Actuator and Sensor Placement

Sharon Padula

ASCAC Methods Development

Peer Review

November 27-29, 2001

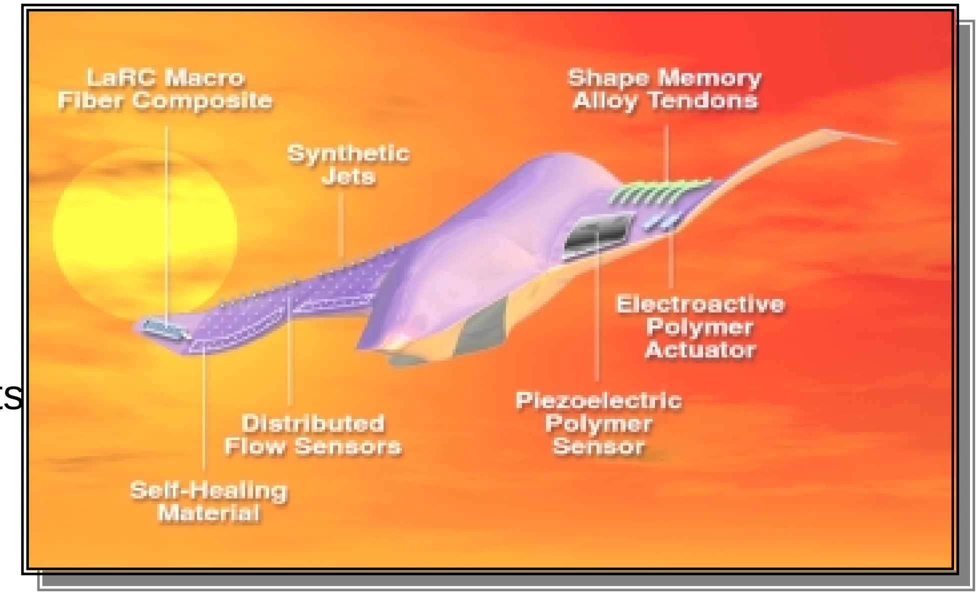
Morphing Project (1998- 2002)

***Long-Term Vision:** Aerospace Vehicles that Efficiently Adapt to Handle Diverse Mission Scenarios*

NASA Morphing Project Objective:
Develop and assess innovative, advanced technologies and integrated concepts to enable efficient, multi-point adaptability in air and space vehicles

Morphing

Technical Challenges:
- Active materials for sensors and actuators
- Compliant, load-bearing structures
- Unsteady aerodynamics
- Non-intrusive, efficient electronics
- Optimization and Controls
- Manufacturability and Reliability
- New structural and vehicle control concepts



Technical Approach:
- Create Innovative Technologies
- Address Application Issues
- Demonstrate Performance
- Devise Revolutionary Concepts

Actuator and Sensor Placement Survey Paper Completed in 1999

- **NASA TM by Padula and Kincaid**
- **Langley Technical Report Server**
  - **http://techreports.larc.nasa.gov/ltrs/ltrs.html**
- **Includes more than 50 references**
- **Wide variety of applications**
  - Aerospace
  - Nuclear power
  - Water resources
  - Cancer Treatment
  - Etc.
- **Very few use formal optimization techniques**

Outline

- **Optimization Methods for Selecting Locations**
- **Sample Applications**
  - Vibration suppression and aeroelastic control
  - Interior noise control
  - Novel 3-axis flight control system
- **Results**

Collaborations

Years	Application	Branch	Contact
1990-1992	Vibration Suppression	Structural Dynamics / SMC	Chris Sandridge
1995-1997	Interior Noise	Structural Acoustics/ AAAC	Dan Palumbo
1998-2000	Flight Control	Dynamics & Control / AirSC	Dave Raney
2000-2001	Adaptive Aeroelastic Demonstrator	Aeroelasticity / SMC	Rob Scott

Choosing Actuator and/or Sensor Locations

- Pick a large number (N) of possible locations
- Choose subset of M locations such that M<<N
- Estimate the effectiveness of one subset compared to another
- Use a heuristic search method to hunt for the best subsets

Heuristic Search Methods

Global search methods

Enumeration - Useful if the number of combinations is small

Local search methods

Random Trials - Easy to code but may reevaluate same subset

Simulated Annealing - Easy to code but converges slowly

Tabu Search - Easy to include knowledge of the problem

Genetic Algorithms - Ideal for parallel processing
- Finds widely scattered solutions

