Systems Engineering Toward Self-Sustaining Adaptive Micro/Nano Systems

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THE INSTITUTE FOR SYSTEMS RESEARCH

History

- An original NSF Engineering Research Center (founded 1985)
- Permanent Institute status within the Clark School of Engineering, University of Maryland (1992); with base budget support
- Graduated from the NSF program (1996); fully self-sustaining

Distinctives

- Collaborations with federal and state agencies, local and international corporations and universities worldwide
- Commercial implementation of research results
- Interdisciplinary, systems-focused education program
- Culture of innovation, collaboration and partnership
- New knowledge creation in emerging disciplines

Mission

ISR is home to interdisciplinary research and education programs in systems engineering and sciences, and is committed to developing basic solution methodologies and tools for systems problems in a variety of application domains.

Main ISR research areas

- Communication systems and networks
- Control systems and methodologies
- Neuroscience and biology-based technology
- **Micro and nano devices and systems**; robotics
- Design, operations and supply chain management
- **Systems engineering methodologies**
- Computing, speech, artificial intelligence, data mining

New initiatives

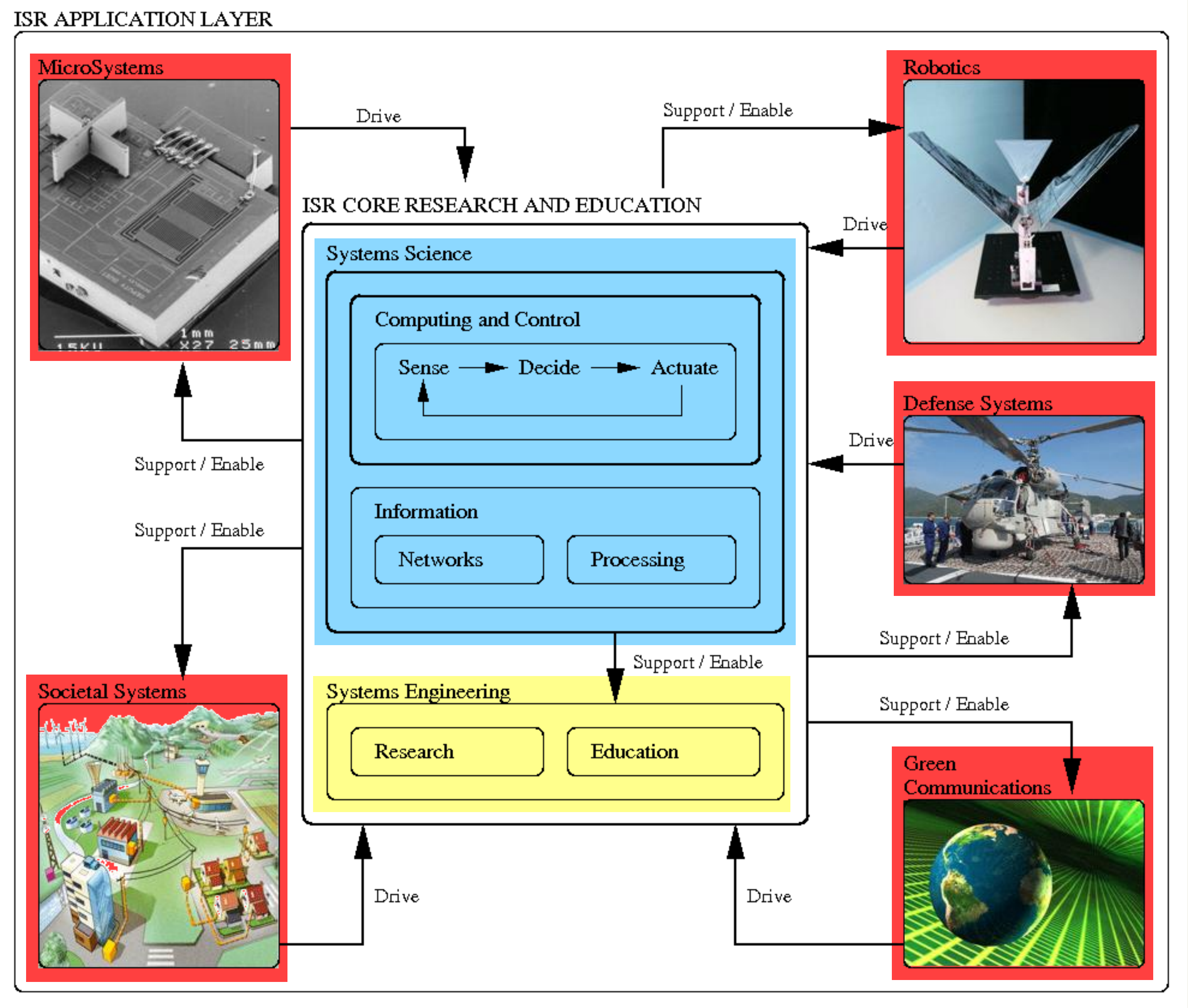
- Robotics
- Microsystems
- Green communications

THE ISR SYSTEMS RESEARCH MODEL

Systems

Enabling Technology

Fundamental Science



SYSTEMS ENGINEERING METHODOLOGIES

Problem domains/areas of expertise

Systems engineering and integration

Systems tools for semantic web technologies

Requirements management tools

Systems integration methodologies for energy-efficient buildings

Cyber-physical systems (CPS) development

Operations research

Methodologies for transportation systems and "systems of systems"

