GECCO 2006: Evolutionary Computation in Practice: EC and IEC for MEMS Design

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Motivation

The Goals of this talk:

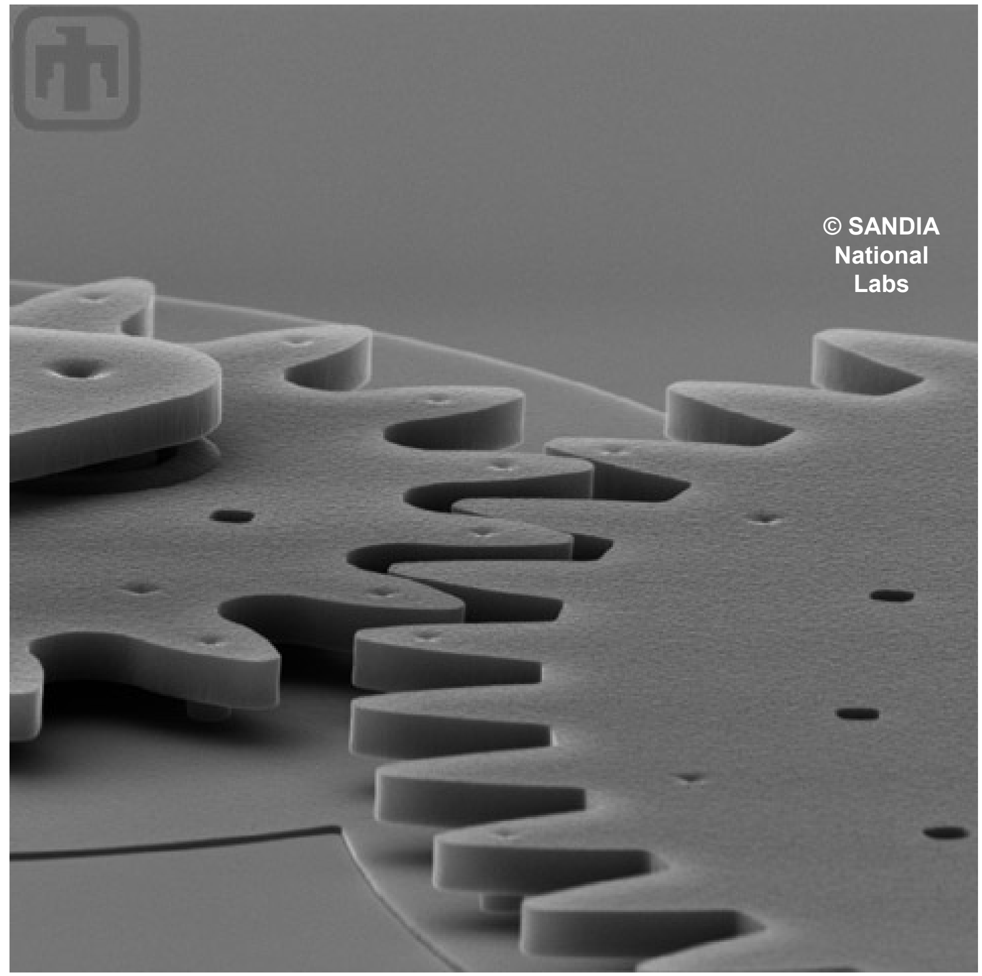
- Introduce field of MEMS
- Discuss issues of MEMS design
- Present work using EC for MEMS design

Contents

- What are MEMS?
- MEMS in our daily lives
- How are MEMS made?
- Simulation
- Design
- *EC* Synthesis for MEMS
- *IEC* Synthesis for MEMS

What are MEMS?

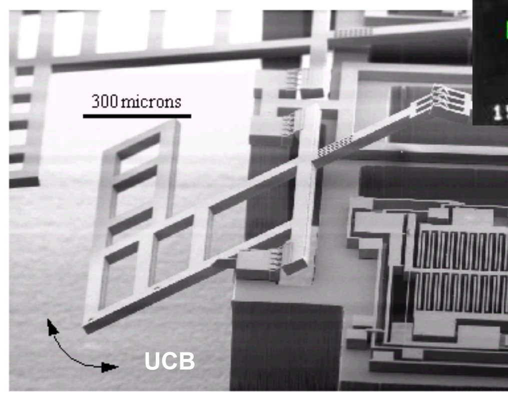
- Micro Electromechanical Systems or *Micromachines*
- Very small electromechanical devices made on silicon
- Microfabrication, like computer chips

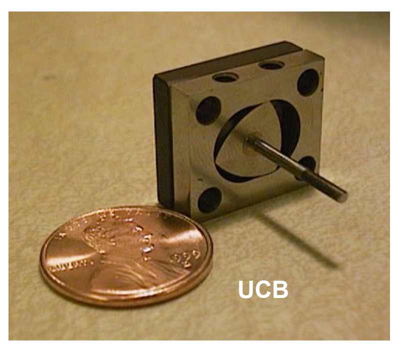


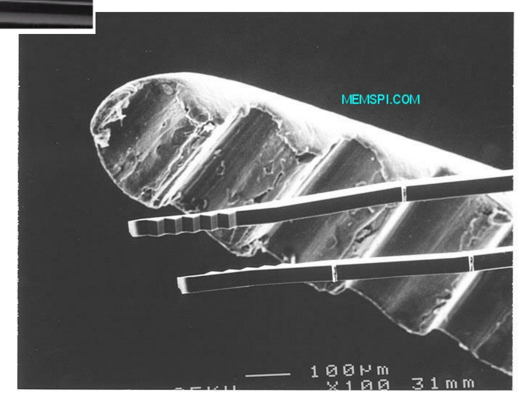
What are MEMS?

- Applications for
  - Sensors
  - Robotics
  - Communications
  - Printer heads
  - Biotechnology
  - Energy Generation

- Component sizes
  < 10 μm
- Device sizes < 1 cm

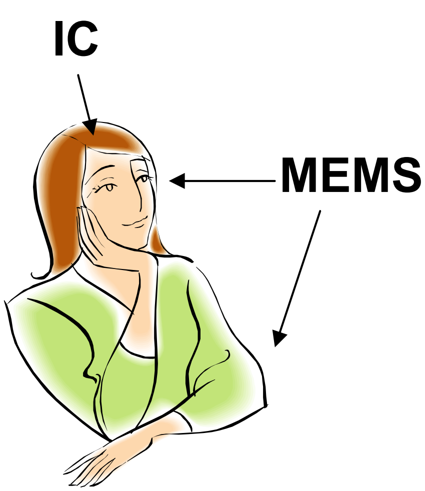






What are MEMS?

- “Micro-Electro-Mechanical Systems (MEMS) is the integration of mechanical elements, sensors, actuators, and electronics.”



Integrated Circuits are the "**brains**" of a system and MEMS are **"eyes" and "arms",** to allow microsystems to *sense* and *control* the environment.

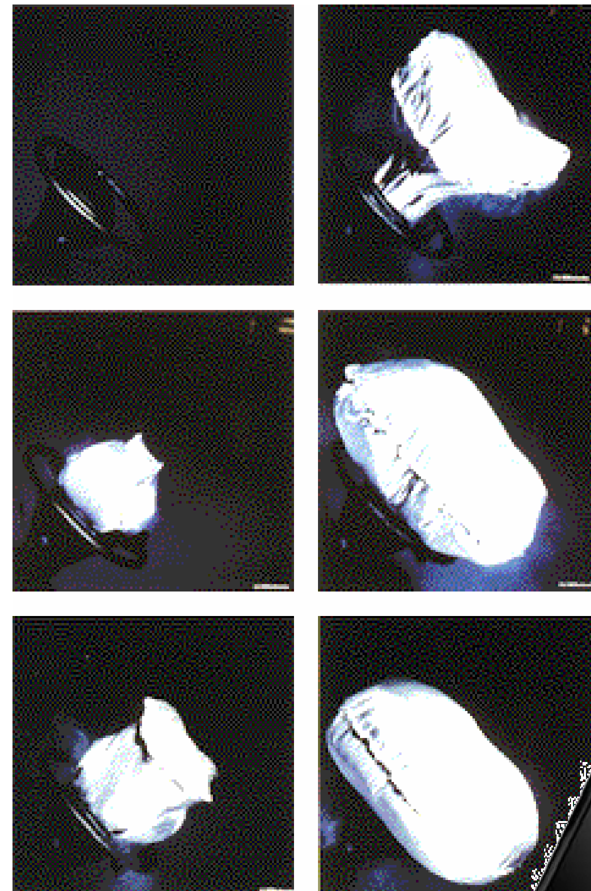
from *http://www.memsnet.org*

A few cases of MEMS already in our daily lives…

- MEMS Accelerometers
- MEMS Gyroscopes
- Digital Micromirror Arrays

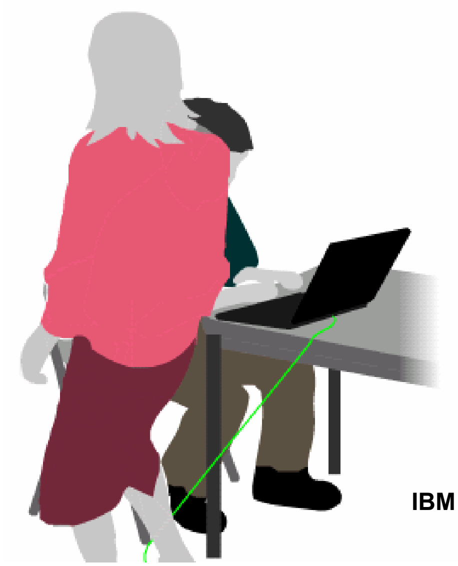
MEMS Accelerometers

- Anywhere you need to measure motion
  - Car Airbags
    - when the car stops suddenly
  - Notebook PC
    - protect the hard drive



MEMS Accelerometers

IBM Active Protection System



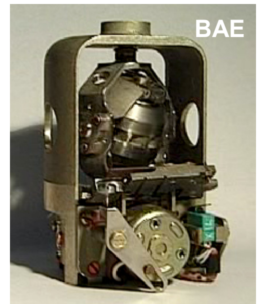
Sudden acceleration in notebook's motion triggers a signal to temporarily arkhard drive's read/write head

Active Protection System

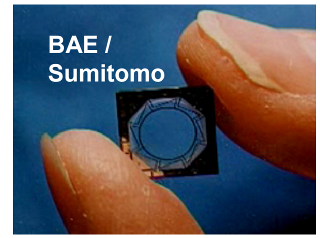
The IBM Active Protection System offers protection for common notebook accidents found in everyday life.

