also require the development of new hardware components and batch fabrication techniques suitable for constructing arrays on a scale suitable for interacting with macro-scale objects.

## Project Structure and Motivation

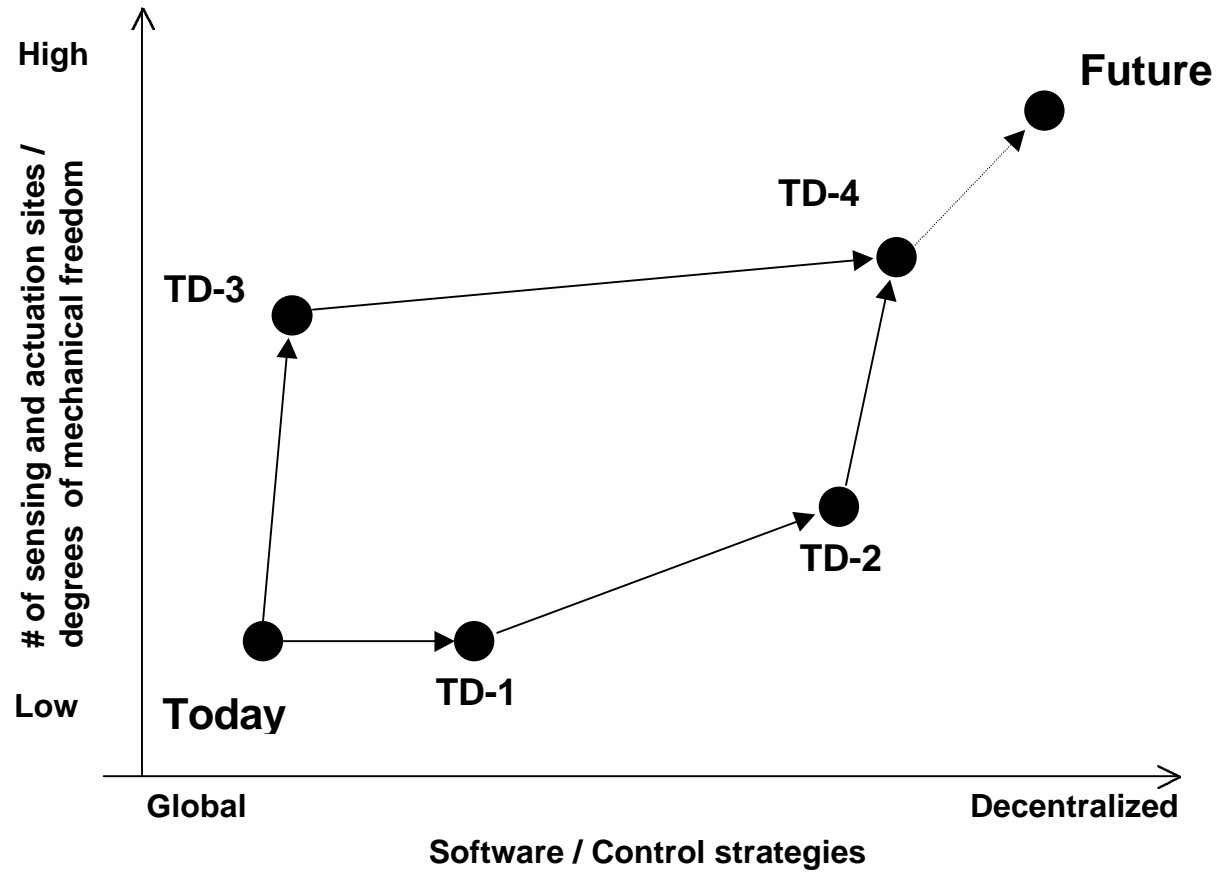
Our work will produce a series of technical demonstrations that build upon each other to achieve an ever-increasing level of integration between sensors, actuators, and computational elements, coupled with the development of increasingly sophisticated and distributed control strategies and system architectures. Some of these demonstrations will be performed through collaboration with Sarcos Research Corporation. An overview of the planned technology demonstrations is shown in Figure 1.

The ideal system that we are considering is one in which large numbers of sensors and actuators work relatively independently to achieve global performance criteria such as structural stability and trajectory tracking precision. The current state of the art in this area considers only relatively small numbers of actuators and sensors (on the order of 10) utilizing centralized control strategies. Each technology demonstration focuses on specific advances that move the state of the art closer to the ideal system along several dimensions, as illustrated in Figure 2.



**Figure 1**

The technical data contained herein is Xerox information and can only be used, reproduced and distributed by the Government for research purposes.



**Figure 2**

## Research Overview

### Active Structural Enhancement

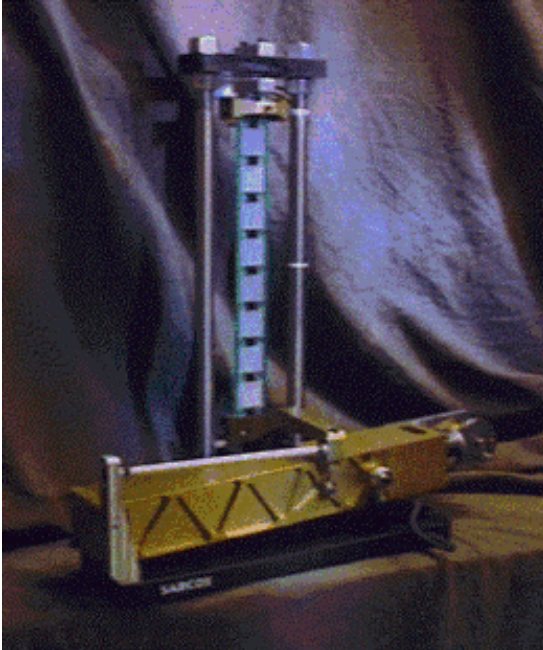
This portion of our project involves exploring what new capabilities may arise once MEMS technology makes it possible to inexpensively mass-produce large arrays of integrated sensors, actuators, and computers. One of the possibilities that we are examining is active enhancement of structures. Our first demonstration example involves active stabilization of compressively-loaded columns.