Public health emergency planning

Telecommunications modeling, policy and technology

Analysis and control of stochastic systems

Markov decision processes

Discrete event and hybrid systems

Network optimization and management

Network and combinatorial optimization, network reliability analysis

Network design logistics, formal models for validation/verification

Computing, optimization and decision technologies

Integrated network management systems

9 joint and affiliate faculty in this area

MICRO AND NANO DEVICES AND SYSTEMS

Problem domains/areas of expertise

MEMS sensors and actuators

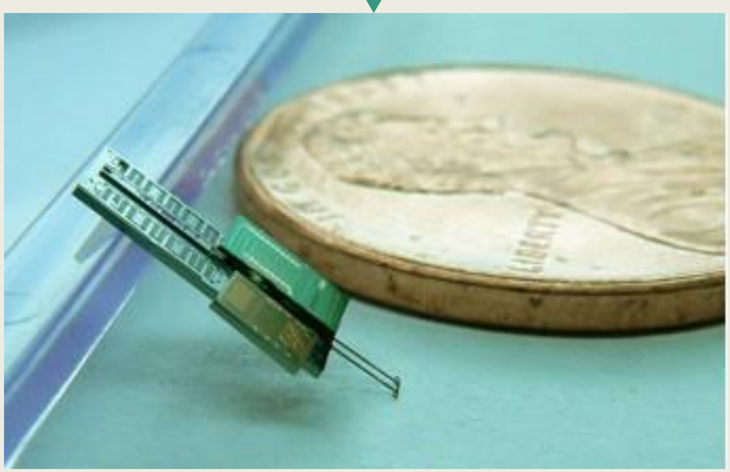
Nanofabrication materials, processes and devices

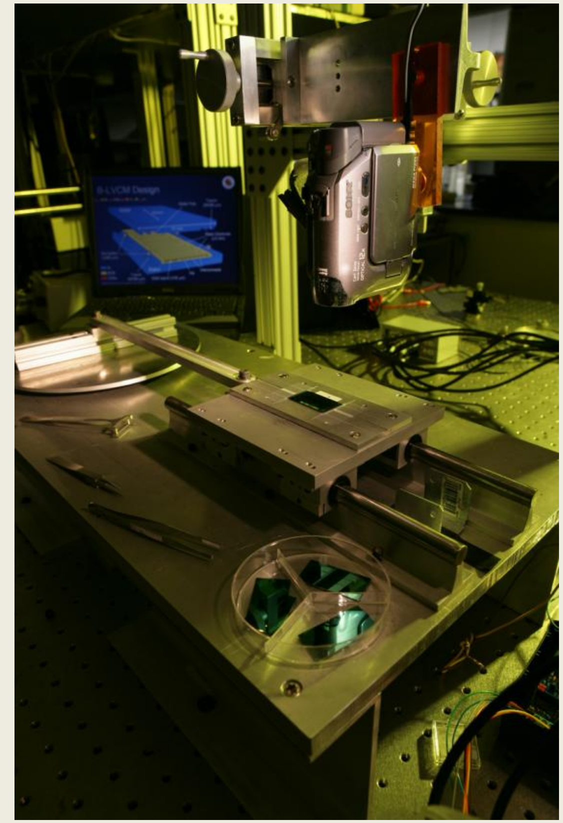
Labs-on-a-chip

Small-scale energy generation, storage and harvesting

Medical devices and treatments

Microrobotic systems





10 joint and affiliate faculty in this area

Bringing world-class scientists and engineers as well as fabrication and characterization infrastructure together to drive technology and fundamental understanding in nano

INSTITUTE FOR RESEARCH IN ELECTRONICS & APPLIED PHYSICS

Engineering
A. James Clark School of Engineering

Physical Sciences
College of Computer, Mathematical and Physical Sciences

Life Sciences
College of Chemical and Life Sciences

MARYLAND NANOCENTER

Research
- Faculty research groups
- Partnerships
- Collaborative research laboratories

Education
- Nano educational programs
- Outreach

Industry & govt
- One-stop shopping
- Partners' Program

Infrastructure
- Initiatives
- Shared user facilities
- Operations – web, facilities, information

Nanofabrication (FabLab)

Nanocharacterization (NispLab)

Shared experimental facilities

Top 10 ranking (Small Times)