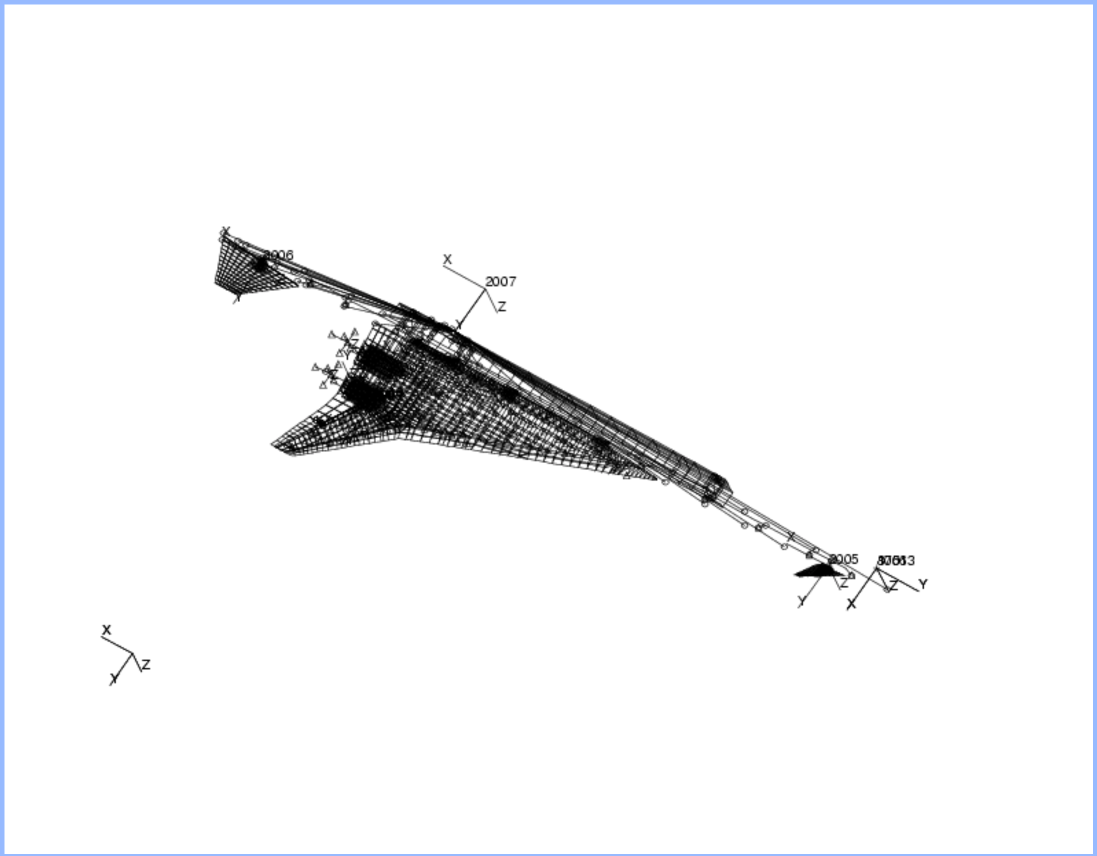
Outline

- **Optimization Methods for Selecting Locations**
- **Three Applications**
  - Vibration suppression and aeroelastic control
  - Interior noise control
  - Novel 3-axis flight control system
- **Results**

Initial Application
Vibration Suppression for Large Space Structures

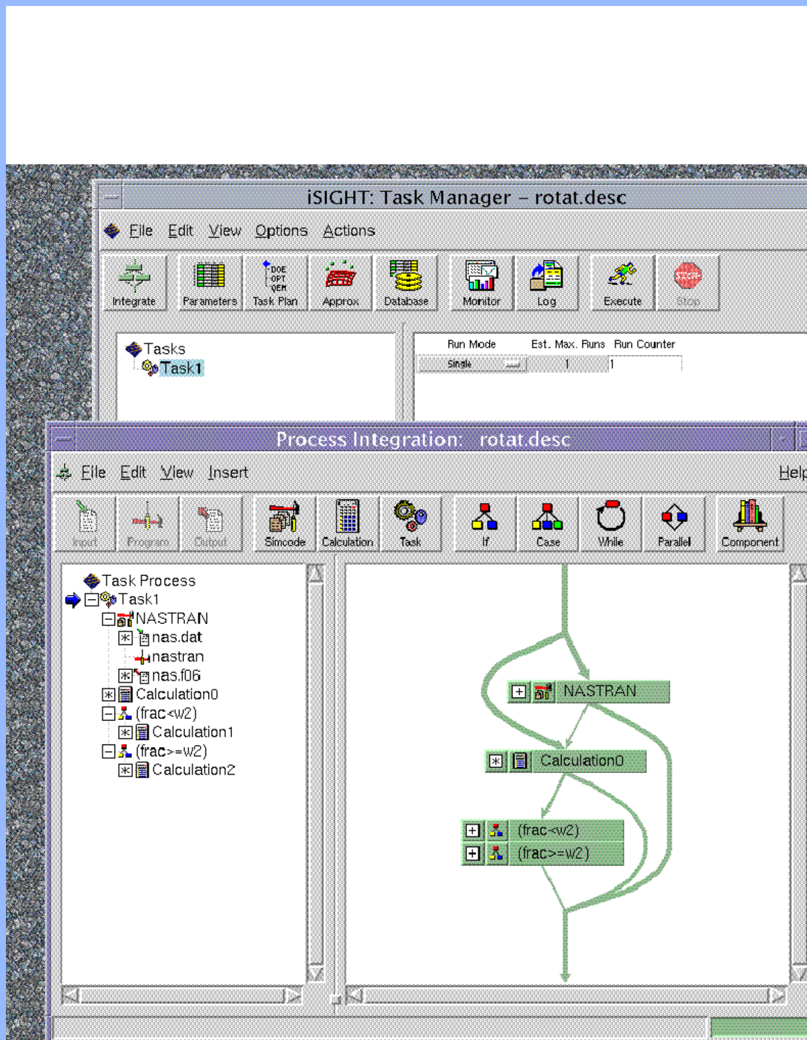
- Actuators: smart struts
- Sensors: smart struts
- Challenge: control all important vibration modes
- Goal: maximize the minimum damping ratio over all modes
- Note: Similar methods can be used for aeroelastic tailoring of structures

Develop procedures to optimize composite ply lay-up and actuator locations for enhanced aeroelastic performance.