MEMS Gyroscopes

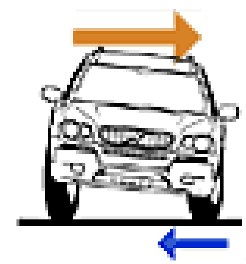
- Measure angular rotation rate using Coriolis effect
- Used extensively in aerospace applications
- Now for **automobile** (stability control) and **consumer** applications (camcorders, Segway,etc)
- MEMS allows measurement in places never before possible

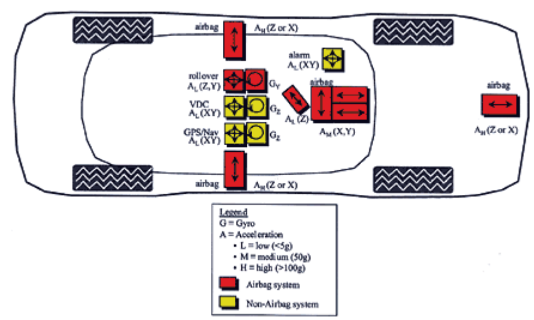


Traditional gyro



MEMS gyro

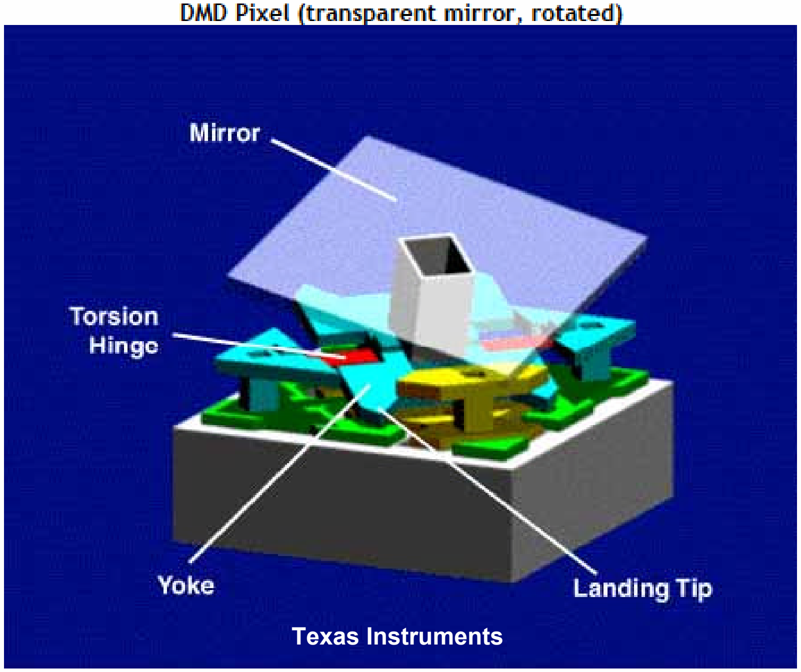

Analog Devices



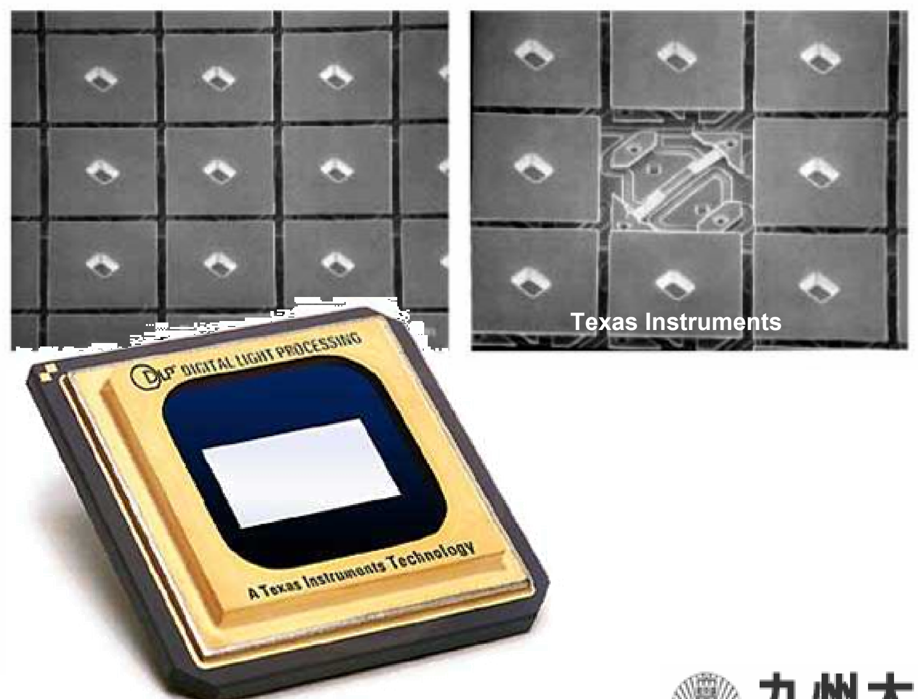
Digital Micromirror Arrays

- By Texas instruments in ’87
- Used in video projectors, hi-end TVs, digital cinema, etc.
- State of the art - HDTV: 1920 x 1080 = 2.7 million mirrors

DMD Pixel (transparent mirror, rotated)



SEM photomicrographs of completed DMD chips after spacer removal



MEMS Advantages

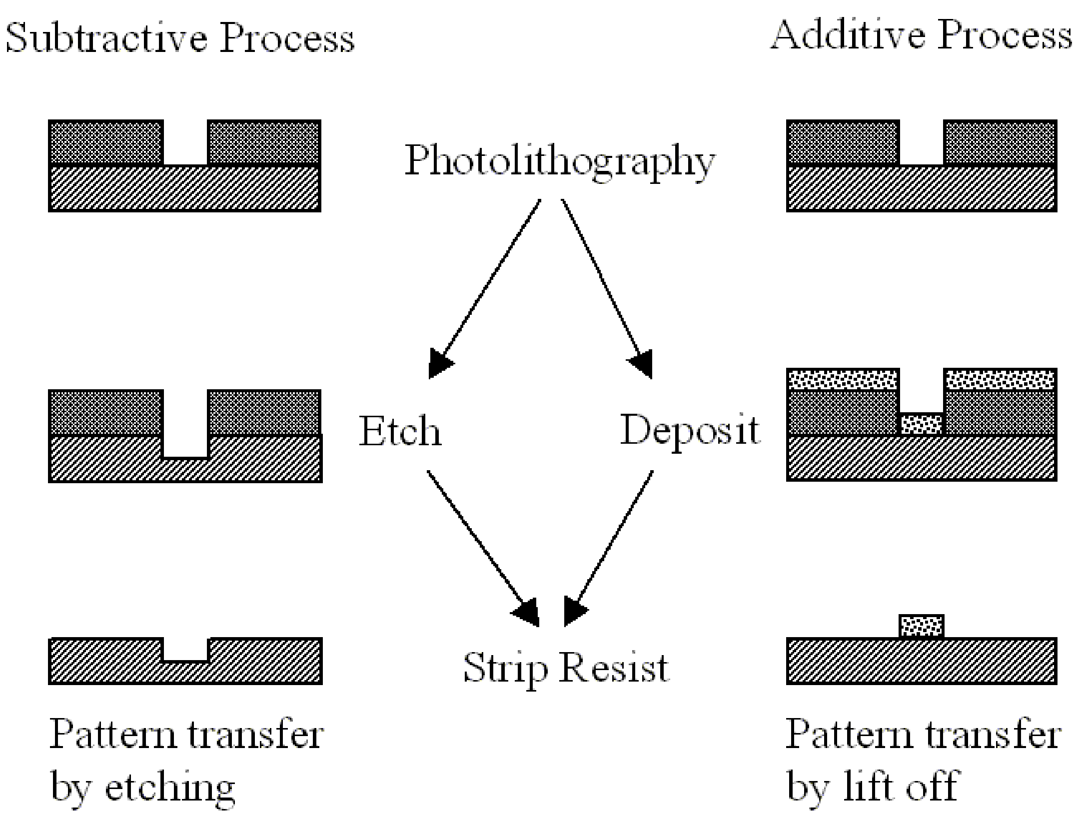
MEMS advantages:

- Integrate the mechanical and electrical onto a single chip
- More functional, smaller, lighter, more reliable
- Drive down cost!
  - *Since volume production in '93, the ADXL 50 reduced auto airbag deployment system from $100+ down to $30.* (source: Analog Devices)
- Small size/low cost enables new applications (laptop, mobile phone, etc)

How are MEMS made?

- Microfabrication
- Packaging

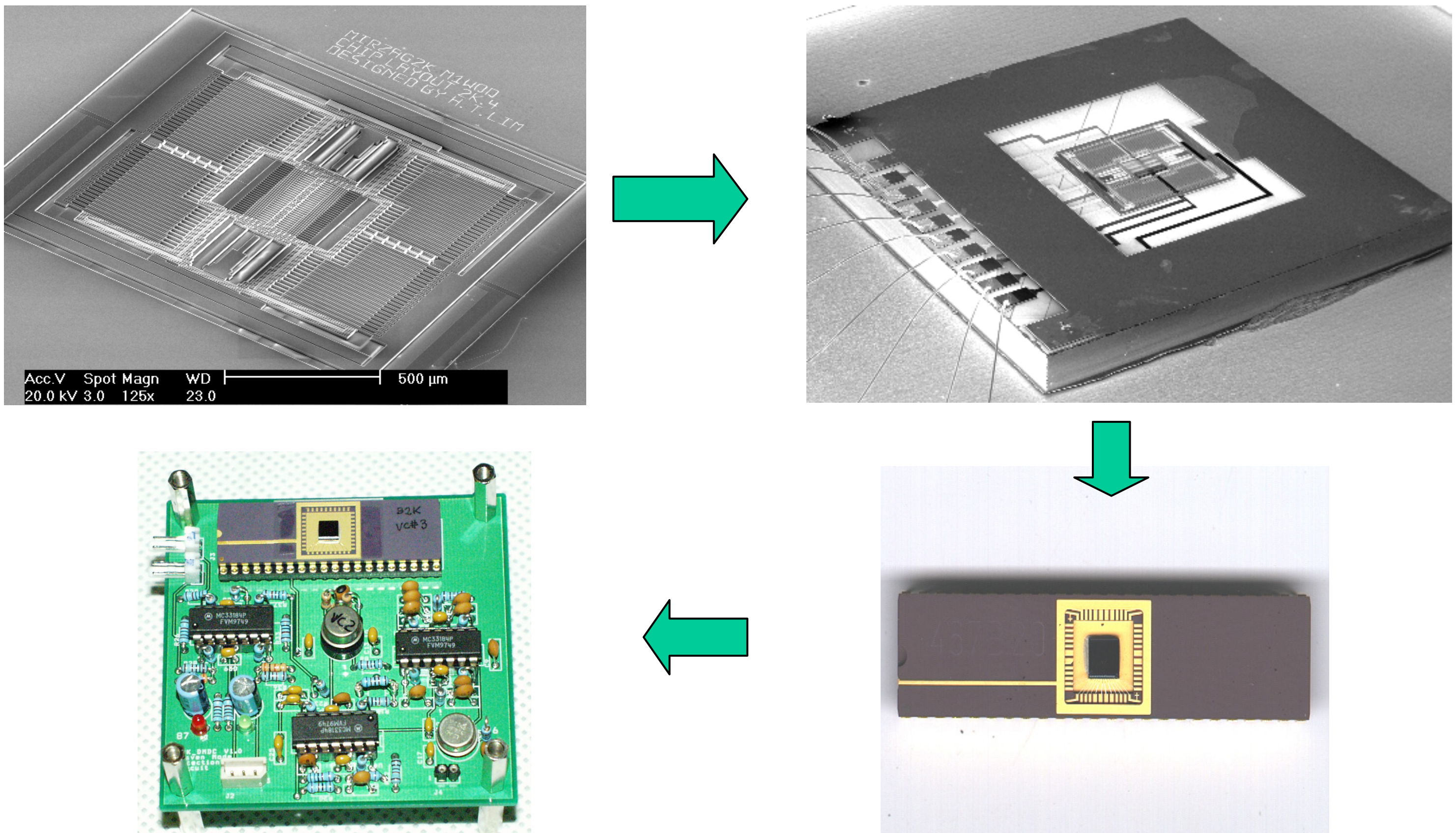
Microfabrication



- By selectively etching away material or depositing new material on to areas not covered by protective patterns, a structure can be made.
- After multiple repetitions of these steps, a *Micromachine* is created.