Active structural enhancement is the creation of structural systems which are capable of adjusting their properties dynamically, providing benefits such as alteration of shape, strength, and stiffness. The first technology demonstration is designed to demonstrate the usefulness and feasibility of integrated MEMS technology in solving a macroscale structural enhancement problem: active control of column buckling to increase load-bearing strength.

#### ***MEMS-based Active Stabilization Experiment***

Active stabilization can be used to actively stiffen, or strengthen (against Euler buckling) a given structure. Actively stabilized structures can adaptively modify their stiffness properties to be either stiff or flexible as demanded. One portion of this research investigates optimal closed-loop control strategies to maximize the critical buckling load of a pinned-end column using MEMS based sensors and actuators. In this instance, active control is employed to actively stabilize a structural member to prevent it from collapsing. From a controls standpoint this problem consists of developing control strategies for a time-varying, inherently unstable system, and developed techniques to predict the performance range of the controlled system.

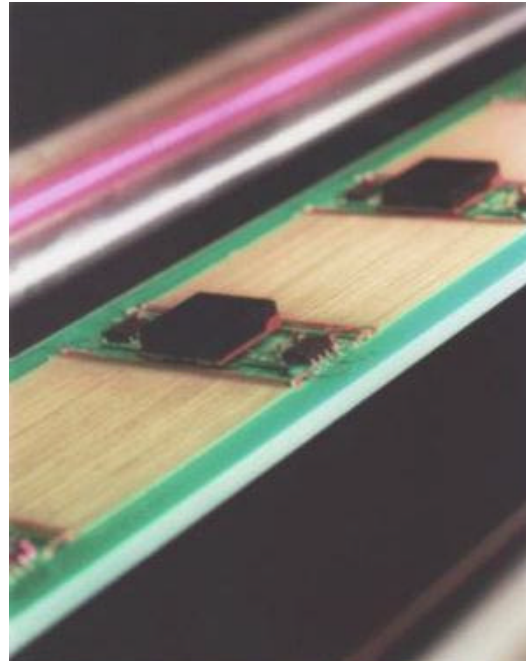
This research is being performed as part of a collaboration between Sarcos Research Corporation and the Xerox Palo Alto Research Center.



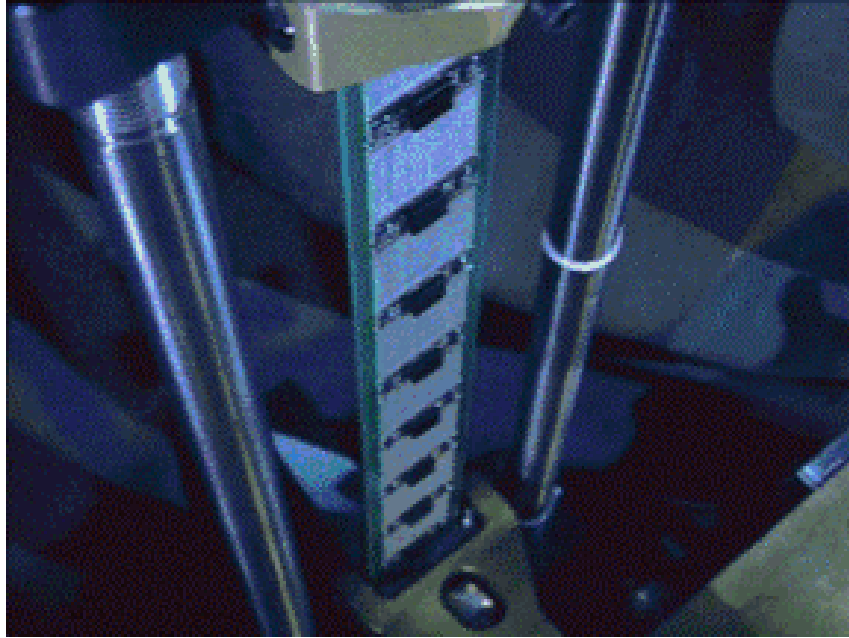
The demonstration test article integrates fiber-based PZT (piezo-ceramic) actuators and a network of MEMS based UAST strain sensors with a structural beam element and a high-speed computer. Using optimal feedback control strategies we have been able to increase the buckling load of this column by 2.9 times. The picture shows the beam and fixture apparatus. The filament based PZT actuators and the UAST sensors are both technologies developed by Sarcos. The combination of smart material actuators and MEMS based UAST sensors with external computation emulates smart matter.

The beam is clamped vertically within the test fixture which allows us to apply a compressive axial load to the pinned-end beam. The load is applied mechanically using a load arm (shown in the foreground) and a moving weight. The weight is driven by a motor under computer control so that the load being applied can vary over time.

The picture on the right shows UAST strain sensors (the little black boxes) and filament PZT patches between them. The beam material is G10 fiberglass composite. For reference, the beam is 18 inches long, 2 inches wide and 0.093 inches thick. The UAST's sense strain with an accuracy of 3 micro-strain. A digital network of 18 sensors are attached to the beam to determine bending strains. Structural deformation is from these measurements. The patches of PZT filaments are used as actuators for the control system. Voltages applied to the PZT enable it to expand or contract, creating surface strains on the beam. Eight pairs of PZT patches create bending strains which are applied as the control input. The control is implemented with a servo rate of 1000Hz using a PC and a TI DSP card.