NASTRAN finite element model of Langley Adaptive Aeroelastic Demonstrator (LAAD)

iSIGHT Tools for Vibration Suppression

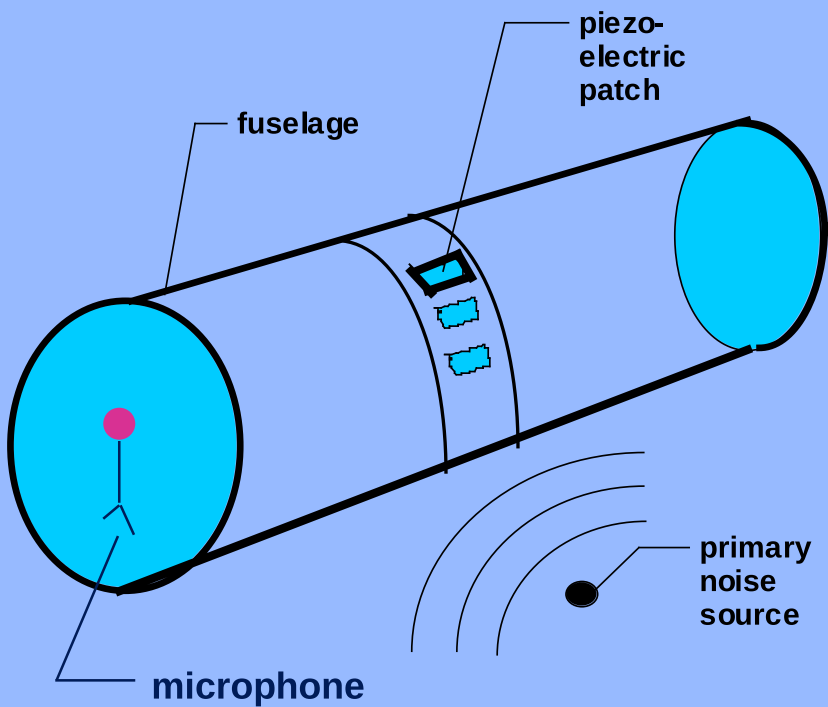


- **Original system hand-coded UNIX scripts and C preprocessors**
- **iSIGHT framework is better:**
  - **Parse inputs and outputs**
  - **Choose Optimizer (e.g. Simulated Annealing and Genetic Algorithms)**
  - **Change objectives and constraints easily**
  - **Save results in database**
  - **Monitor progress**
  - **Parallel processing**

Outline

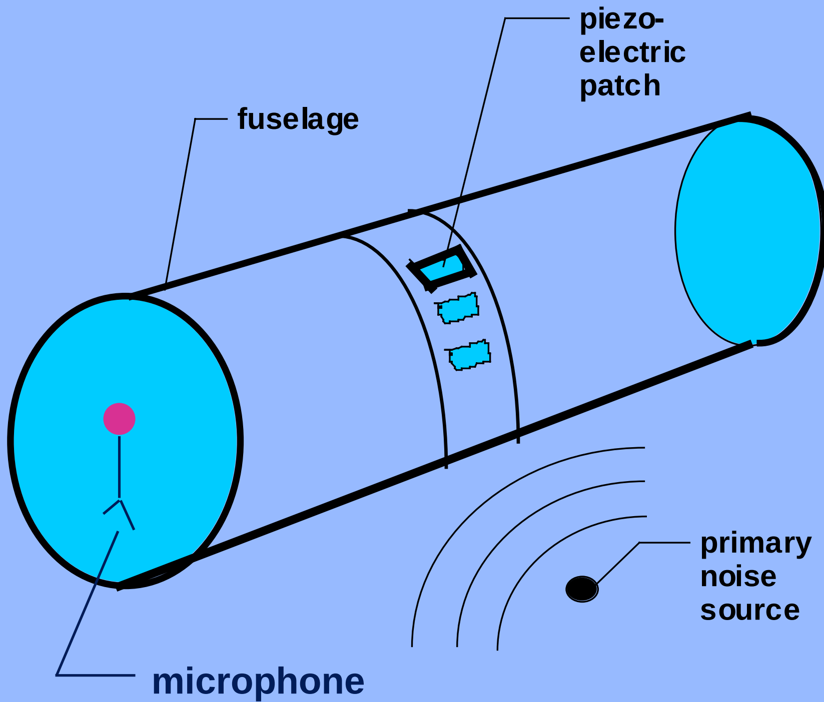
- **Optimization Methods for Selecting Locations**
- **Three Applications**
  - Vibration suppression
  - Interior noise control
  - Novel 3-axis flight control system
- **Results**