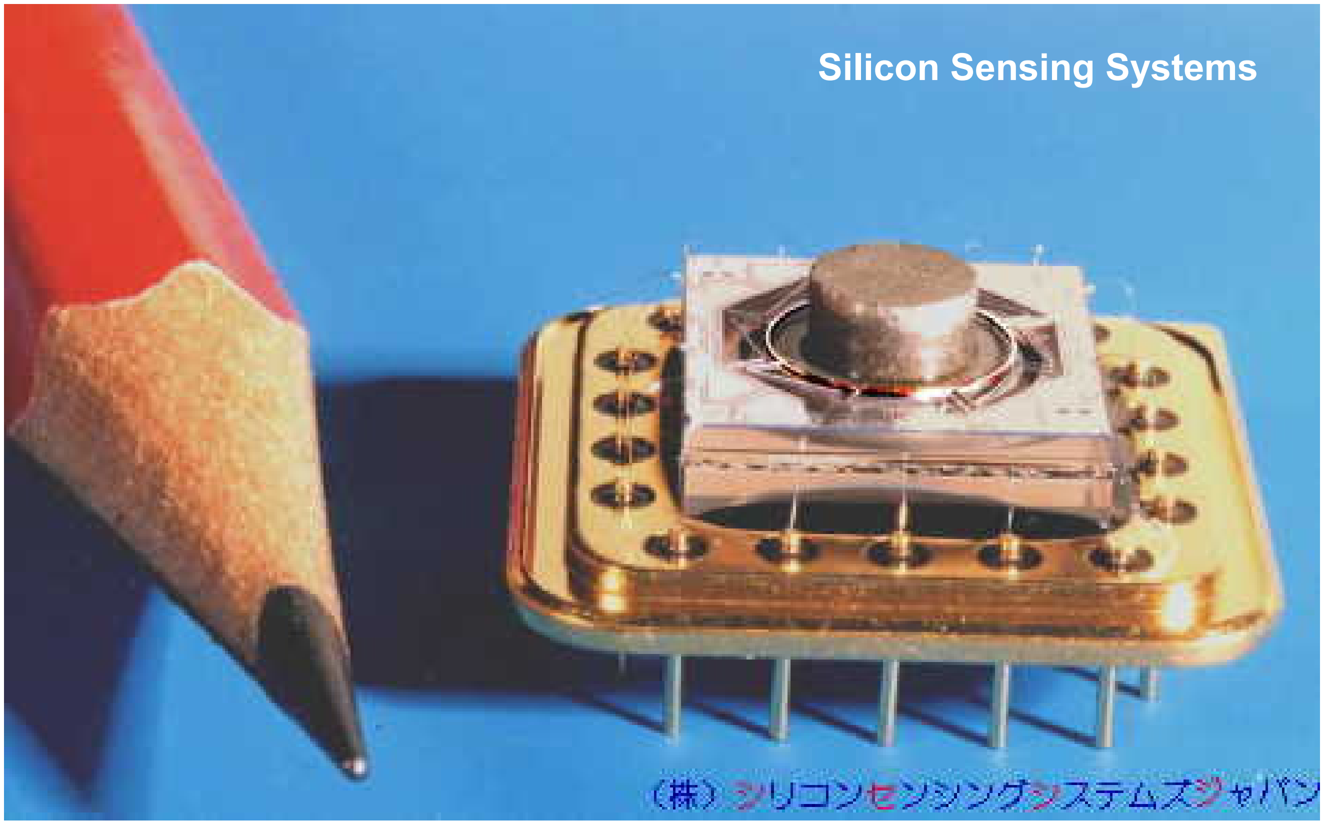
from ***http://www.memsnet.org***

MEMS Packaging



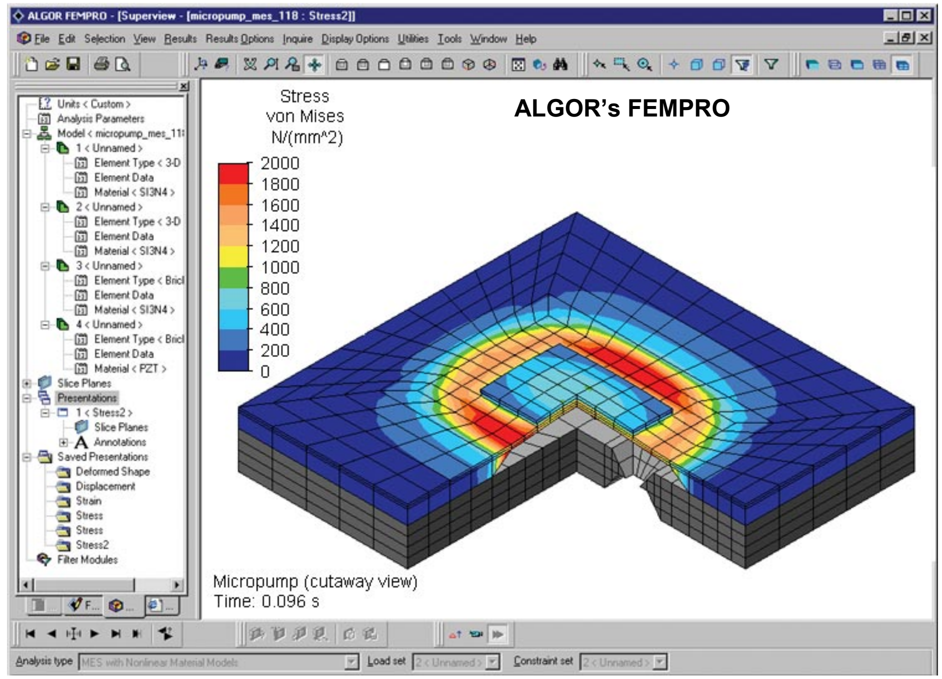
from Lab for Microsensors and Actuators – Seoul National University

MEMS Packaging

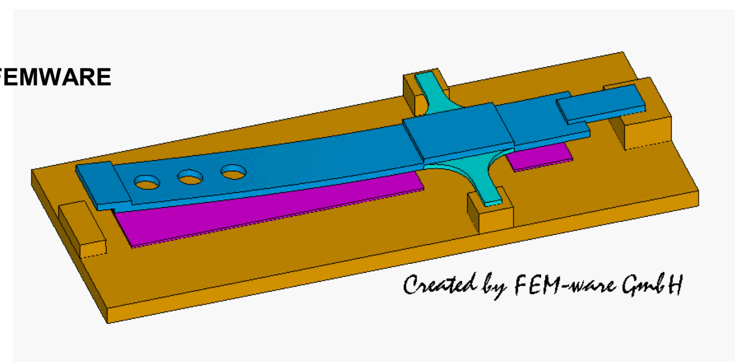


MEMS Simulation-1

- Finite Element Modeling –
  - Capability of tools growing
  - Slow but accurate
  - Break up model into thousands of small elements
  - Multi-domain:
    - Mechanical/ Electrical/ Thermal/ Electrostatic/ Magnetic, etc.

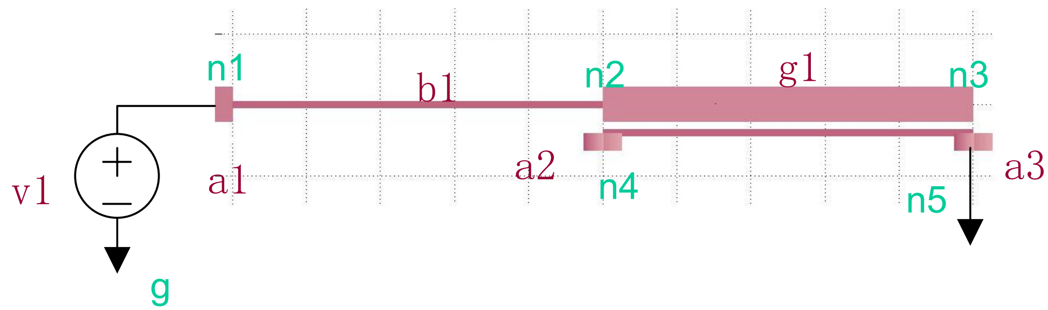


FEMWARE



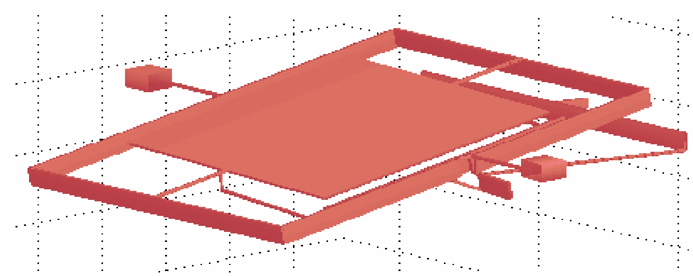
MEMS Simulation-2

- Reduced Order Modeling –
  - ‘Spice for MEMS’
  - Modified Nodal Analysis
  - Orders of magnitude faster than FEM




```
uses mumps.net
v1 Vsrc     *   [n1 g]   [V=10]
e1 eground *   [g]      []
a1 anchor  p1  [n1]     [l=5e-6 w=10e-6 oz=180 R=100]
b1 beam2de p1  [n1 n2]  [l=1e-4 w=2e-6 oz=0 R=1000]
g1 gap2de  p1  [n2 n3 n4 n5]  [l=1e-4 w1=1e-5 w2=2e-6 …
                   gap=2e-6 R1=100 R2=100 oz=0]
a2 anchor  p1  [n4]     [l=5e-6 w=1e-5 oz=-90 R=100]
e2 eground *   [n4]     []
a3 anchor  p1  [n5]     [l=5e-6 w=1e-5 oz=-90 R=100]
e3 eground *   [n5]     []
```

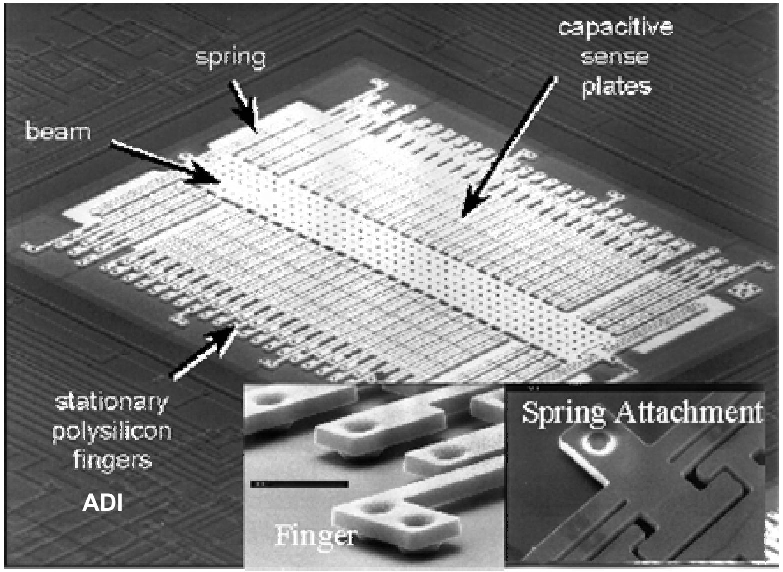
- Caveat: Simulation is only as good as characterization!