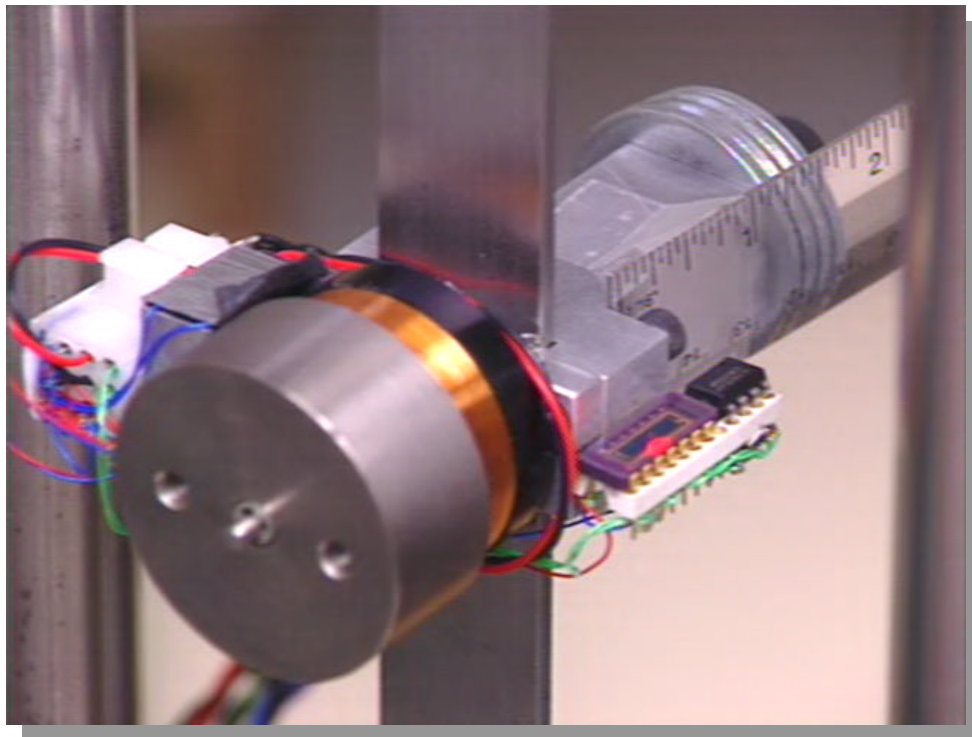
The photo below shows the TD1 beam under active control in its straight (stiff) position.



### ***Alternative actuation strategies***

We are exploring ways in which active buckling control technology can be scaled up to handle larger structures. Larger structures will require the application of larger restoring forces but typically allow for a somewhat longer response time. To experiment with mechanisms for applying larger forces, an inertial patch actuation strategy is attractive due to the widespread availability of compact linear motors capable of exerting large forces. Several physical experiments were conducted to explore the applicability of inertial actuation to the stabilization of compressively loaded structural members.

Our results showed that although inertial actuation is in general not sufficient to stabilize a member due to its inability to correct for static forces, the high bandwidth available from inertial actuation was quite effective as a means for correcting for dynamic forces and perturbations. Thus, one way to scale up buckling control system would be to utilize inertial actuation to correct for dynamic perturbations, while utilizing a slower bandwidth actuation mechanism (such as Nitinol actuators or tendons) to correct for the effects of static forces such as those resulting from gravity or eccentric loading conditions.



Inertial patch developed to test how active buckling control scales up.

## Experimental Observations

---

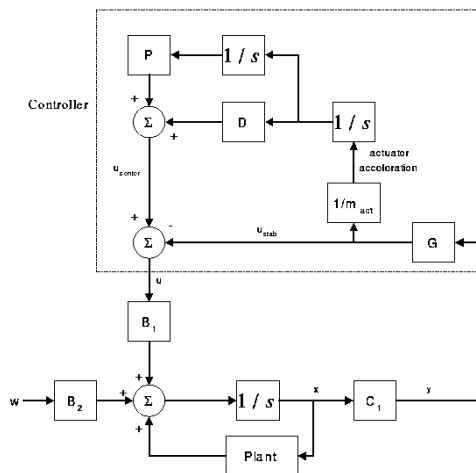
- Low freq. oscillations require large strokes
- Frequencies are slow when loaded near  $P_{cr}$ ,
  - It performs better as the load increases past  $P_{cr}$ .
- Real beams have natural curvature  $\rightarrow 0\text{Hz}$ .
  - Rely on stiction.
  - Experimented with perturbation
- At 1.3  $P_{cr}$  absorbed 6 times the energy required to break stiction

THE DOCUMENT COMPANY  
XEROX

### ***On-line Centering and its anticipated impact on Vibration control and Active Mass Dampers in Tall Structures***

During the course of the active buckling control experiments, a strategy was developed for partially mitigating the limitations imposed by the finite stroke lengths of inertial actuators. The strategy involves combining control actions that center the inertial actuator with actions that exert control forces on the structural member. We have experimented on the use of this strategy on inherently stable systems, e.g. vibration control, with very promising results. We suggest that this integrated centering control strategy may be applied to a wide variety of tall structures, such as the active mass dampers used to compensate for wind-induced motion of tall buildings.

## Integrating Centering with Feedback Control



- Novel centering control
- Two Feedback Loops
  - Buckling or Vibration Control Feedback
  - Stroke Limit Control Feedback

THE DOCUMENT COMPANY  
XEROX

***Active Stabilization of Plate Buckling: Feasibility Study***

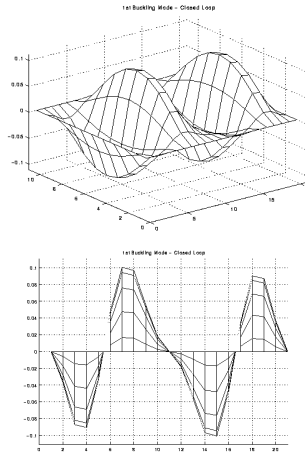
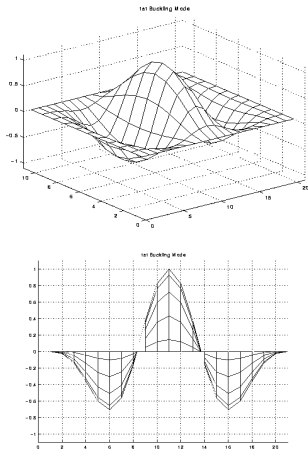
Can active control of buckling be extended from the initial proof-of-concept demonstrations conducted using column geometries to other geometries of military interest, such as plate structures? We have developing a set of finite-element models and control strategies to answer this question via an optimization-based approach enabled by simulation. The results are somewhat borderline. For reasonable assumptions of actuation authority, we have found that (in simulation) it is possible to achieve active control of plate buckling. However, the benefits achieved by doing so in comparison to alternative approaches for stiffening the plate against buckling are not compelling based on the actuation modalities available today (such as PZT filaments). We recommend that further research on active control of plate buckling be put on hold for now, and be revisited in the future as actuation technology improves.