Interior Noise Control



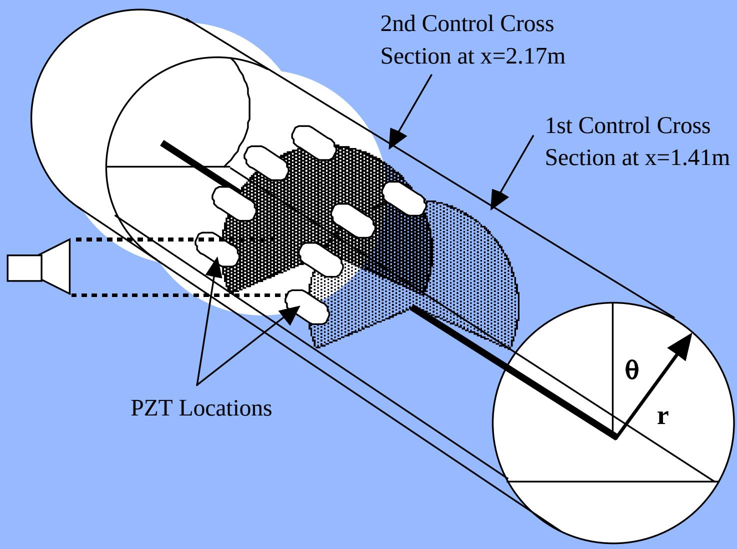
- Actuators: piezoelectric patches bonded to fuselage
- Sensors: microphones inside aircraft cabin
- Challenge: best locations for actuators and sensors
- Goal: global noise reduction

Predicting Noise Reduction



- Measure noise at each mic with no actuators
- Measure noise again using one actuator at a time
- Assume linear superposition
- Use measured data to estimate noise reduction for subsets of actuators and sensors
- Use tabu search to find best subsets

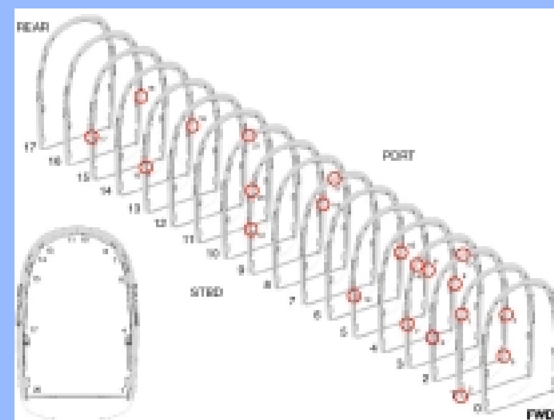
Interior Noise Control - Laboratory Tests

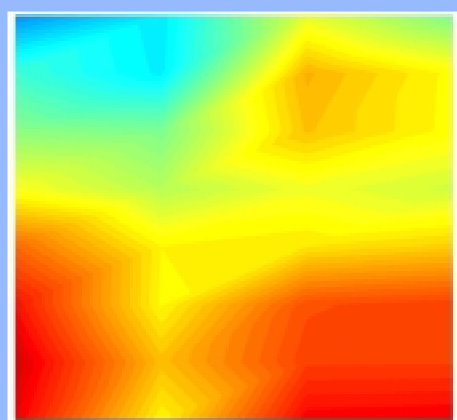


- Actuators: Pick 4 out of 8
- Sensors: Pick 8 out of 462
- Goal: Reduce noise at 462 microphone locations
- Tests show that tabu search picks better locations than manual method

Interior Noise Control - Flight Tests

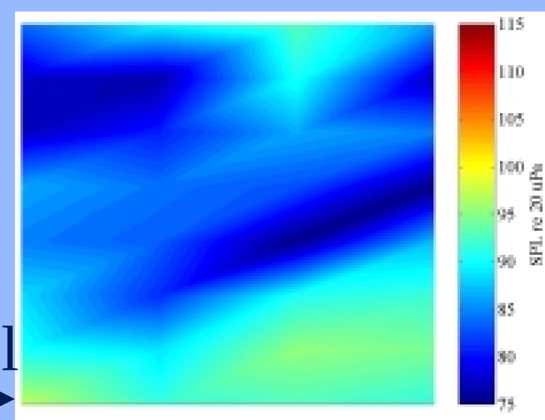
Selected 21 out of 84 possible actuators