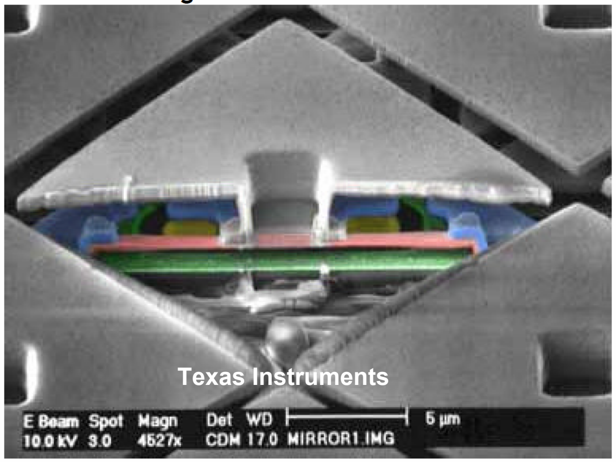
from N. Zhou - bsac.eecs.berkeley.edu/cadtools/sugar/

MEMS Device Design

- Still an immature field
- Designs are becoming very complex –
  - Multiple competing objectives
  - Multiple constraints from fabrication, safety, practical limits, etc
  - Dozens of variables
- Fabrication of prototypes a *slow*, *expensive* process

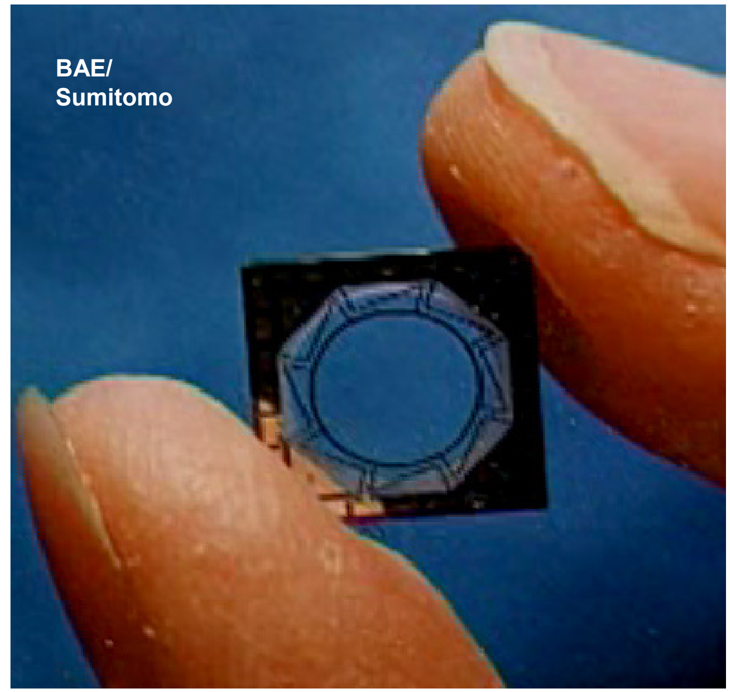


Ion Mill Sectioning of DMD Pixel to Reveal Cross Section

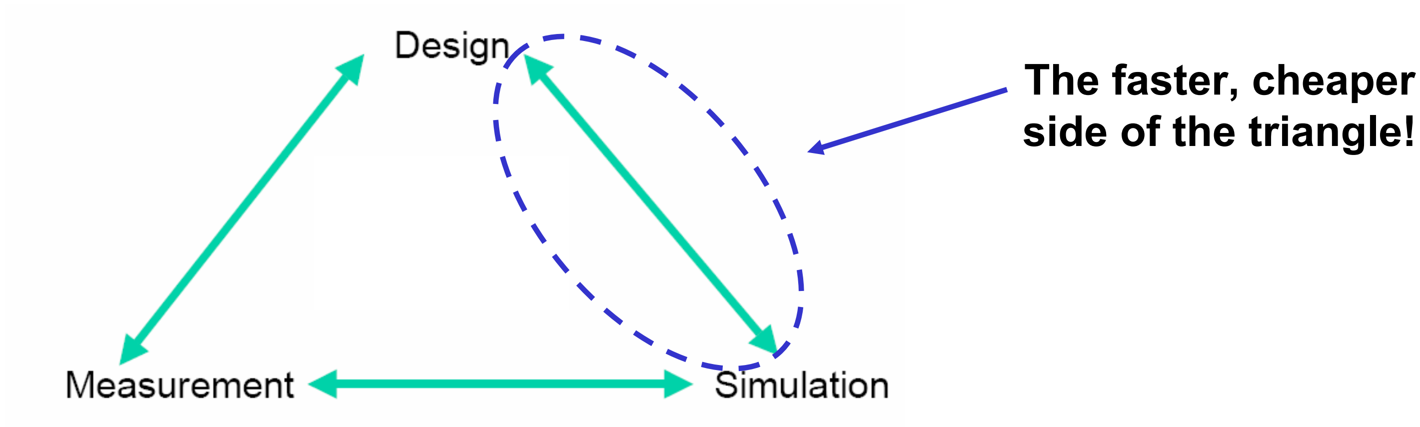


State of the Industry…

- Current design process very limited, simple
  - Hand calculations
  - FEM for confirmation
  - Grid Search (at best!)
  - Trial and error (fab/test/repeat)
- MEMS developing into competitive market
  - Applications/complexity growing rapidly
    - Inertial sensors, optical switches, etc already successful products
  - Improved design techniques required as market matures



The Solution: MEMS Design Synthesis Tools



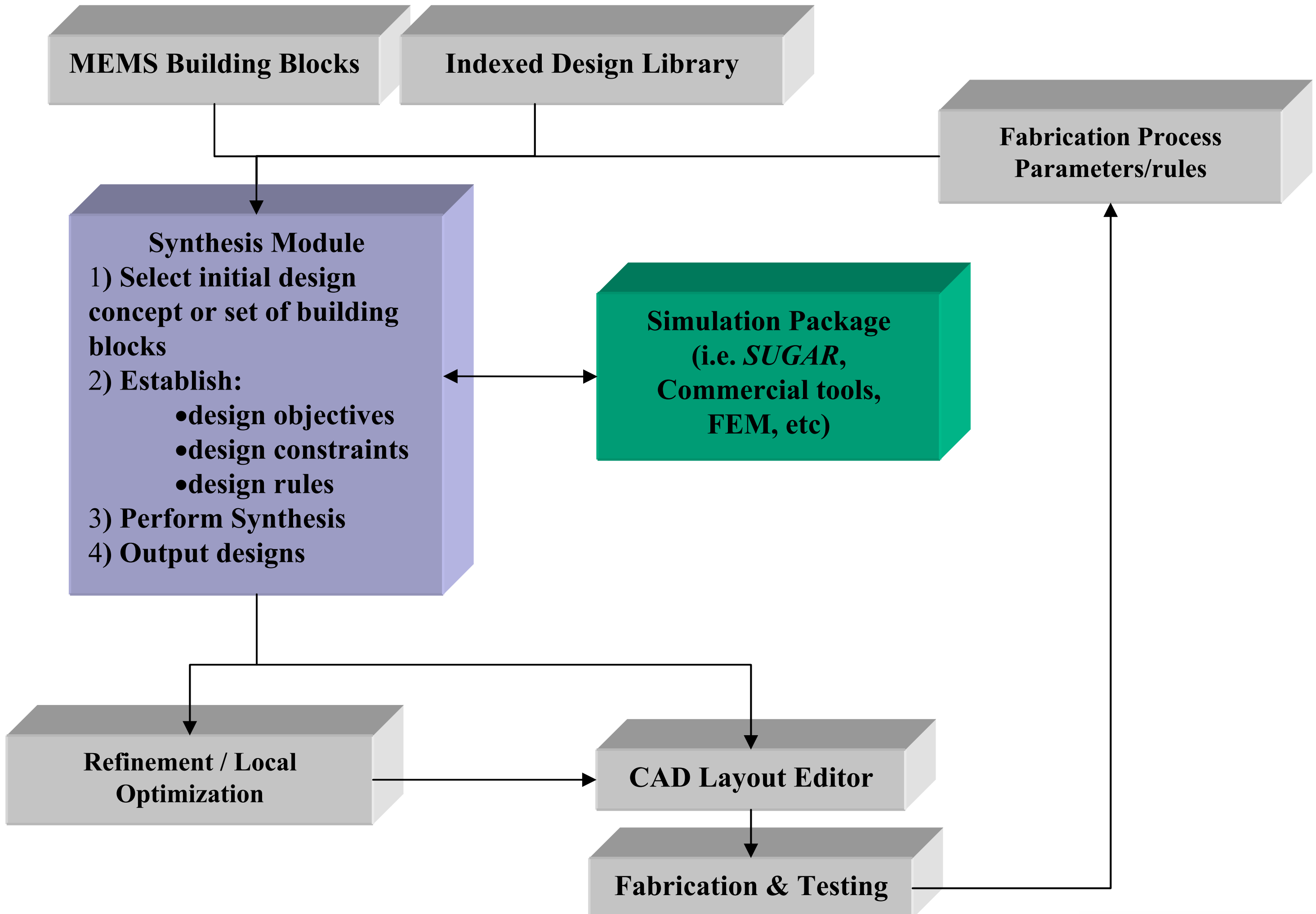
- **What?** Automatically generate designs with a desired performance
- **Why?** Faster, more capable than manual design/hand calculations
  - More CAD = Less time in the fab = shorten design cycle = save $$$!
  - Improved performance (multiple objectives)
    - Too many knobs to turn by hand!