Can active control of buckling be extended from the initial proof-of-concept demonstrations conducted using column geometries to other geometries of military interest, such as plate structures? We developed a set of finite-element models and control strategies to answer this question via an optimization-based approach enabled by simulation. For reasonable assumptions of actuation authority, we have found that (in simulation) it is possible to achieve active control of plate buckling. However, the extent of the benefits achieved by using active control in comparison to alternative approaches for stiffening the plate against buckling is still being evaluated. We anticipate completing this study early in 1998.

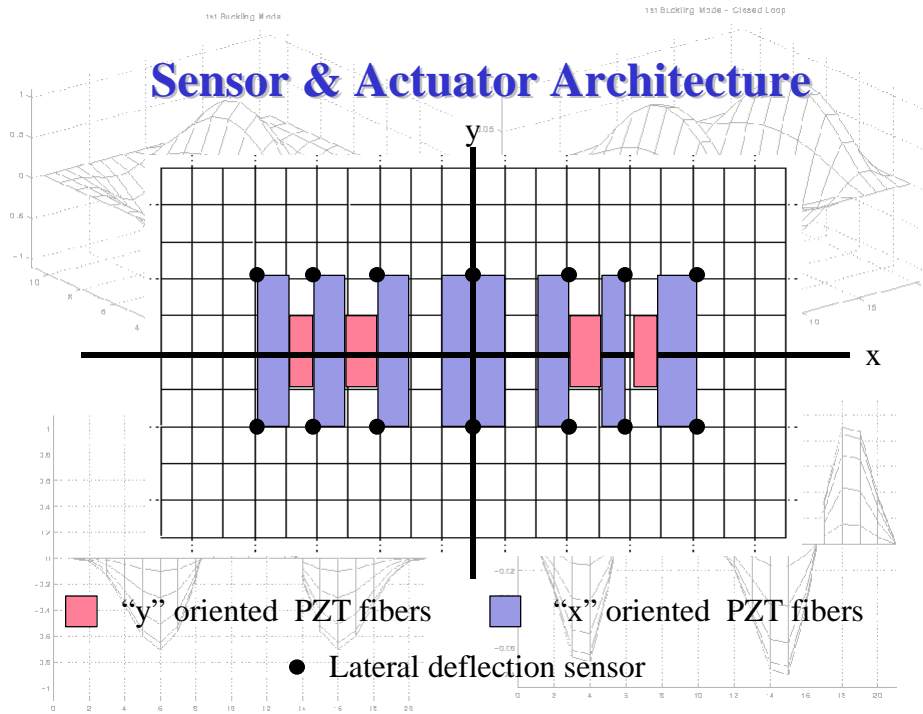
## 1st Buckling Mode - Controlled & Uncontrolled

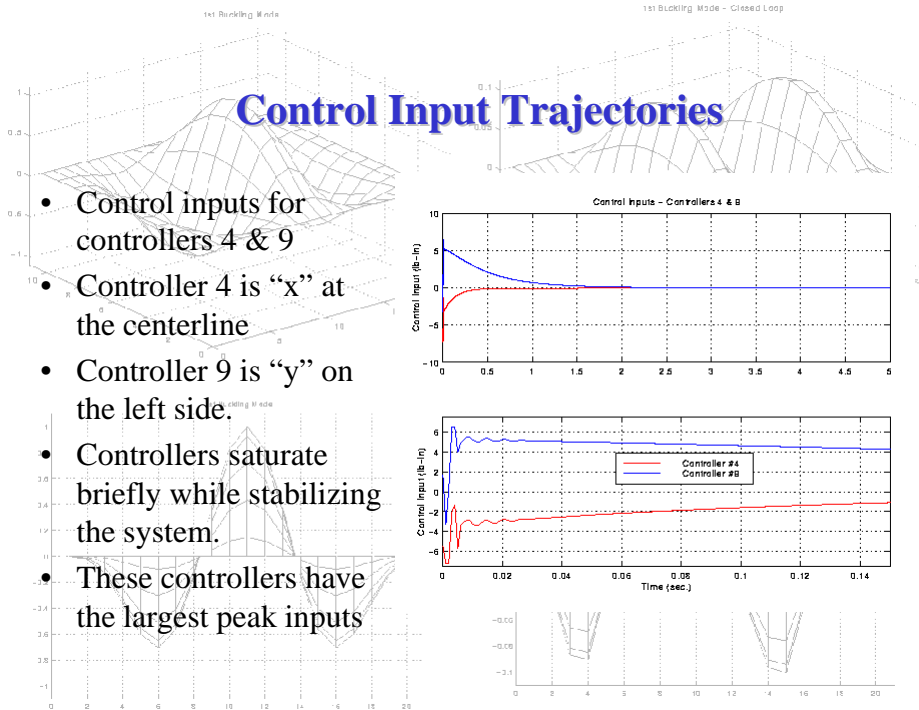
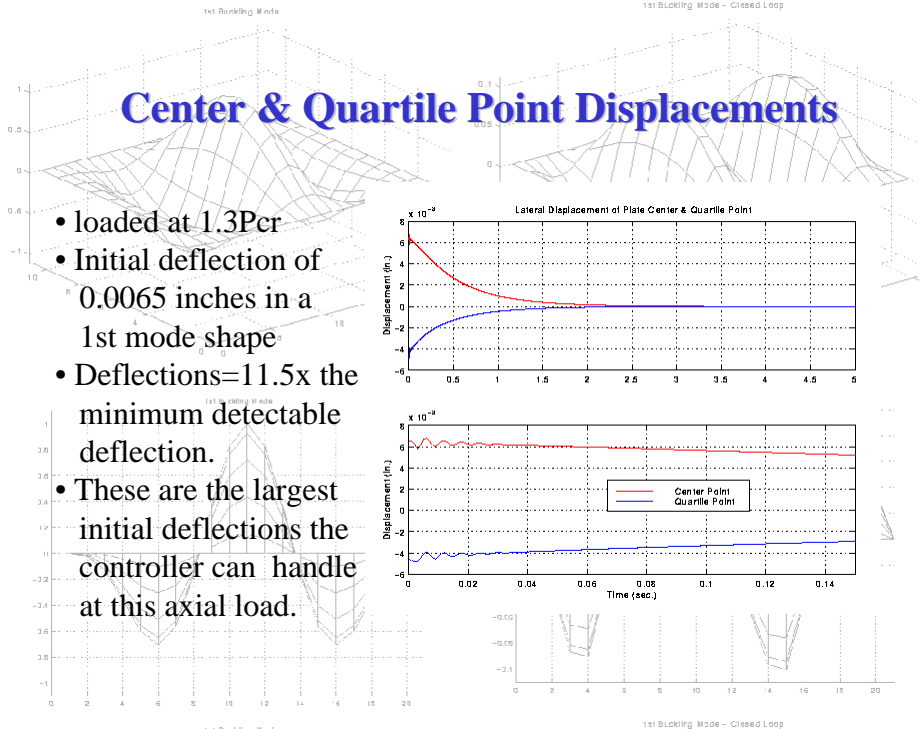
Uncontrolled ( $P_{cr} = 980 \text{ lb/in}$ )