No control

With control



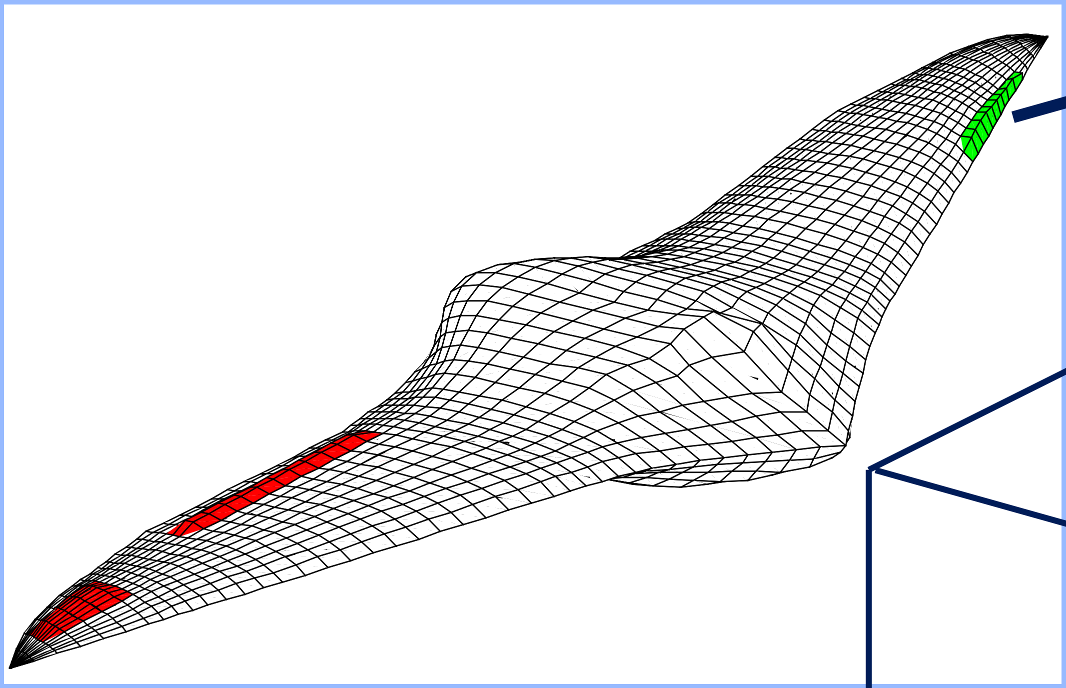
Outline

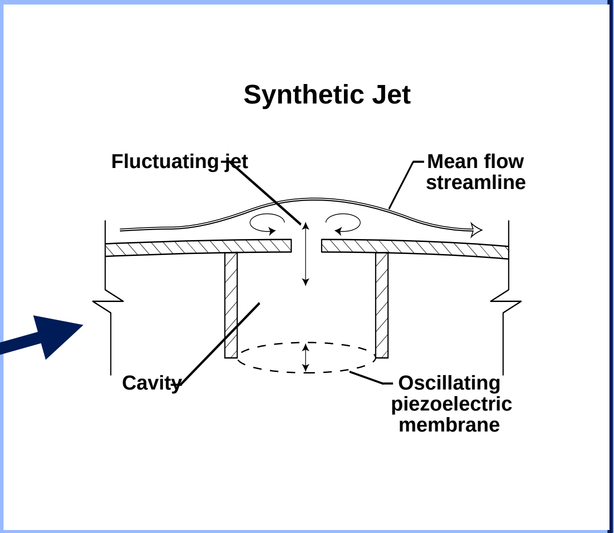
- **Optimization Methods for Selecting Locations**
- **Three Applications**
  - Vibration suppression
  - Interior noise control
  - Novel 3-axis flight control system
- **Results**

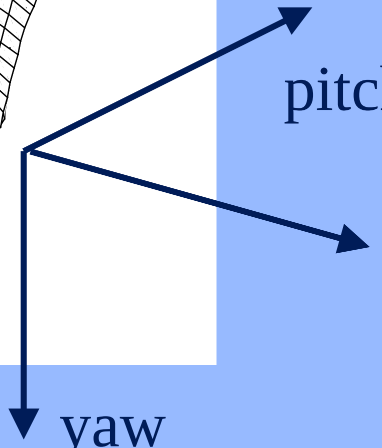
Novel Three-axis Flight Controller

- Actuators: zero mass-flow jets which change apparent shape of wing
- Sensors: N/A
- Challenge: provide uncoupled pitch, roll and yaw with fewest number of actuators
- Goal: stealth and mild maneuvering

Objective: Minimize number of effectors to provide uncoupled pitch, roll, and yaw.



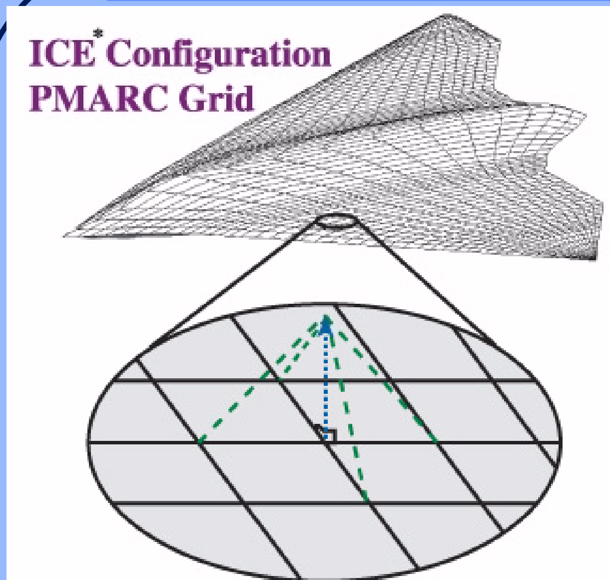




Optimized Effector Locations

- Initial demonstration problem has 34 potential locations - implies 1.7 billion combinations
- Exhaustive search would require 286 million hours of computer time
- MDO technology reduced actual computer time to 1 hour
- Technology used
  - Automatic differentiation
  - Approximate analysis
  - Genetic algorithm