The Solution: MEMS Design Synthesis Tools

- **How?**

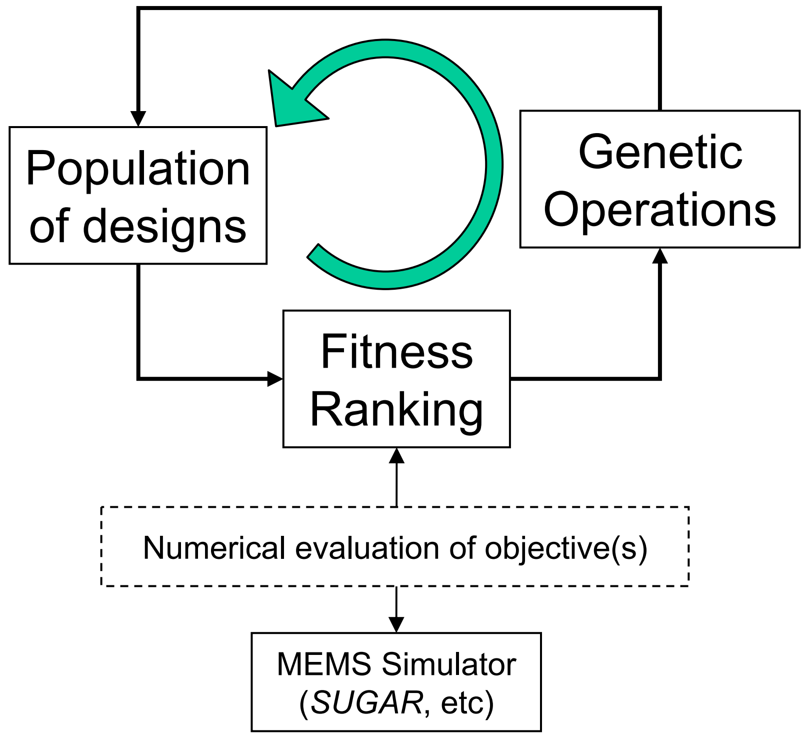
  Use Evolutionary Synthesis/Optimization algorithms
  - Can deal with
    - discrete variables
    - non-convex spaces
  - Require only ‘black box’ evaluation from simulator
    - No gradients, no equations needed
  - Configuration optimization + size optimization
    - Not just optimizing lengths and widths of components
    - Decide how many components, how they are connected

Proposed Architecture for MEMS Synthesis Tool



Use of EC for MEMS Design Synthesis

- Genetic Algorithms (GA)
  - Multiobjective GA (MOGA) balances multiple competing objectives
  - A population of “good” candidate designs returned at end of evolution

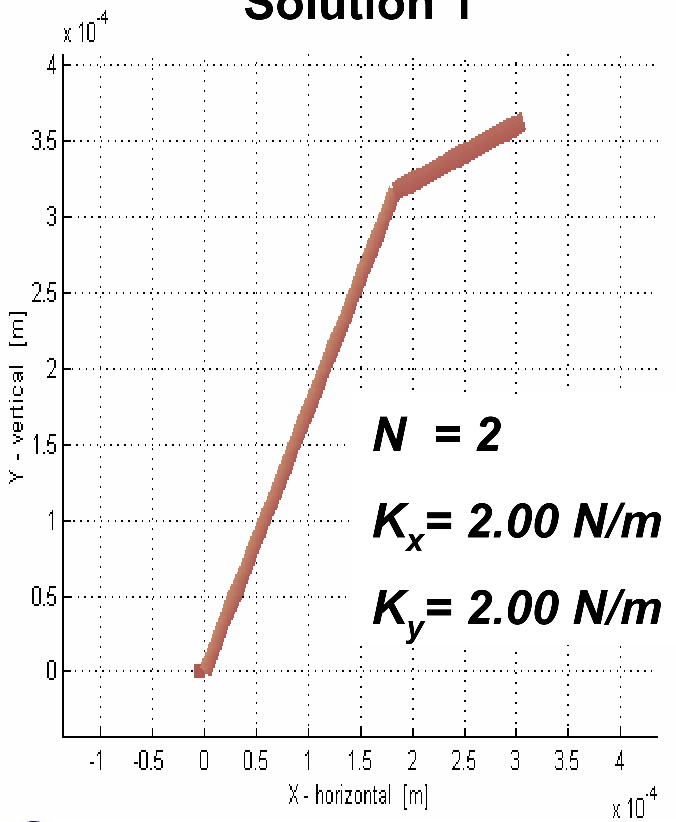


- Simulated Annealing (SA)

Simple Example – Synthesis of a MEMS Spring

2 Objectives: $\boldsymbol{K_x}$**= 2.00N/m** $\boldsymbol{K_y}$**= 2.00N/m**

Solution 1

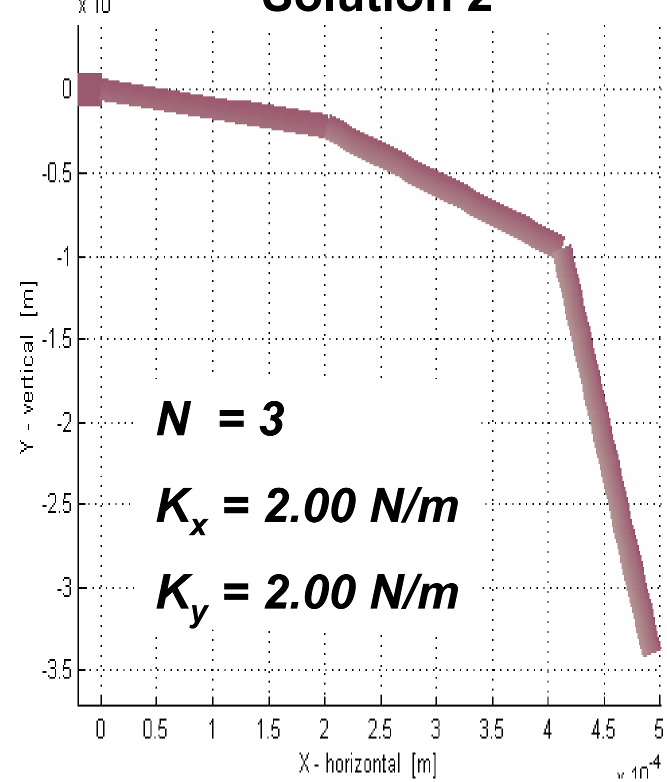


Genotype Encoding:

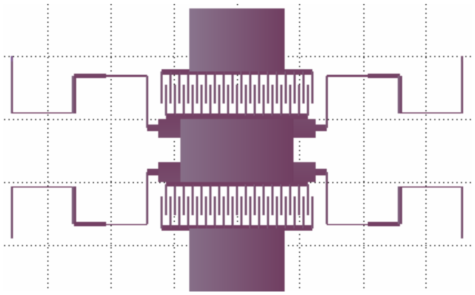
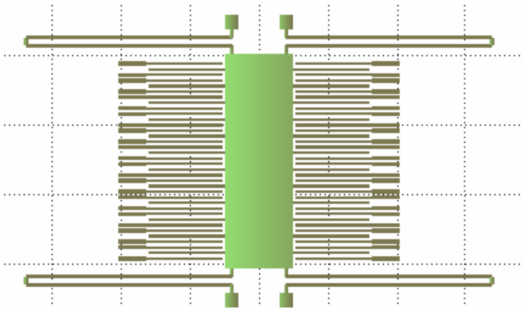
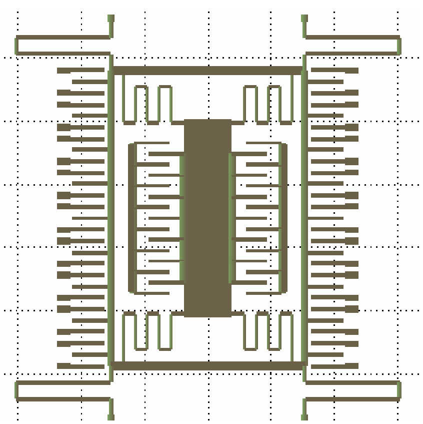
$$\begin{bmatrix} l_1 & w_1 & \theta_1 \\ l_2 & w_2 & \theta_2 \\ l_3 & w_3 & \theta_3 \\ l_4 & w_4 & \theta_4 \\ \vdots & \vdots & \vdots \\ l_N & w_N & \theta_N \end{bmatrix}$$

Dimensions of N beam segments in one spring

Solution 2



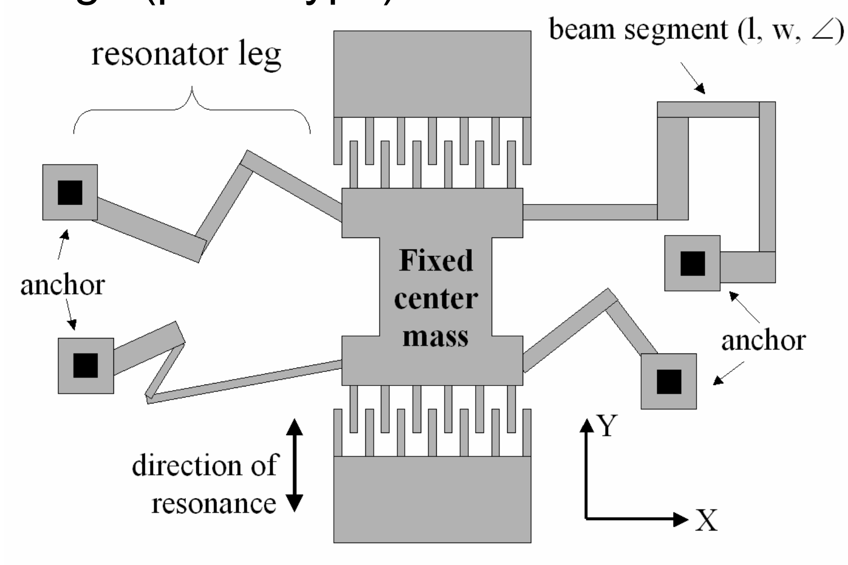
MEMS Application Examples

- Devices
  - Resonating Mass
  - Accelerometer
  - Gyroscopes
- Constraints
  - Symmetry?
  - Manhattan Angles?
- Potential Objectives
  - Resonant Frequency ω_r
  - Suspension Stiffness - K
  - Mode Shape
  - Device Area
  - Measurement Sensitivity

Resonating Mass Example

Design (phenotype):



Encoding (genotype):

Geometry info for each of the *q* legs of design

$$\begin{bmatrix} Leg\_1 \\ Leg\_2 \\ \vdots \\ Leg\_q \end{bmatrix} \rightarrow \begin{bmatrix} l_1 & w_1 & \theta_1 \\ l_2 & w_2 & \theta_2 \\ l_3 & w_3 & \theta_3 \\ l_4 & w_4 & \theta_4 \\ \vdots & \vdots & \vdots \\ l_m & w_m & \theta_m \end{bmatrix}$$

Dimensions of *m* beam segments in one leg

- Mass suspended by springs, actuated by electrostatics
- Configuration of center mass fixed
- Legs variable