www.nanocenter.umd.edu

NANOCENTER EXPERIMENTAL FACILITIES

FabLab

NispLab

Shared user facilities

Open to outside users and collaborators

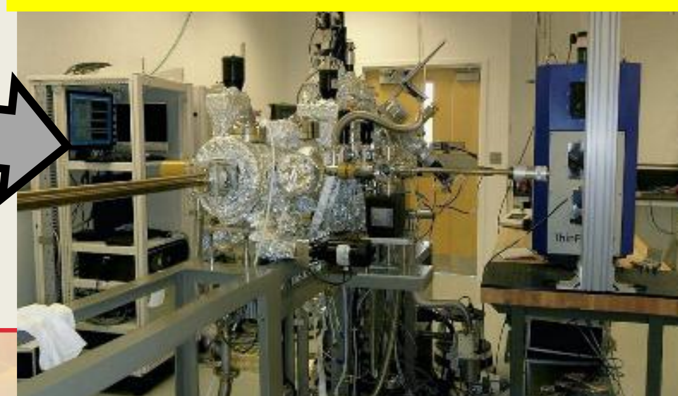
Fully state of art & beyond

Individual research labs

Often shared by campus collaborators

Available to external collaborators

Numerous research group labs



NANOCENTER RESEARCH DIRECTIONS

Nanostructures for energy

Biomolecular and cell-based biomicrosystems, biofabrication

Nanoelectronics - graphene

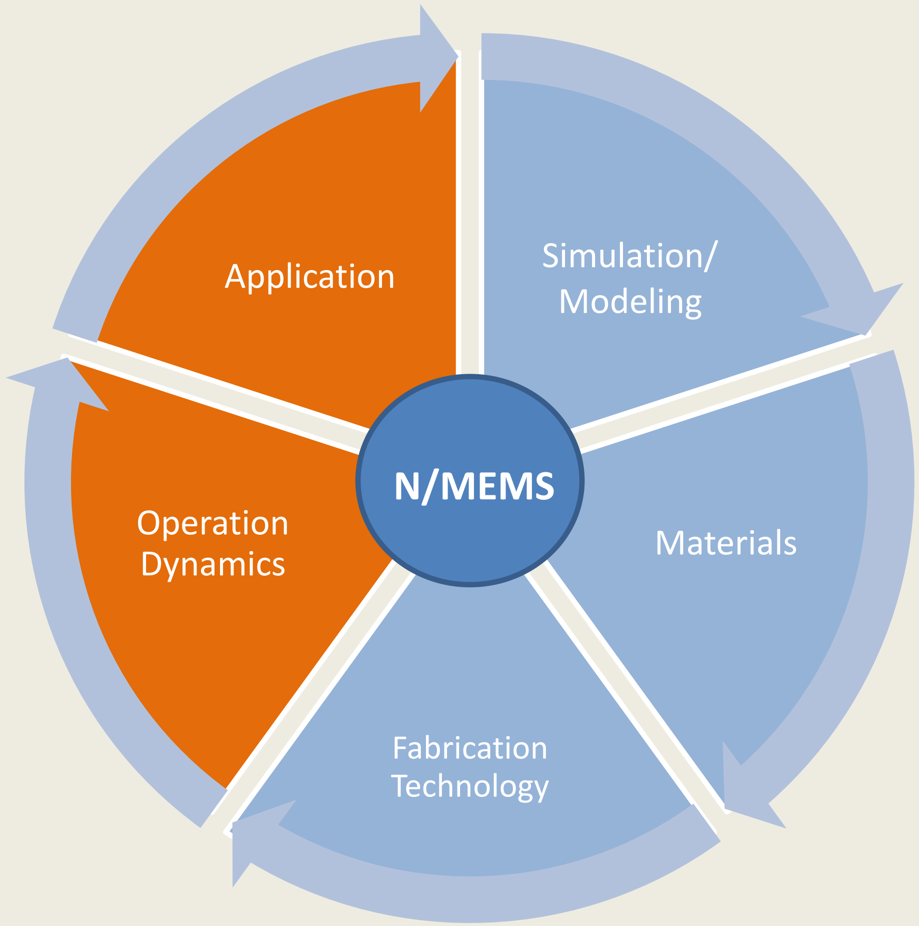
Designer nanomaterials – inorganic, soft, bio, composites

Nanoparticle synthesis and systems

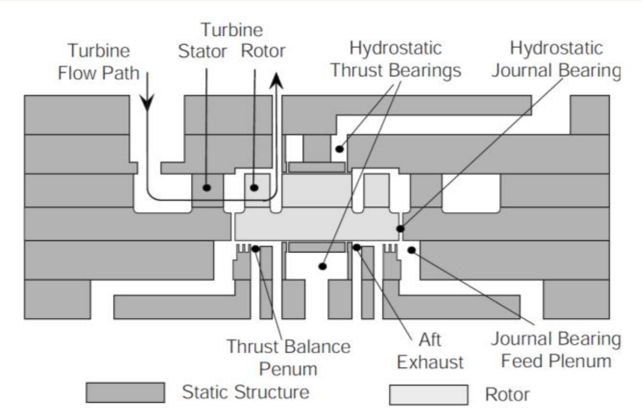
Novel microscopies and microsystems

Processes and integration for nano/micro fabrication

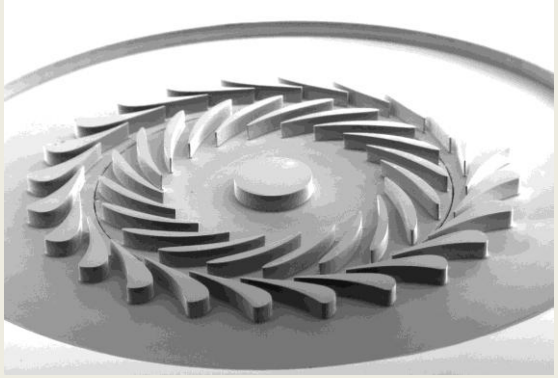
MICRO/NANO SYSTEMS AND SYSTEMS ENGINEERING