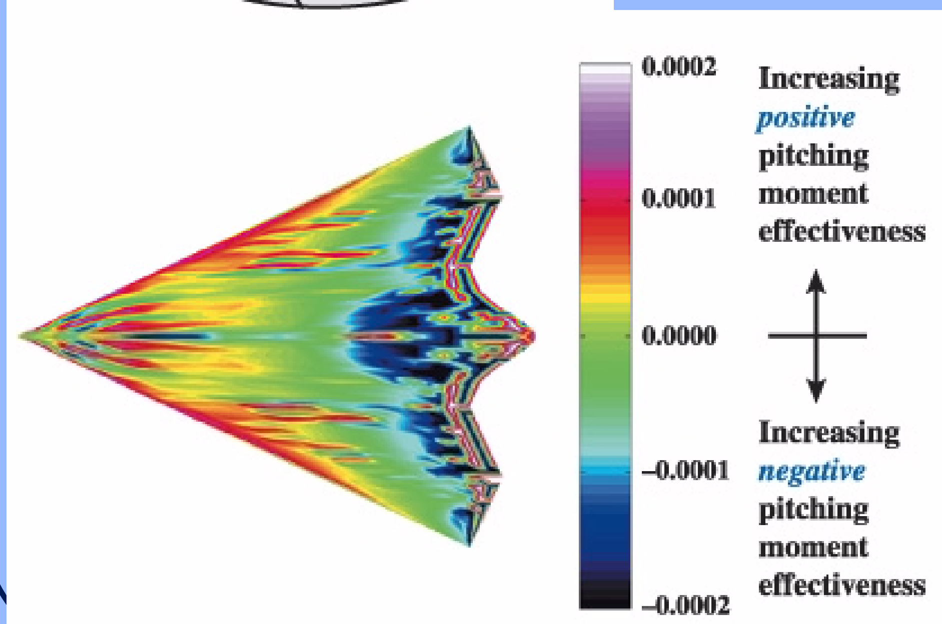
ASCAC Methods Development

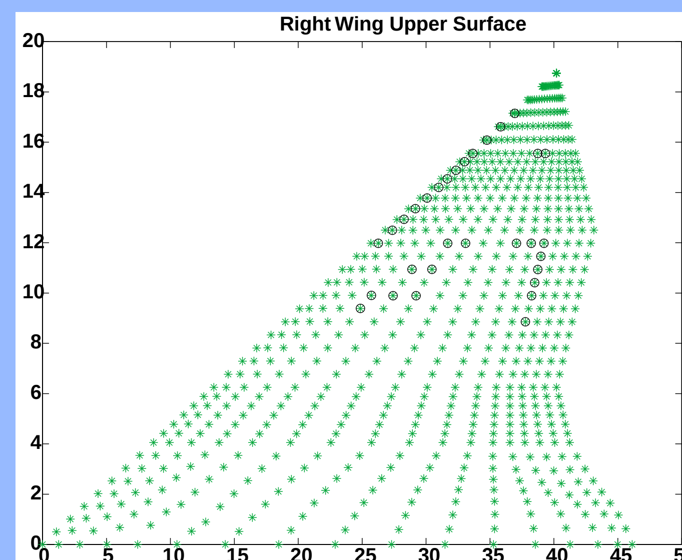


1.) Control Effectiveness Determined by Automatic Differentiation of PMARC - MDOB