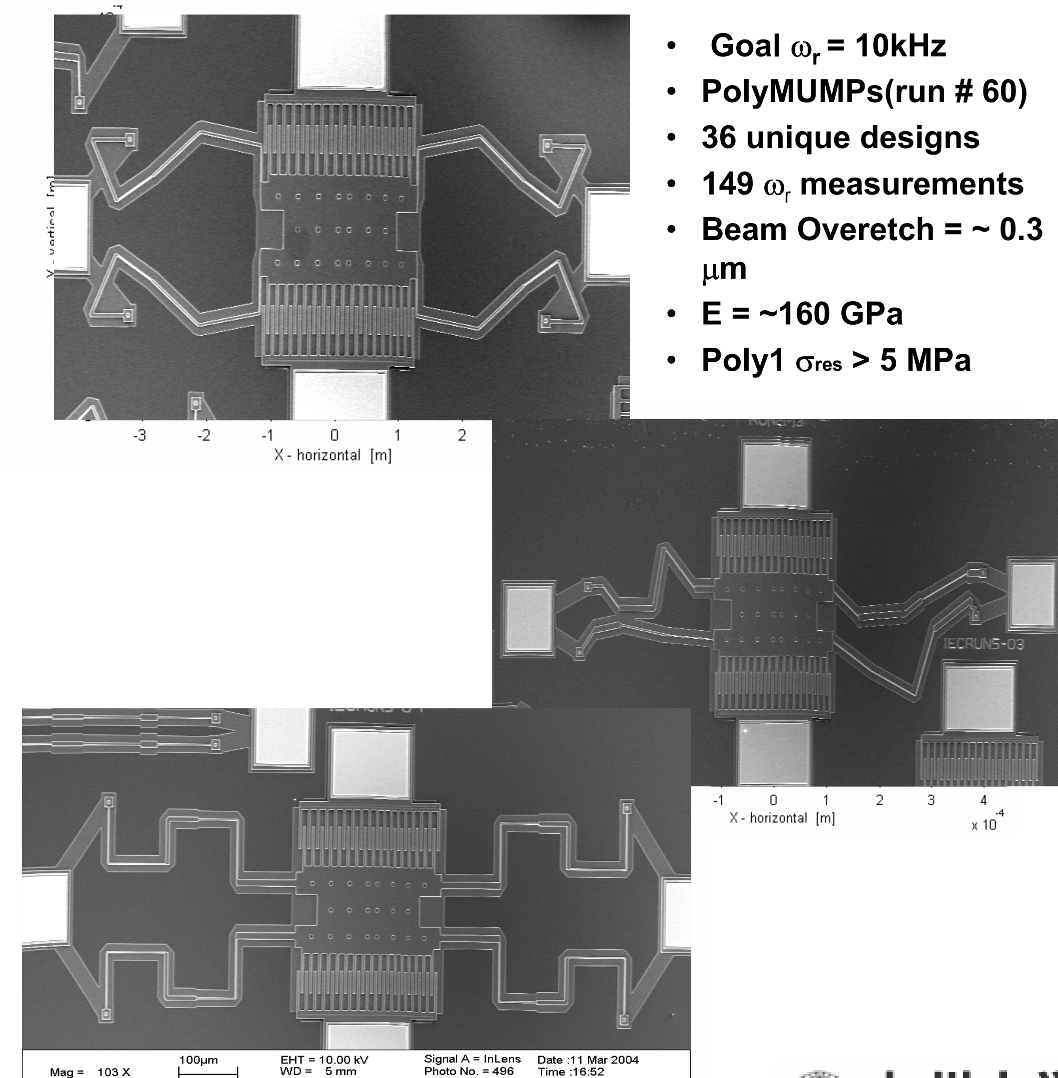
- Apply MOGA - two to four design objectives:
  - ω_r
  - Area
  - K_y
  - K_x
- Universal Constraints:
  - Min/max beam dimensions
  - Resonance in Y-direction

Synthesis Validation

"Closing the Loop"

4 objective GA resonator synthesis and characterization:

- Further characterizes MUMPs process
- Improved our understanding of impact of constraints and objectives on fabricated structures
- Validates this approach



- **Goal ω_r = 10kHz**
- **PolyMUMPs(run # 60)**
- **36 unique designs**
- **149 ω_r measurements**
- **Beam Overetch = ~ 0.3 µm**
- **E = ~160 GPa**
- **Poly1 σ_{res} > 5 MPa**

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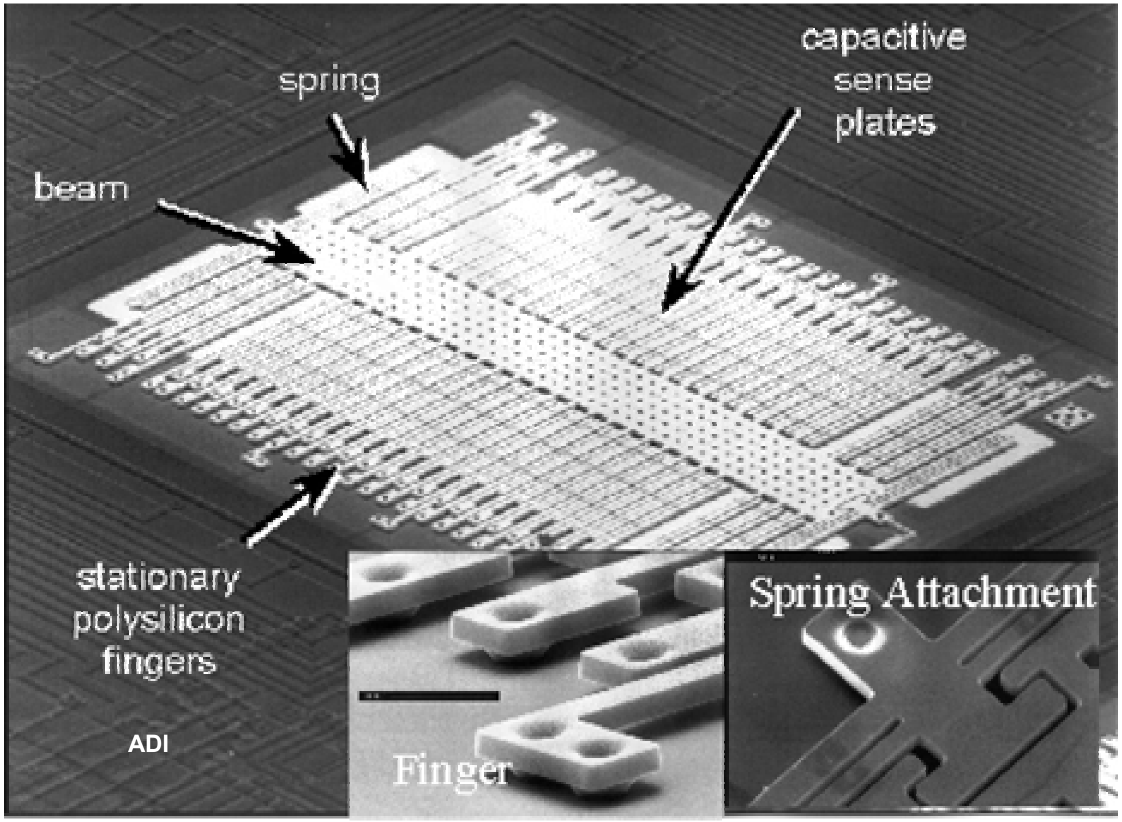
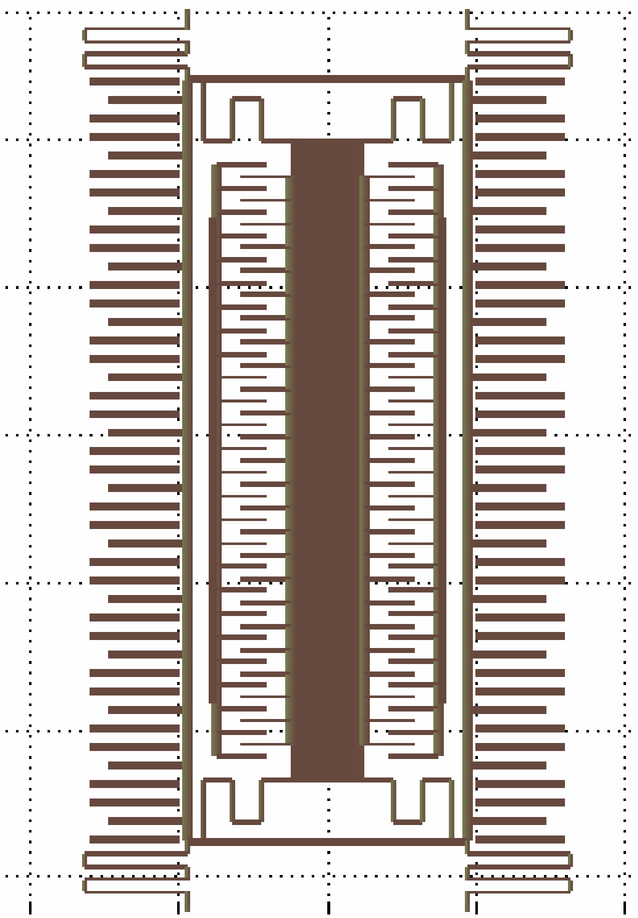
ADXL-type Accelerometer Example



Please see Y. Zhang's "***Design Synthesis of Microelectromechanical Systems Using Genetic Algorithms with Component-Based Genotype Representation***" at *GECCO-06* for the latest research in MEMS Accelerometer Synthesis