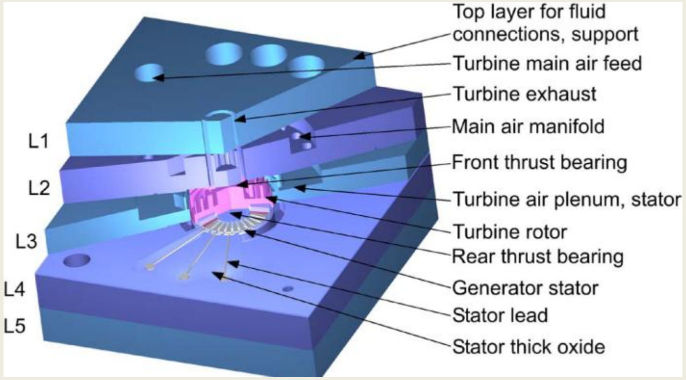
AIR BEARING SUPPORTED GAS TURBINES FOR POWER GENERATION AT MIT

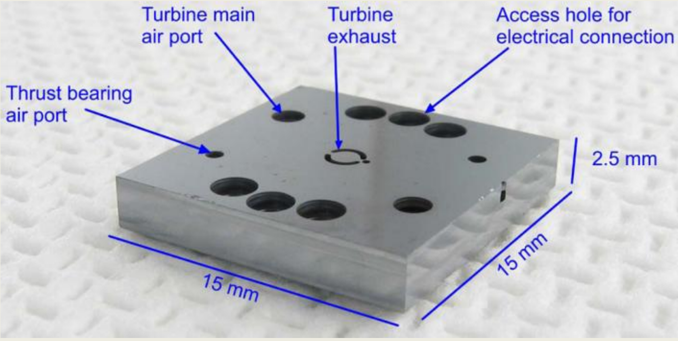


Schematic Device Layer Stack



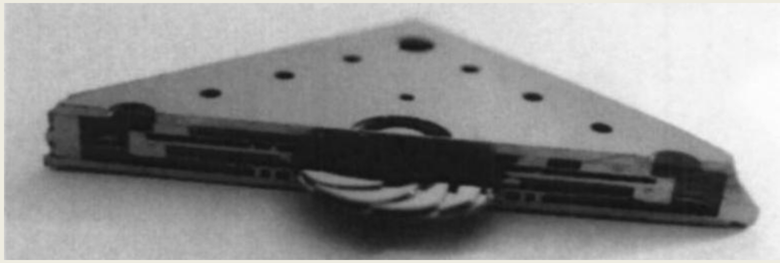
SEM Image of a Turbine





Picture of an Induction Turbine

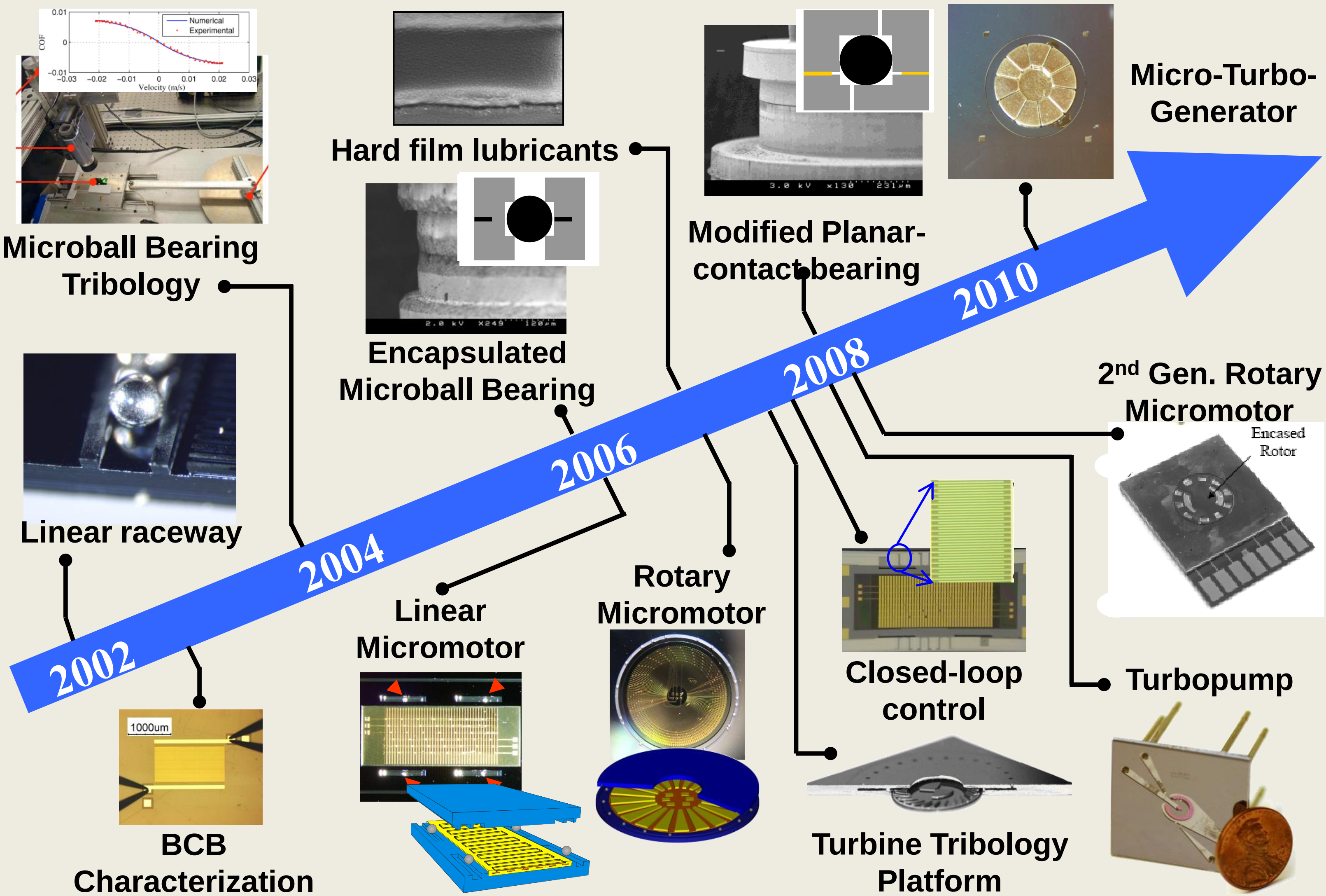
C. Livermore, J Microelectromech S



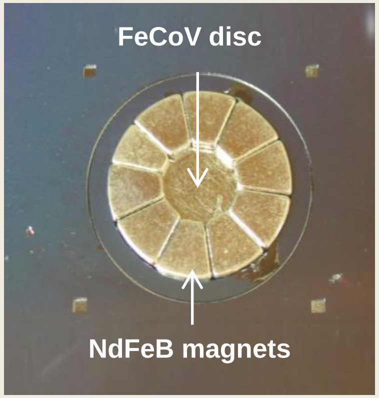
Picture of a Gas Turbine

Gas Turbine Generator, A. Epstein, J. Eng. Gas Turb. Power, J. Tribol.