2.) Candidate Effector Locations Selected by Controls Expert - DCB

3.) Effector Locations Optimized using Genetic Algorithm and MATLAB - MDOB



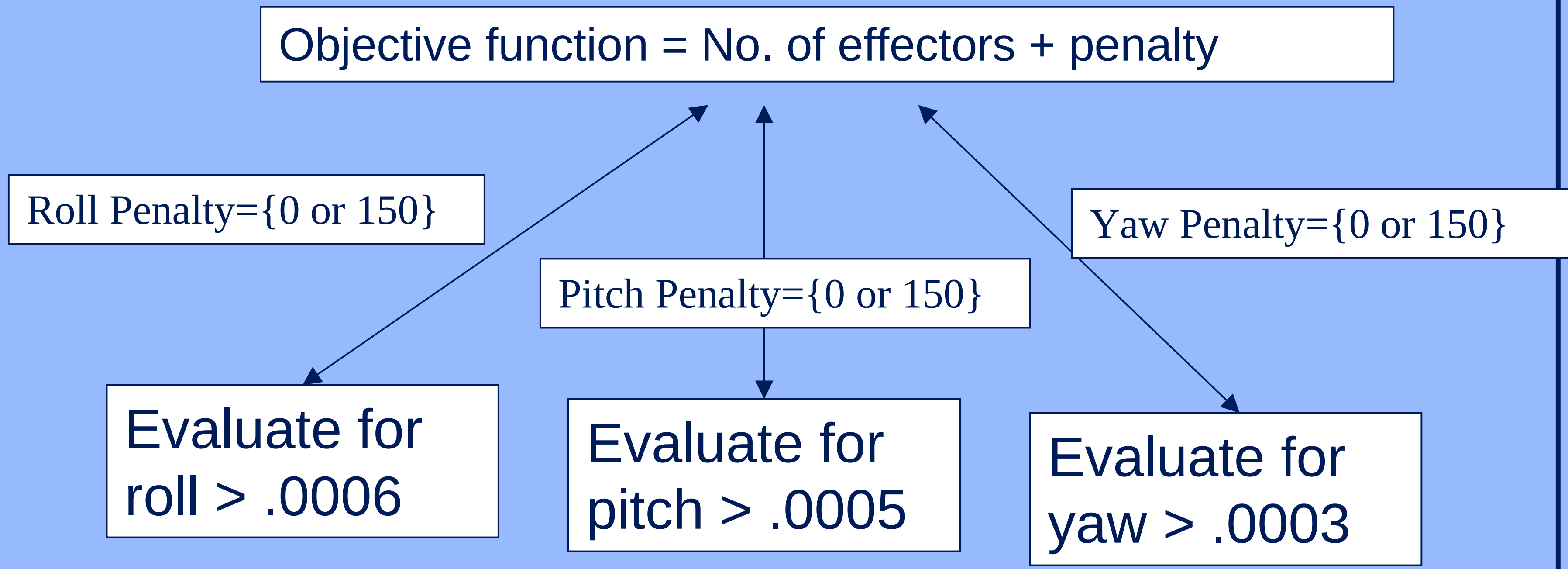


* Lockheed Martin Tactical Aircraft Systems–Innovative Control Effectors (ICE)

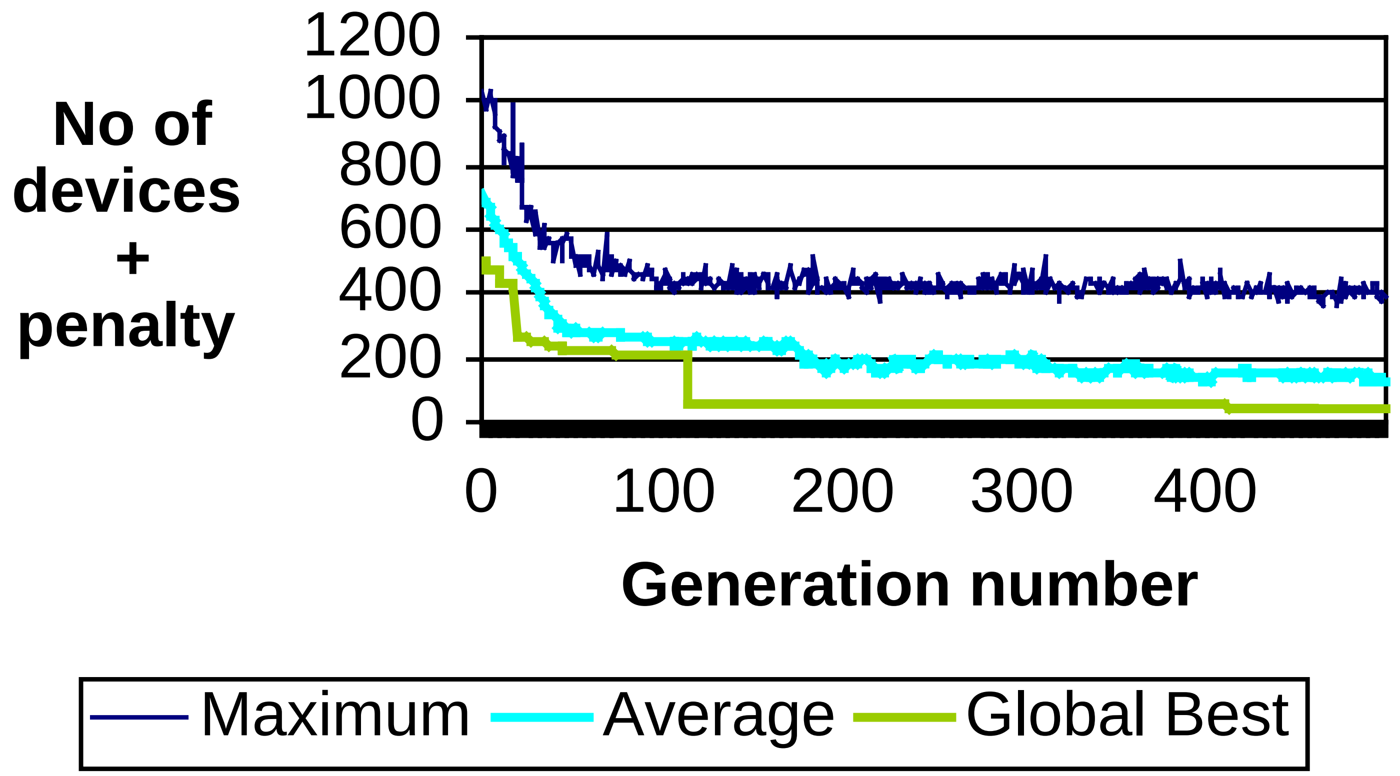
Assess Control Effectiveness

- Use MATLAB to evaluate each effector array
- Place arrays on upper and/or lower surface of semi-span model (i.e., assume symmetric pairs of arrays)
- Estimate moments for Roll (C_l), Pitch (C_m) and Yaw (C_n)
- Change height of effectors to produce desired uncoupled moment (e.g. C_l without C_m or C_n)