Vibratory Rate Gyro Example

Similar to W. Clark or C. Acar style VRGs

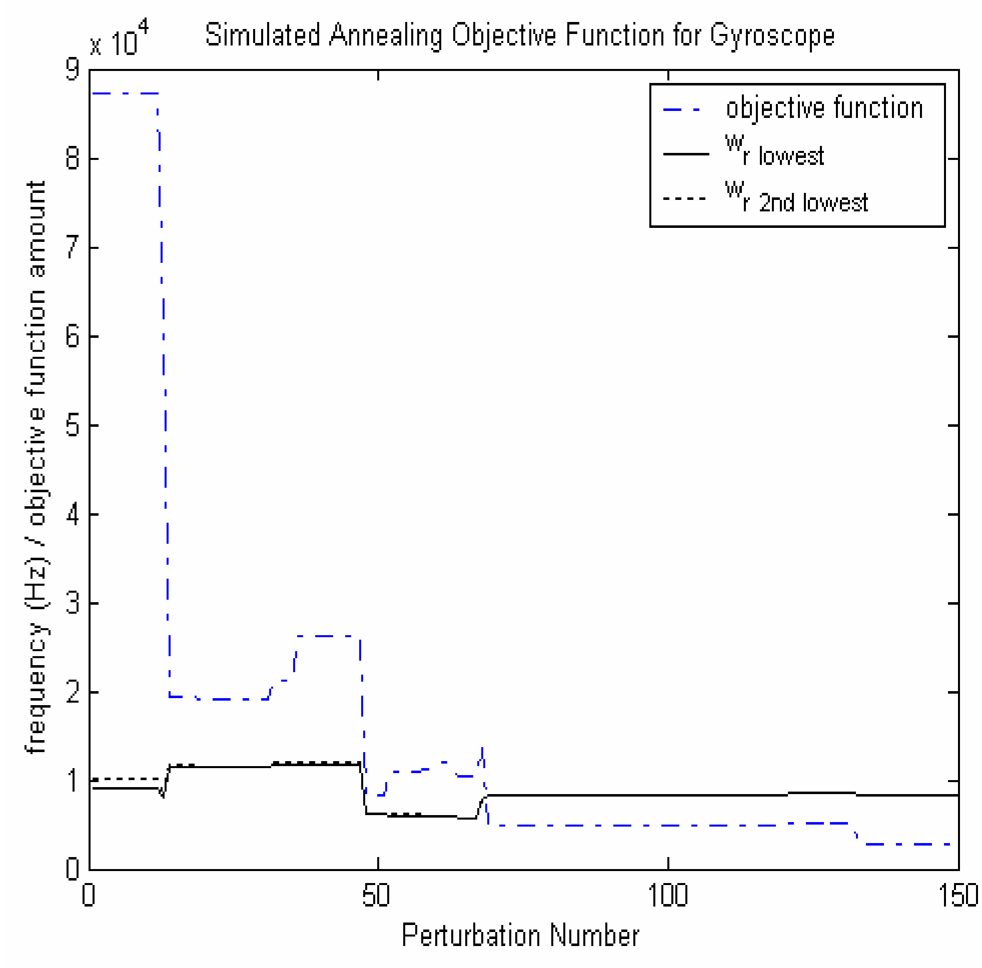


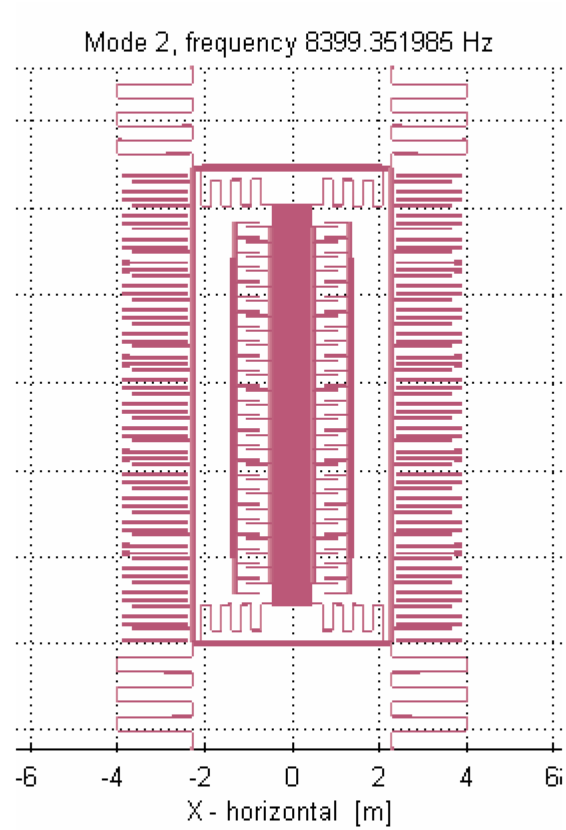
$\omega_{r\ goal}$ = 10 kHz $\Delta\omega_r$= minimized
k = weighting factor = 10, 100

- Match 1st and 2nd resonance modes as closely as possible (@ 10 Hz)
- Use modeshape to verify direction of resonance (from eigenvectors)
- Simulated Annealing objective function:

$$F(x) = \left|\omega_{r-lowest} - \omega_{goal}\right| + k\left|\omega_{r-lowest} - \omega_{r-2nd\_lowest}\right|$$

Example Gyro Synthesis Output





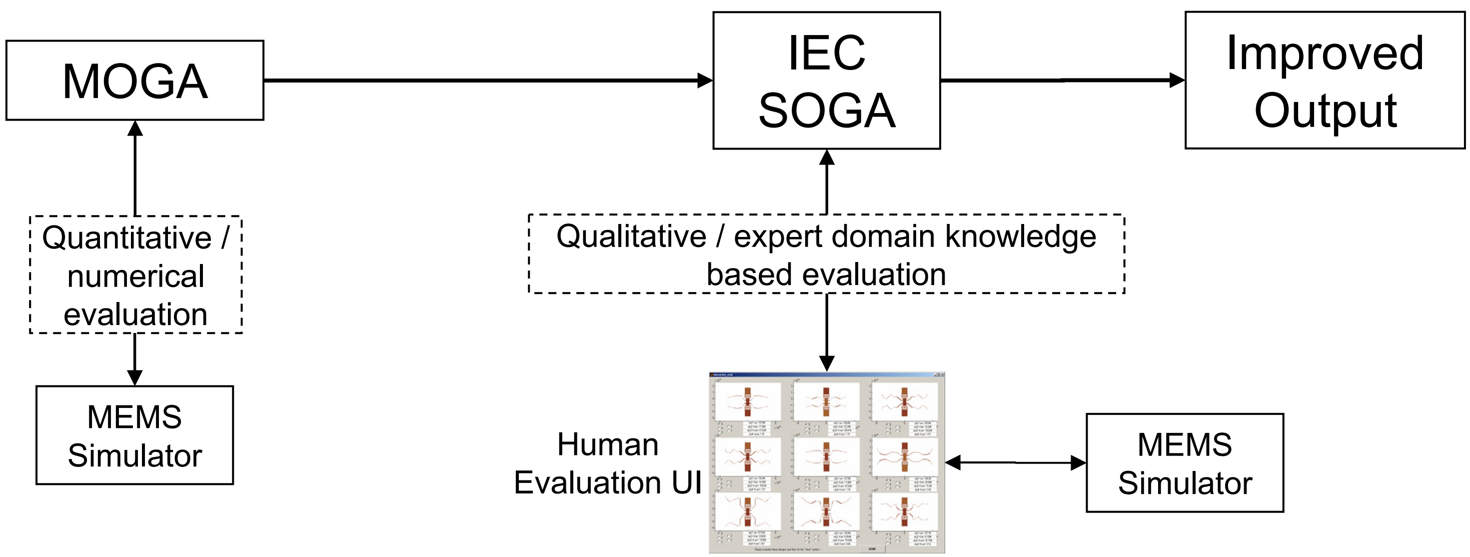
Issues with EC for MEMS Synthesis

- GAs play by the rules you give them, whether they are complete or not.
  - *It will find the holes in your formulation!*
- There are limitations in simulators
  - Non-simulatable phenomenon can not be included in fitness ranking.
- Not every rule or guideline can be turned into a line of code…

- Our solution:
  - Use ***Interactive Evolutionary Computation (IEC)***
    - based on human's evaluation of fitness
    - Originally developed for aesthetic or sensory design
  - Human interaction allows 'implied' constraints
  - Expert domain knowledge / experience can guide the evolution process.

IEC for MEMS Synthesis 1:

- First iteration: MOGA+IEC
- Take output of automated MOGA and do single objective GA (SOGA) using human evaluation.
- Human can ‘hone’ output.

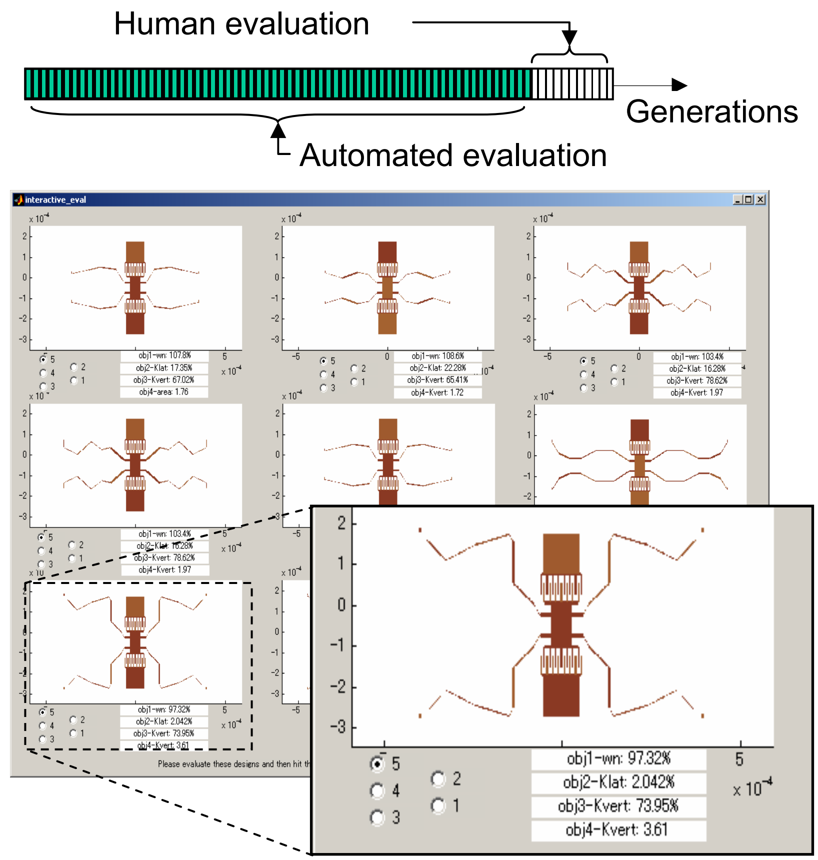


IEC for MEMS Synthesis 1:

- Human shown design topology AND simulation results

- Human gives evaluation based on their expert knowledge/ experience

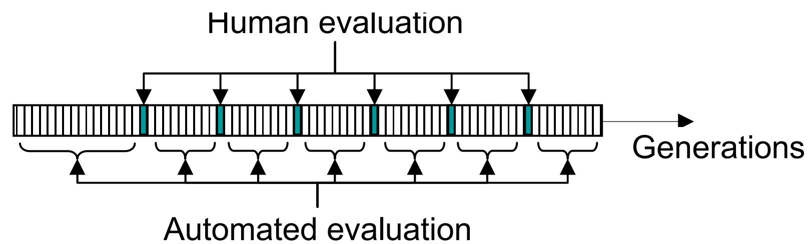
- Constraints/ Objectives applied by human need not be pre-determined or static.

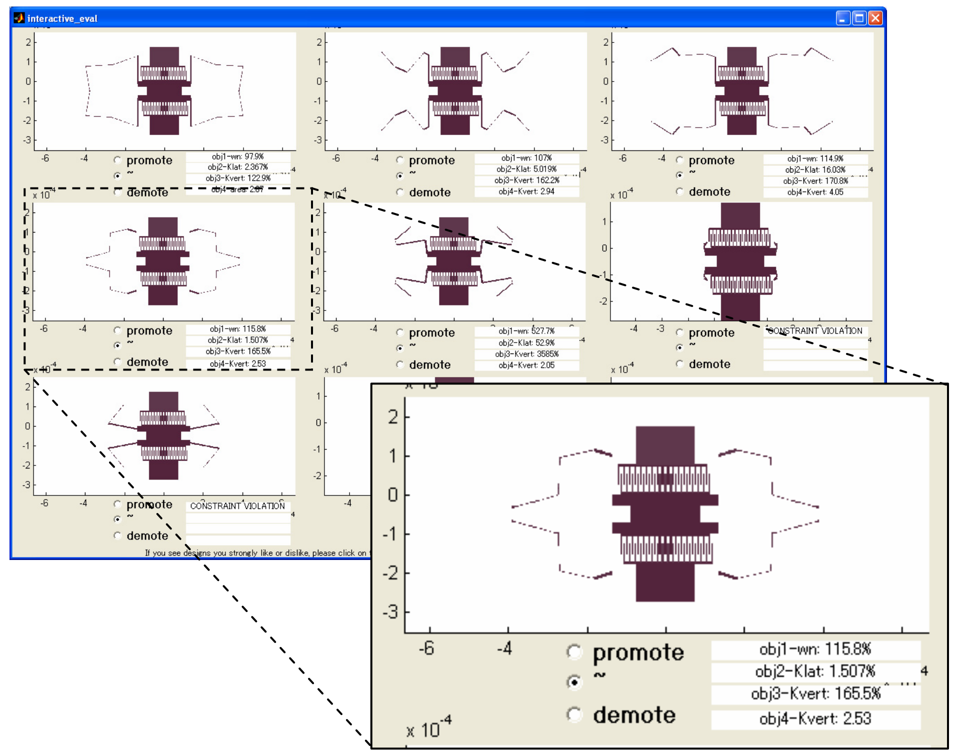


- User study shows significant improvement using MOGA+IEC vs. MOGA alone

IEC for MEMS Synthesis 2:

- Alternate IEC implementation:
  - Supervisory: Better combination of expertise of human with tirelessness of computer
  - Intersperse human into automated EC
  - Change from ‘absolute score’ to relative (+ / ~ / -)
    - use Pareto Rank shifting
  - Human effort reduced significantly
  - Produces better designs than automated EC alone.