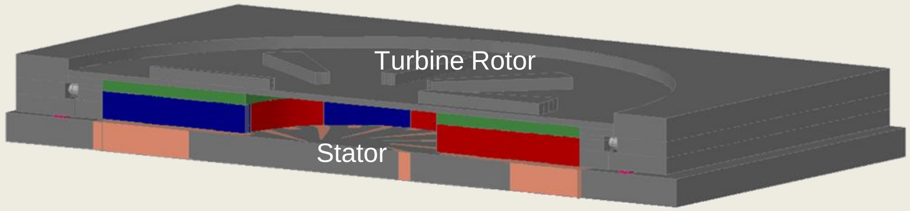
MICROBALL BEARING TECHNOLOGY EVOLUTION AT UMD



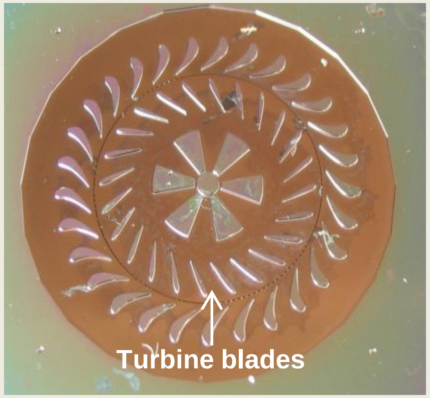
ELECTROMAGNETIC MICRO-TURBO-GENERATOR WITH BALL BEARINGS AT UMD



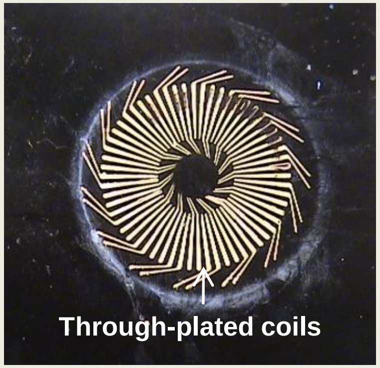
Magnetic Materials Integrated in Rotor



Schematic View of Micro-Turbo-Generator on Ball Bearings



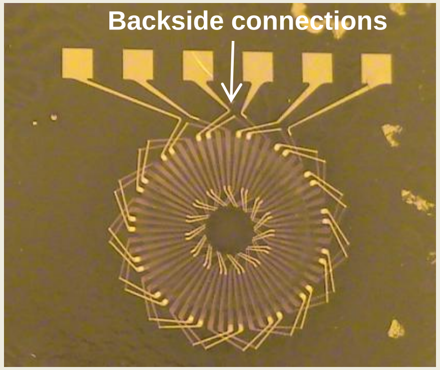
Rotor Turbine Structures for Pneumatic Actuation



3D Coil Structures Incorporated in Stator

Mechanical Coupling

First Generation Fuel-to-Electricity Power System



Complete Stator Coils for Electromagnetic Induction

WHY NANO SYSTEMS?

Advances in nanostructure synthesis

- Dimensional control
- Massive arrays
- Extremely high aspect ratios (depth/width)

Large surface area

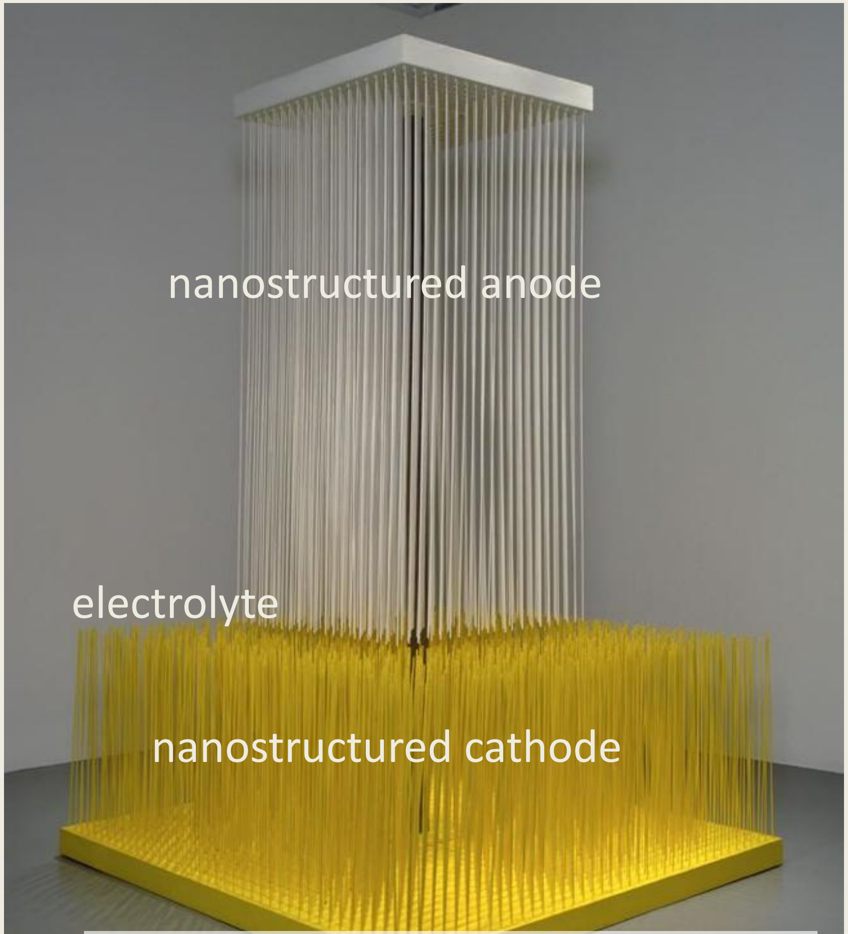
- ➔ easy access to charge storage materials
- ➔high power