GA Selects Best Effector Suite from Combinations of Potential Arrays

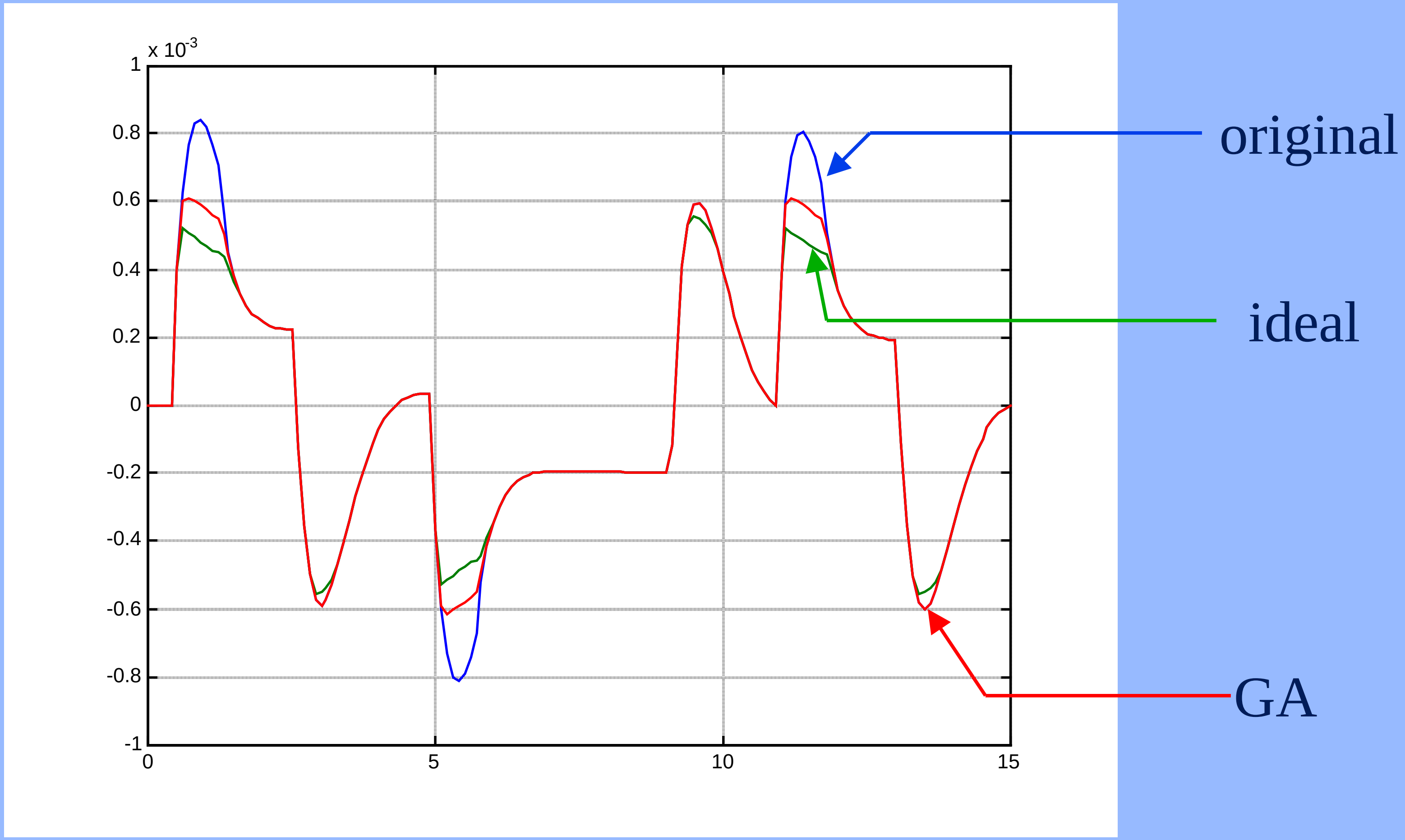


Typical GA Convergence



Test of Simulated Controller

Effectors chosen by GA perform slightly better than original



Note: Simulated +/- 20 deg. bank angle doublet with roll rate < 10 deg/s

Summary

- Combinatorial optimization finds best actuator and sensor locations in wide set of applications
- Application to interior noise control is most mature. Successfully used and flight tested by Structural Acoustics Branch
- Application to 3-axis Flight Control problems delivered to Dynamics and Control Branch
- Application to vibration damping and gust load alleviation explored - future funding uncertain

Sharon Padula
Actuator Placement - Selected References

Padula, S. L.; and Sandridge, C. A.: *Passive/Active Strut Placement by Integer Programming*, Topology Design of Structures, Bendsoe and Mota Soares (ed) Kluwer Academic Publishers, 1993, pp 145-156.

Wlezien, R. W.; Horner, G. C.; McGowan, A. R.; Padula, S. L.; Scott, M. A.; Silcox, R. J.; and Simpson, J. O.: *The Aircraft Morphing Program.* Presented at SPIE's 5th Symposium on Smart Structures and Materials, San Diego, CA, March 1-5, 1998.

Padula, S. L.; Palumbo, D. L.; and Kincaid, R. K.: *Optimal Sensor/Actuator Locations for Active Structural Acoustic Control.* 39th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Long Beach, CA, April 20-24, 1998.

Padula, S. L.; and Kincaid, R. K.: *Optimization Strategies for Sensor and Actuator Placement.*. NASA TM–199–209126, April 1999.

Padula, Sharon L.; Rogers, James L.; and Raney, David L.: *Multidisciplinary Techniques and Novel Aircraft Control Systems.* . Eighth AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Long Beach, CA, September 6-8, 2000.

Andrea M. Cook and William A. Crossley: "Investigation of GA Approaches for Smart Actuator Placement for Aircraft Maneuvering", 39th AIAA Aerospace Sciences Meeting, January 2001, Reno, NV.