Industry Reaction to Automated Synthesis for MEMS

- Resistant to automated synthesis
  - Not Programmers!
    - …usually are fab experts, not designers.
  - Many applications are beyond the scope of practical simulation tools
  - Want more direct interaction with problem
    - Don't like being hands-off
    - Our current IEC is not enough!
      - Can't change specific variables, etc

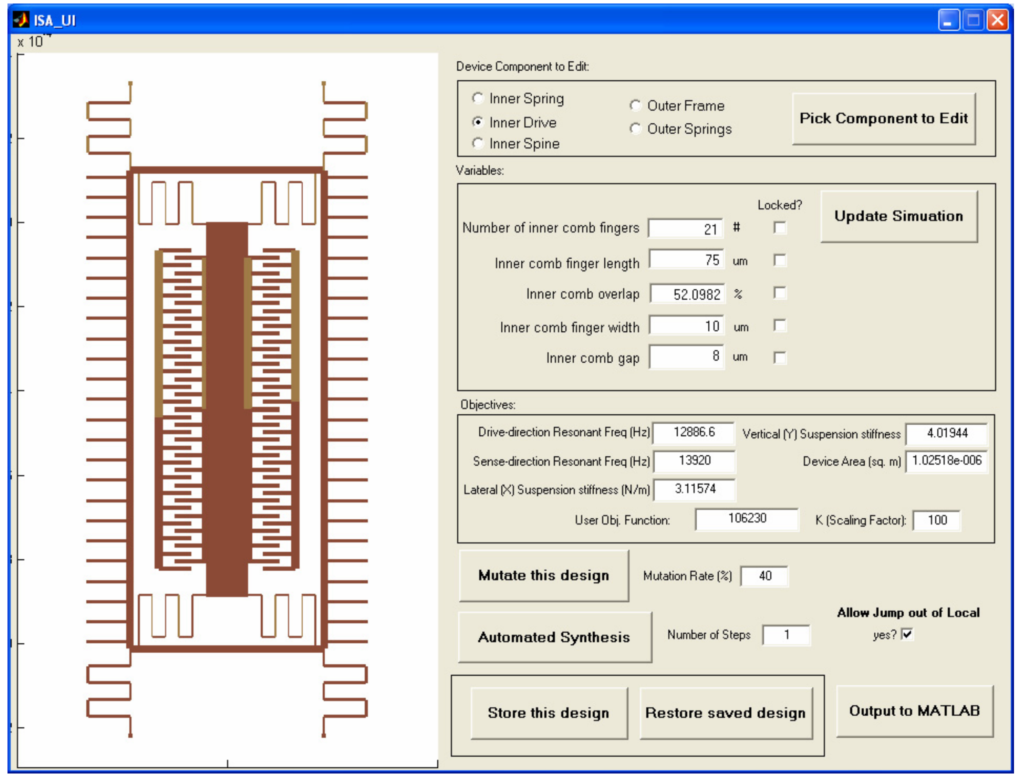
- Need to find a middle ground between automated and manual:
  - 'Computational Steering' / Interactive Design Synthesis

Proposed Solution

- A MEMS CAD GUI for design modification, simulation and synthesis
- Offer simple evolutionary synthesis capability:
  - Random Walk
  - Simulated Annealing (SA)
- Closer to Parmee's approach to IEC than to our traditional one.
  - Parameters of automatic EC search are controlled by human interactively.

Interactive Evolution GUI:

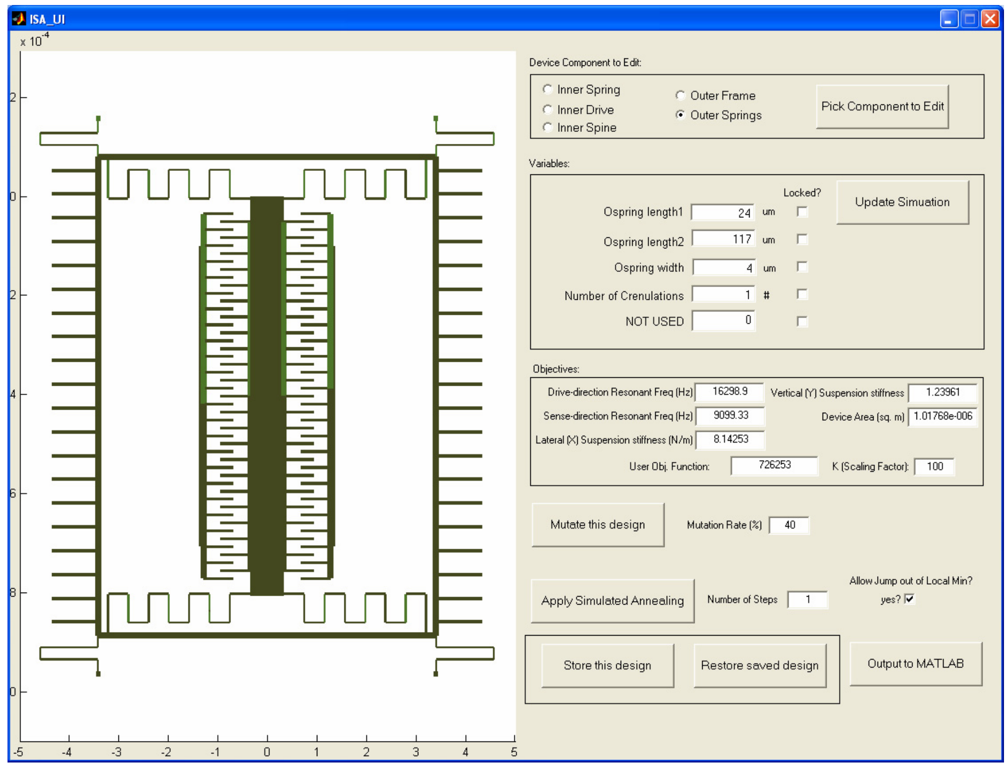
- Interactive CAD Simulator
  - Independently adjust desired variables
  - Get performance #'s from simulator package
- Synthesis Tool
  - Single mutation step
  - Multi-step Random Walk or SA
  - User can lock desired variables
    - Reduces search space



Can be used as fully manual parameter tuning or fully automated synthesis or somewhere in between

Interactive Evolution GUI:

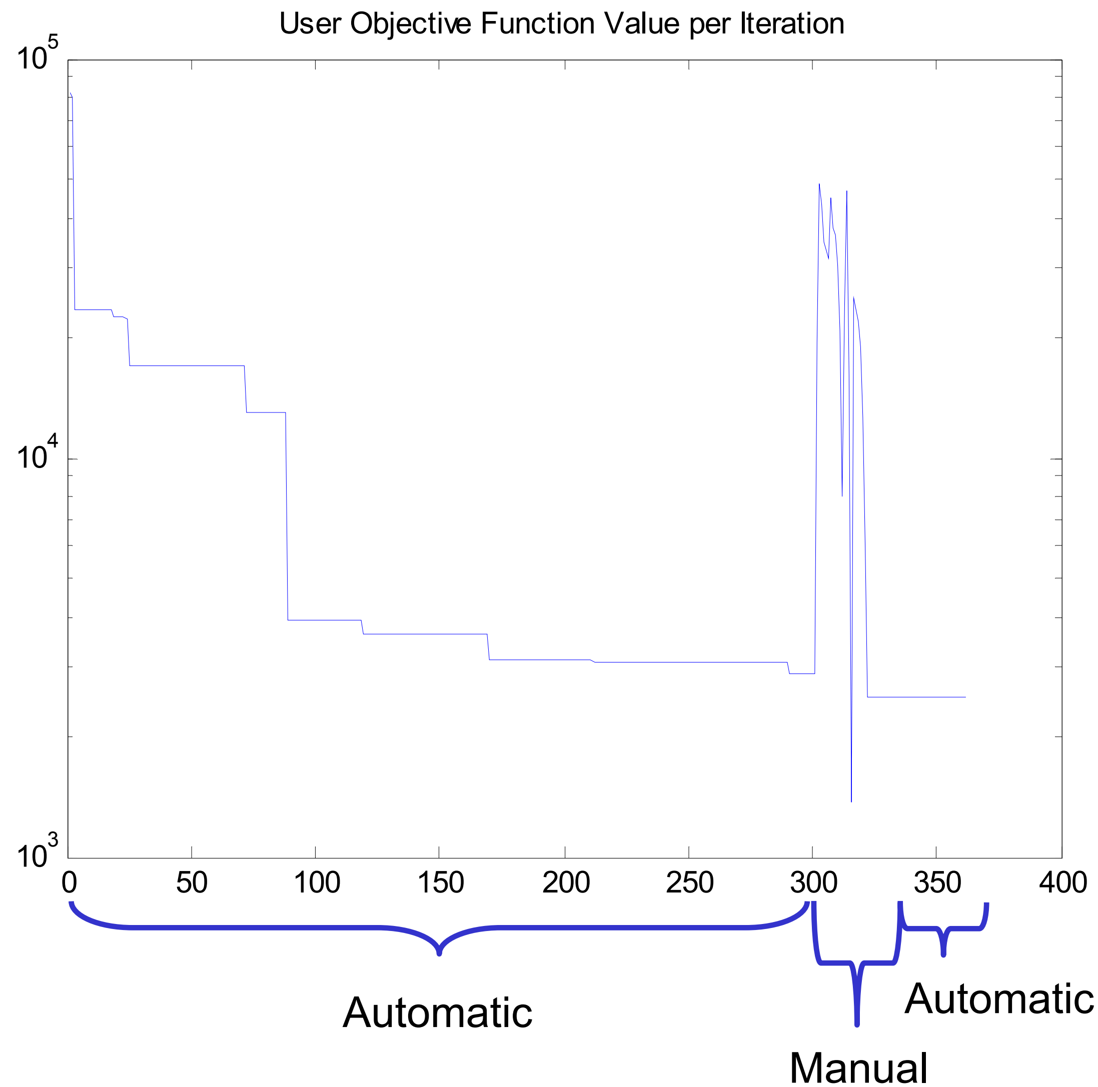
- Generality / flexibility important.
  - Simple, standardized data structure
- Interface via MATLAB with any simulation package
  - SUGAR, FEA, etc
- User need only create functions to interface with simulator only.



Interactive Evolution GUI: Results

- Able to find designs
  - Use pattern depends on user
    - Manual → Automatic?
    - Automatic → Manual?
  - Hard to quantify this performance!

- Process of using this tool also helps provide engineer with design experience / knowledge



Conclusions

- Summary
  - MEMS an important new field in need of design tools
  - Interactive evolution based MEMS synthesis introduced
  - Based on Industry feedback / lack of interest –
    - Search for proper balance between automatic and completely manual design approach needed
    - Keeping it flexible and generic is key!
- Further work
  - Alternate approaches?
  - Additional features?
  - Try to get industry to adopt these methods.

Questions? Acknowledgements

- For more information
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