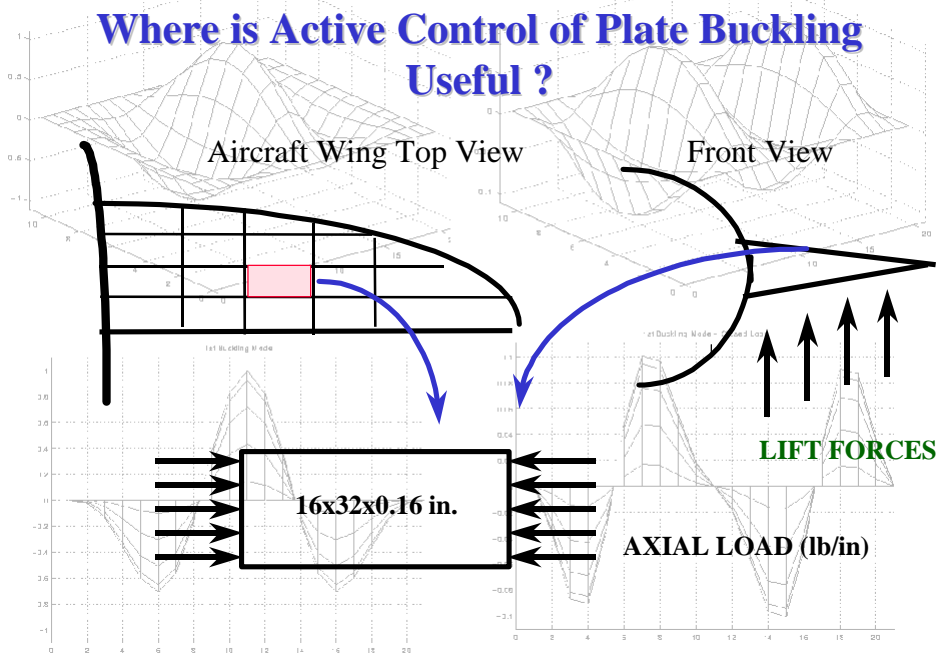
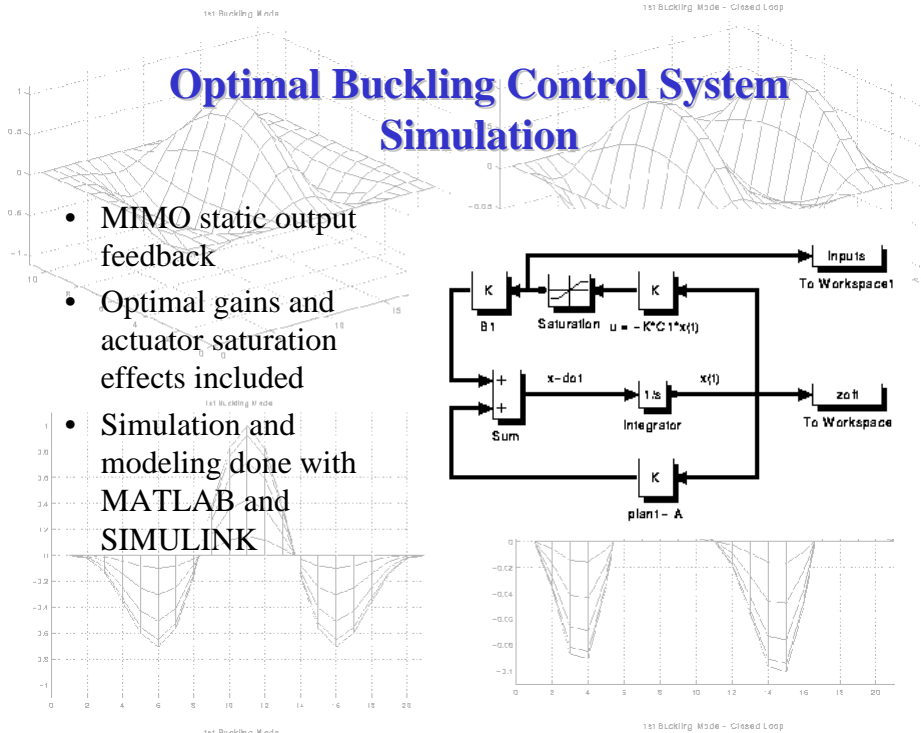
Controlled ( $P_{cr} = 1570 \text{ lb/in}$ )