Thin material layers

- ➔ fast transport into and throughout charge storage materials
- ➔mechanical flexibility to accommodate charge cycling

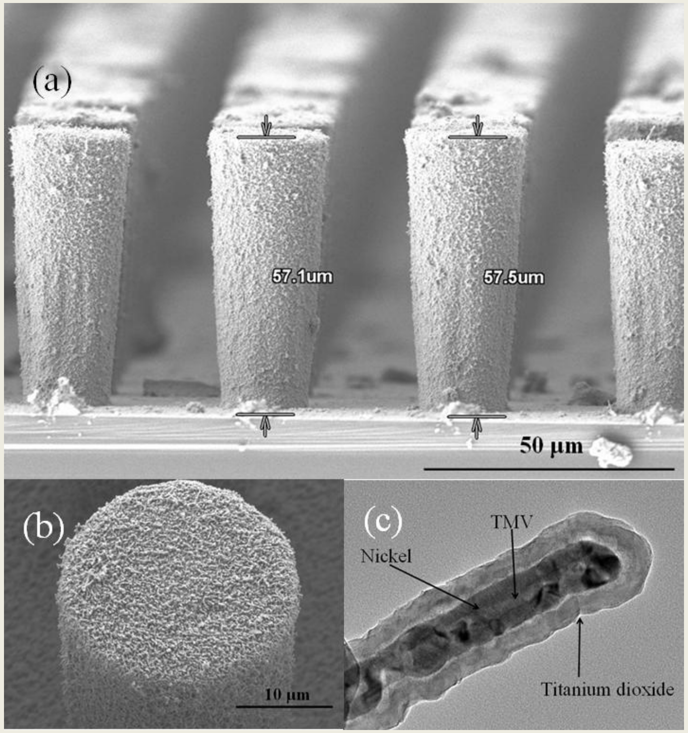
Large electrode volume

- ➔high energy density

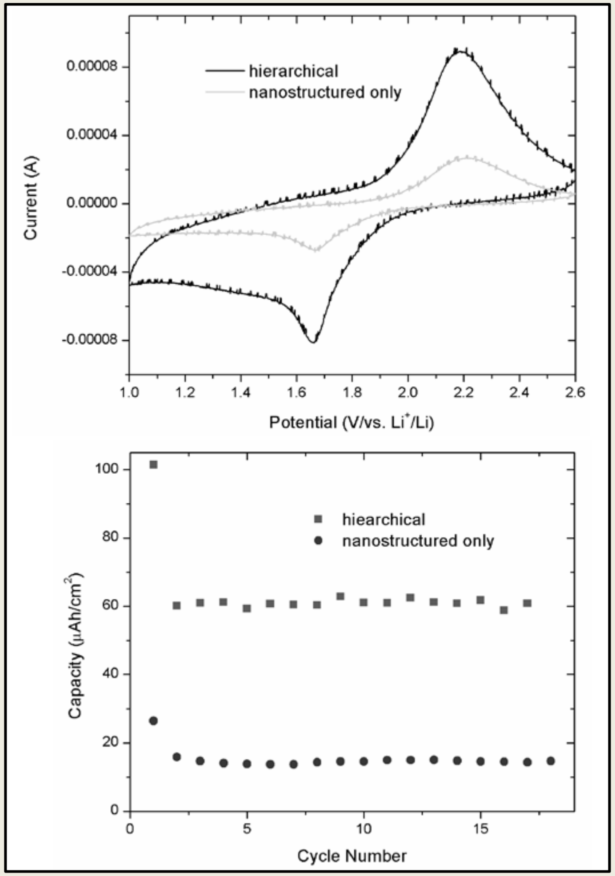


Jesús Rafael Soto, Two Volumes in the Virtual
Hirshhorn Museum, Washington DC

HIERARCHICAL ELECTRODES WITH MICRO/NANO STRUCTURES

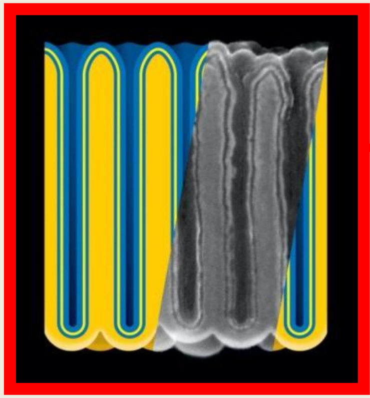


(a) Gold micropillars coated with virus-structured materials, (b) top view of an individual electrode (c) cross-section TEM showing the active material nanostructure