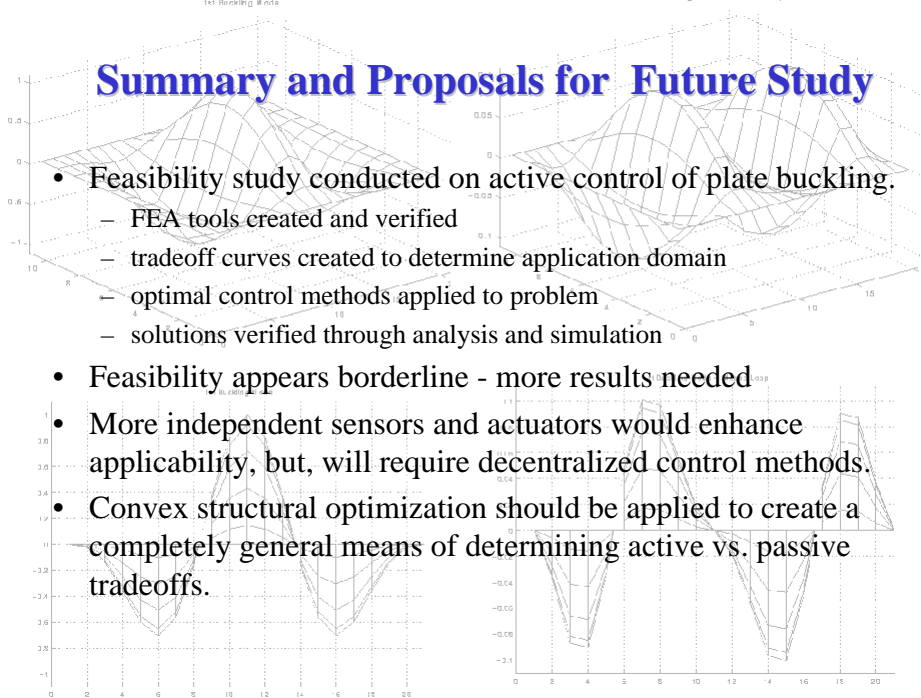
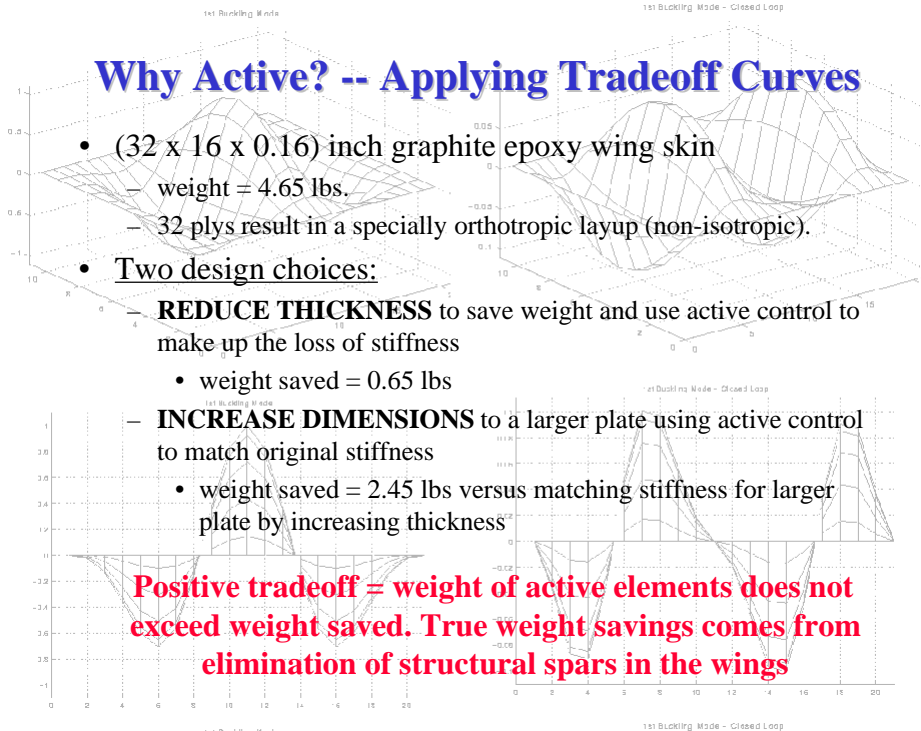


PZT actuators act like (active) stiffeners to alter mode shapes









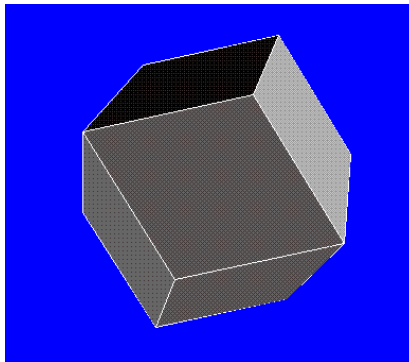
## Distributed Control applied to MEMS-scale Modular Robots

We continued work on a small effort to apply expertise developed as part of our distributed control strategy development to problems involving the programming of MEMS-scale modular robots that were identified at the DARPA Santa Fe Workshop on Complex Systems. This workshop brought together MEMS researchers with quantum electronics and complex systems researchers. A small exploratory project was undertaken at PARC to explore distributed control strategies for MEMS-scale modular robots. As part of this project, The Rhombic Dodecahedron shape for a modular robotic module was developed. A simulator to explore the control and programming issues associated with these robots was developed, and numerous control strategies were created and evaluated.

### RD Blocking Constraint

---

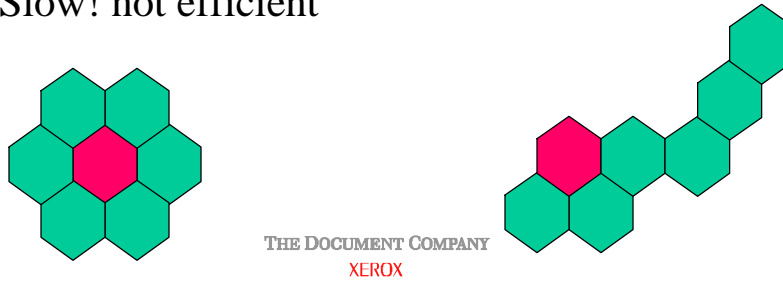
- Full RD 7 Side Constraint
- Rounded corners 5 Side Constraint



THE DOCUMENT COMPANY  
XEROX

## One RD at a time

- Each goal is adjacent to a previous goal
- No local minima problems
- Simple global communication: “at goal”
- Not robust. Single RD failure is catastrophic
- Slow! not efficient



## All move towards closest unfilled goals

- Fast
- Same local minima
- Communication “at goal”
- Robust
- Each RD must know full goal configuration