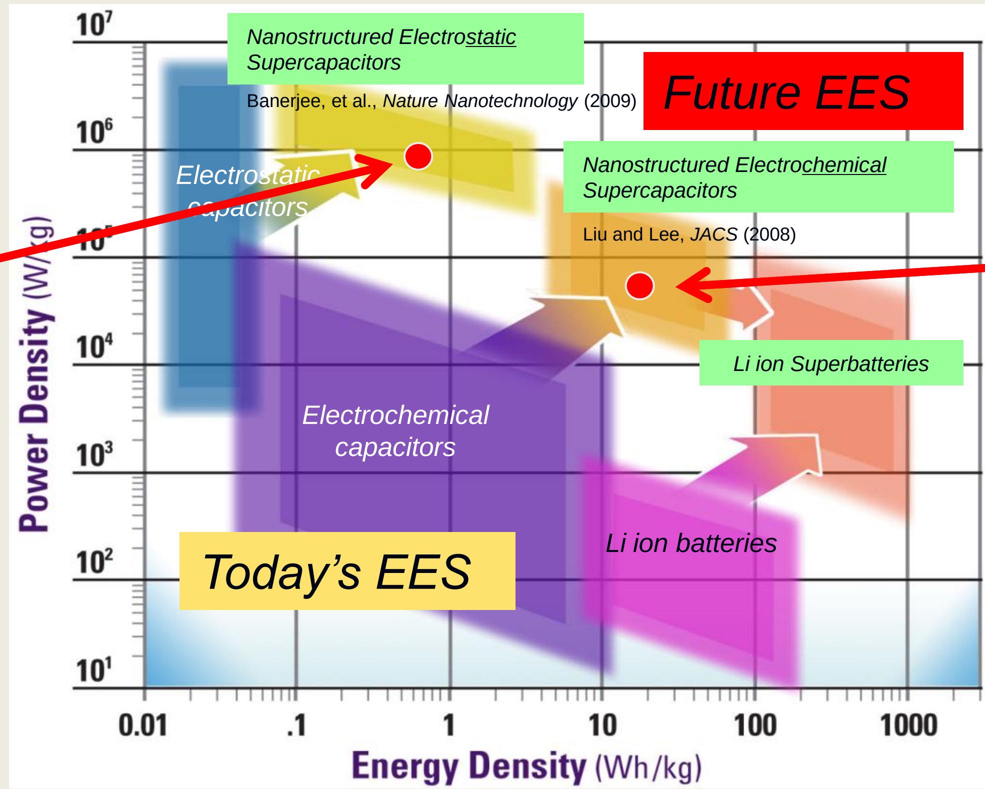


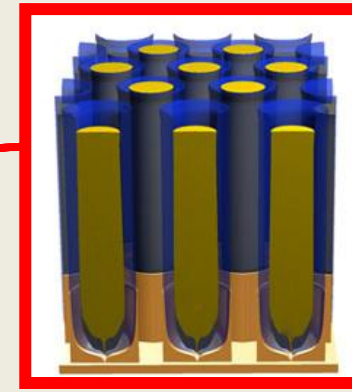
Testing results showing a 3-fold increase in capacity for hierarchical electrodes compared to nanostructures