## All moving to pre-assigned goal

---

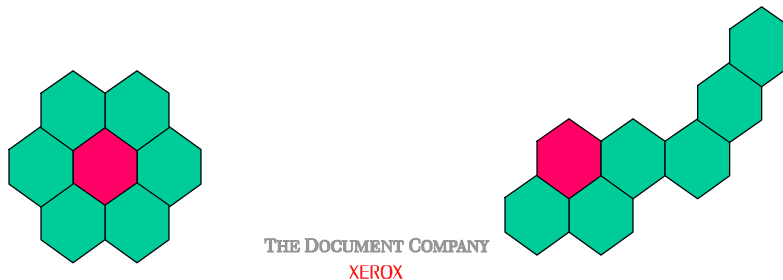
- Fast
- Easy to get stuck (local minima)
- Only local communication to maintain constraints
- Small amount of info needed per RD



## All move to one goal

---

- Local minima (hacks can help)
- Communication “at goal”, “reverse”
- More robust
- Goal info may be distributed (less robust)

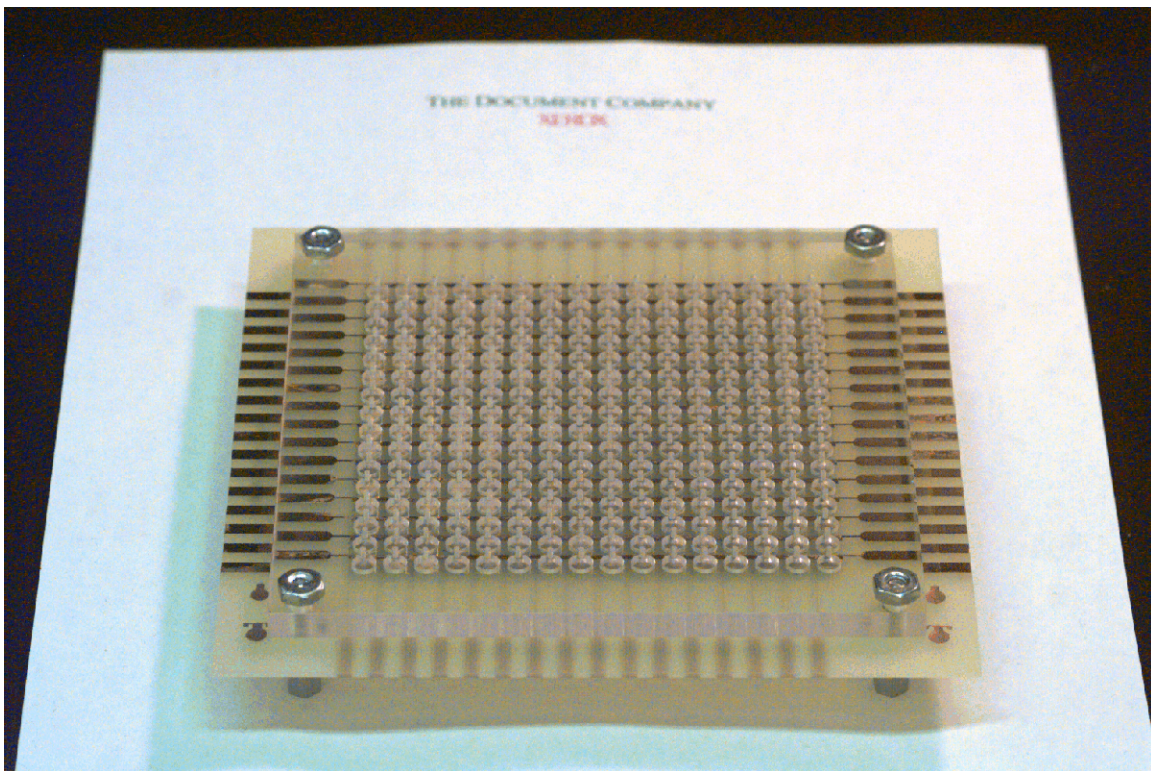


## **Precision Motion Control and mEMS**

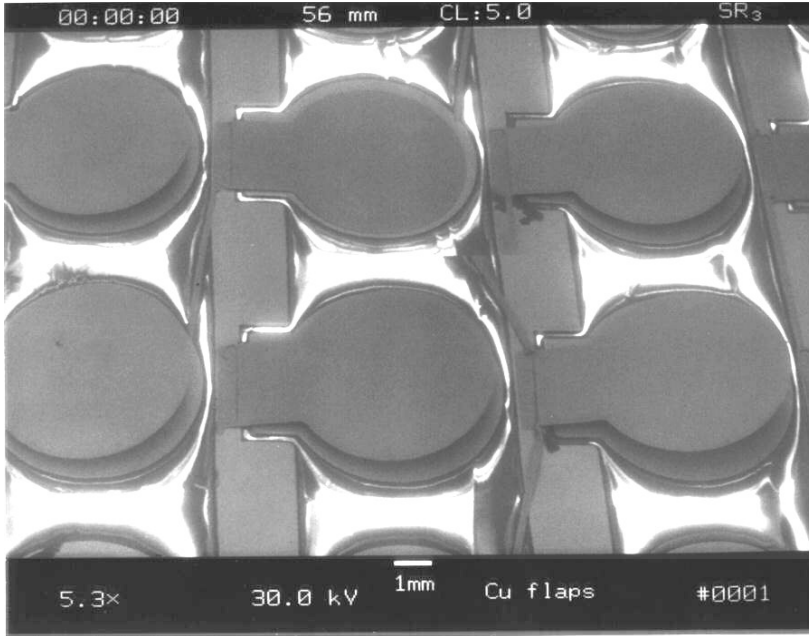
In parallel with work on the active structural enhancement demonstrations, in preparation for the third technology demonstration (TD3) we will be developing components and fabrication technologies suitable for use in creating MEMS-based active surfaces which manipulate objects in their vicinity. The third technology demonstration (TD3) explores the creation of batch-fabricatable surfaces which contain large numbers of sensors and actuators. We are currently exploring a variety of sensing and actuation strategies that would couple MEMS-scale devices with the macro-scale world, such as modulation of air jets and thermal sensing arrays.

### Steps towards mEMS (milli-Electro-Mechanical-Systems)

We have developed a set of techniques for scaling MEMS-style batch fabrication techniques up to the pc-board scale. Using photo-resist and other materials as sacrificial layers, combined with lamination and electrodeposition and etching, we have demonstrated the capability to produce large-area arrays of milli-scale MEMS-like devices. We call this new scale of batch fabrication mEMS, for milli-Electro-Mechanical-Systems.



**mEMS** array of 256 cantilevered valves produced by hybrid of printed-circuit board and MEMS batch fabrication techniques. The valve array is shown overlaid on a standard 8.5x11 sheet of paper. The valves were produced by using photo-resist as a sacrificial layer.



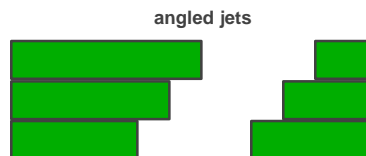
### Electron Micrograph of batch-fabricated cantilevered valves.

- Batch fabrication
- Resist as sacrificial material
- Extremely thin flaps possible
- Conformal deposition of parylene as dielectric



### Printed-Circuit board as substrate

- multi-layer of conductors
- incorporates other designs (angled jets, spiral coils)
- excellent mechanical /electrical properties
- mature technology
- easy to prototype



THE DOCUMENT COMPANY  
XEROX

## Technical Update

For detailed technical information about our recent activities, please refer to the attached technical papers.

## Publications and Presentations:

Biegelsen, Jackson, Berlin, and Cheung, "Air Jet Arrays for Precision Positional Control of Flexible Media", International Conference on Micromechatronics for Information And Precision Equipment (MIPE'97), July 20-23, 1997, Tokyo

Berlin, Chase, Yim, Jacobsen, Olivier, Maclean, "MEMS-based control of structural dynamic instability", submitted 12/97 for special edition of the Journal of Intelligent Material Systems and Structures.

Berlin, A., "Active Surfaces based on mEMS", Invited Talk, UCLA Department of Mechanical Engineering, September 1997.

Berlin, A., "Active Surfaces based on mEMS", MIT Artificial Intelligence Laboratory Revolving Seminar Series, November, 1997.

Berlin, A., "Distributed MEMS: Coupling Computation to the Physical World", invited talk at Stanford University Department of Electrical Engineering.

Berlin, A. and Gabriel, K., "Distributed MEMS: New Challenges for Computation, *IEEE Computational Science and Engineering Magazine*, Jan-Mar 1997.

Berlin, Chase, and Yim, "Active Control of Structural Buckling Instability: Practical Tradeoffs and Design Considerations", in preparation.

Breneman, S., Chase, J.G., and Smith, A., "Robust and LTI H-infinity Static Output Feedback Design for Systems with Limited Actuator Authority", *American Control Conference*, Albuquerque, NM., 1997.

Chase, Yim, Berlin, Jacobsen, Olivier, Maclean, "MEMS-based control of structural dynamic instability" ASME Congress presentation and publication, November 16-21 Dallas, TX

Chase, Yim, Berlin, "Integrated centering control for inertially actuated systems" submitted to *Control Engineering Practice* 11/97

Chase and Bhashyam, "Optimal stabilization of plate buckling", submitted for publication.

Chase and Bhashyam, "Optimal stabilization of indefinite plate buckling problems" submitted for publication.

Chase, J.G. and Yim, M., "Optimal Stabilization of Column Buckling", submitted for publication.

Cheung, P., Berlin, A., Biegelsen, D., Jackson, W., "Batch Fabrication of Pneumatic Valve Arrays by Combining MEMS with Printed Circuit Board Technology", to appear in the proceedings of the *Symposium on Micro-Mechanical Systems*, ASME International Mechanical Engineering Congress and Exhibition, Dallas, TX, Nov. 16-21.

Yim, Chase, and Berlin, "Inertial Stabilization of Buckling" submitted to ASME Dynamic Systems Measurement and Control 11/97

Yim and Mao, "Rhombic Dodecahedron Shape for Self-Assembling Robots", submitted for publication.

## **Media Coverage**

During this past year, several articles reporting on aspects of this project have appeared in the media, including the following:

The New York Times  
ABC World News Tonight  
Knight-Ridder Satellite Network  
Science News  
Defense News  
ABC Radio Network  
KGO Radio  
Der Spiegel  
The St. Louis Post Dispatch

## Personnel Supported

Personnel supported by this contract:

Dr. Andrew A. Berlin  
Dr. J. Geoffrey Chase (since 9/95)  
Dr. Patrick Cheung (since 10/95)  
Dr. Mark Yim (since 4/96)  
Professor Feng Zhao (Consultant)  
Natalya Cohen (Summer Intern, summer 1995)  
Srinivas Bhashyam (Summer Intern, summer 1997)  
Rachel Lau (Summer Intern, summer 1997)

Personnel supported by Xerox collaborating on substantial portions of this project:

Dr. David Biegelsen (PARC Electronic Materials Laboratory)  
Dr. Warren Jackson (PARC Electronic Materials Laboratory)  
Dr. Tad Hogg (PARC Systems and Practices Laboratory)  
Eric Mao (Summer Intern, summer 1997)

## Key Points of Contact:

Principal Investigator: Andrew A. Berlin  
Xerox Palo Alto Research Center  
3333 Coyote Hill Road  
Palo Alto, California 94304  
Phone: (415) 812-4372  
Fax: (415) 812-4477  
E-mail: berlin@parc.xerox.com

Administrative Contact: Eleanor Datu  
Xerox Palo Alto Research Center  
3333 Coyote Hill Road  
Palo Alto, California 94304  
Phone: (415) 812-4035  
E-mail: datu@parc.xerox.com

Media Relations Contact: Lois Wong  
Manager, PARC Communications  
Xerox Palo Alto Research Center  
3333 Coyote Hill Road  
Palo Alto, California 94304  
Phone: (415) 812-4434  
Fax: (415) 812-4497  
E-mail: lawong.parc@xerox.com