NANOTECHNOLOGY FOR NEXT-GENERATION ELECTRICAL ENERGY STORAGE



AAO-ALD embedded metal-insulator-metal device



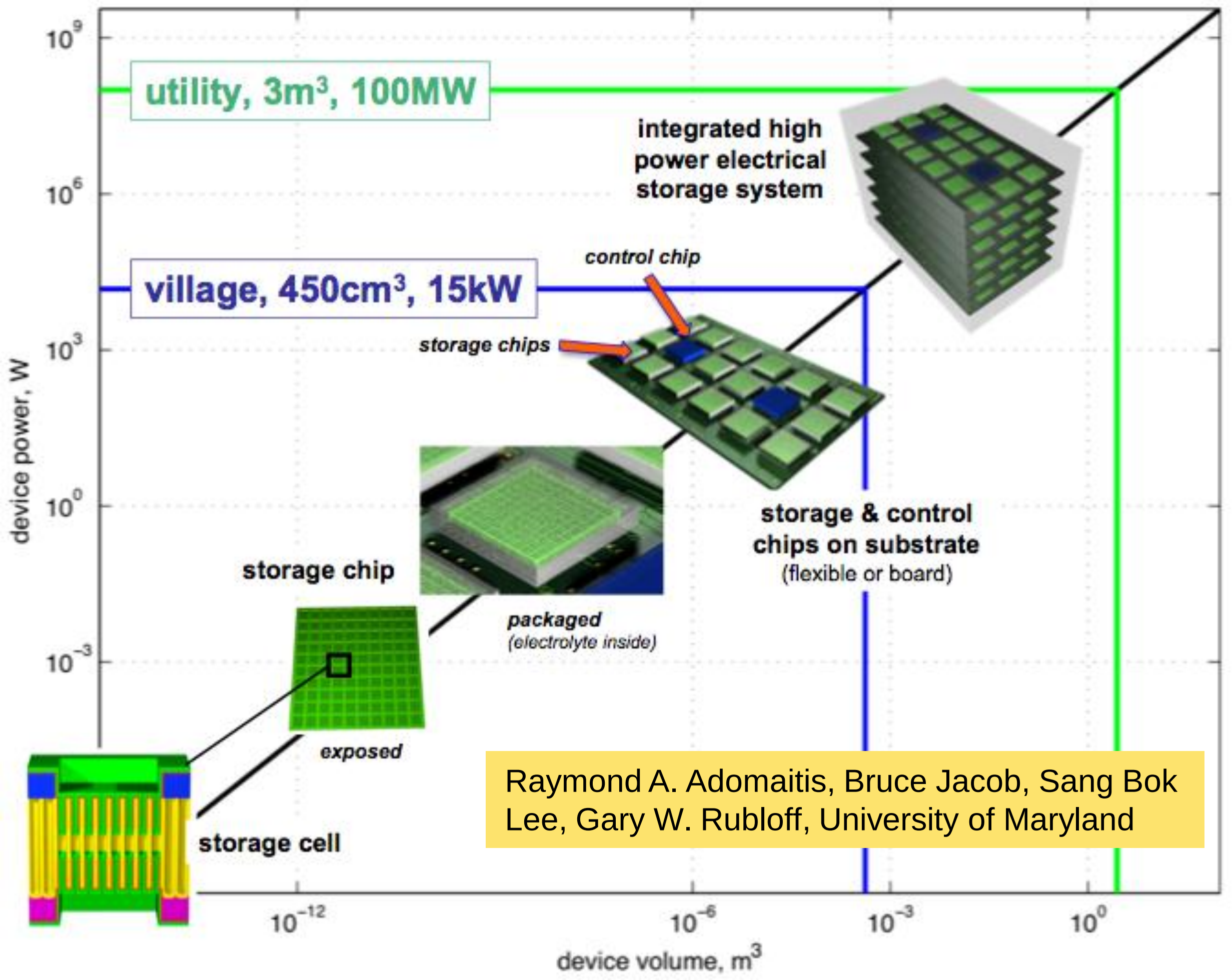


Free-standing MnO_2/PEDOT coaxial nanowires

- Massively parallel nanoengineered devices formed within nanopores
- Much higher power and higher energy density

HIGH POWER NANODEVICES AND SYSTEMS FOR POWER LEVELING

- High power storage technologies based on **massive arrays of electrochemical nanoscale supercapacitors**
- Design, integration, fabrication, and process/device optimization guided by physics-based **multiscale simulation** methods
- **System architecture** where embedded controllers are integrated with energy storage elements to enable concurrent charging and discharging of multiple storage nodes, load balancing, and lossless construction of AC signals



Raymond A. Adomaitis, Bruce Jacob, Sang Bok Lee, Gary W. Rubloff, University of Maryland

INTEGRATED N/MEMS AND IC DESIGN FLOW—CURRENT LIMITATIONS

N/MEMS design currently:

- Not well organized
- Typically requires teams of expert specialists—mostly confined to IDMs that have their own fabs
- Traditionally separated from IC design and verification
- Little connection between the design of a N/MEMS device and the electronic circuitry it interacts with
- Handoff between N/MEMS and IC designers is *ad hoc,* manual and error-prone
- Absence of cell library of basic building blocks
- Not well suited to address cost and time-to-market demands

INTEGRATED N/MEMS AND IC DESIGN FLOW—CURRENT LIMITATIONS

Need for a "structured" automated design flow, that links N/MEMS 3D design with custom IC design

•Modeling approach defined up front repeatable, rather than made up on the fly to suit each new design

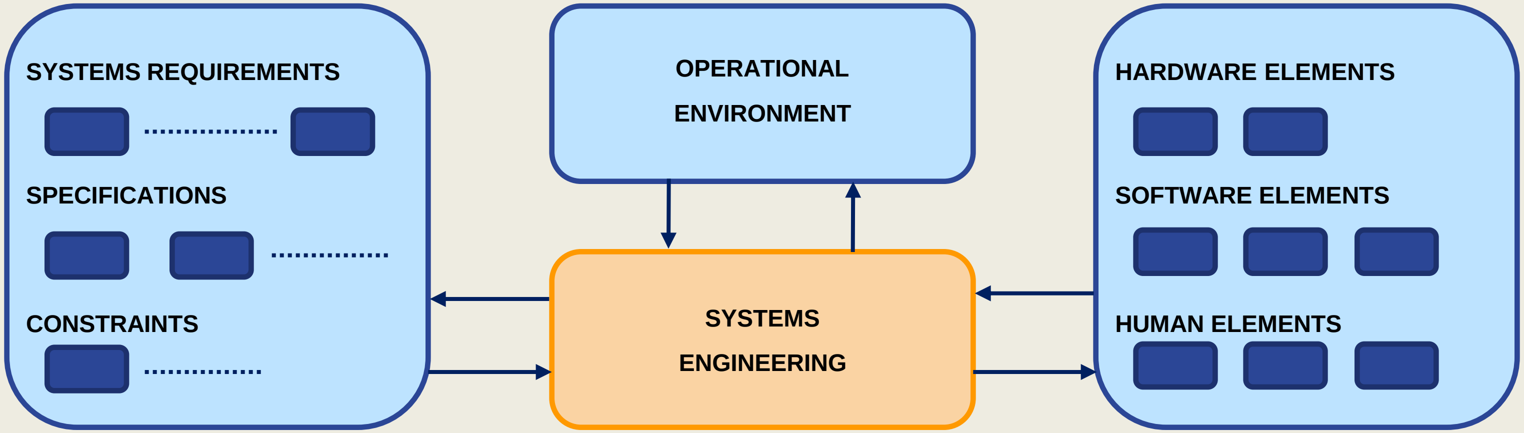
•Process variables, material properties, and geometric properties (lengths, widths, thicknesses) should be parametric to provide maximum design flexibility

•A well-characterized library of reusable N/MEMS building blocks (can be assembled into arbitrarily complex designs)

•Each block should have a 3D view (structure) and a behavioral model supporting all types of simulations

•Extraction and design-rule checking for N/MEMS devices

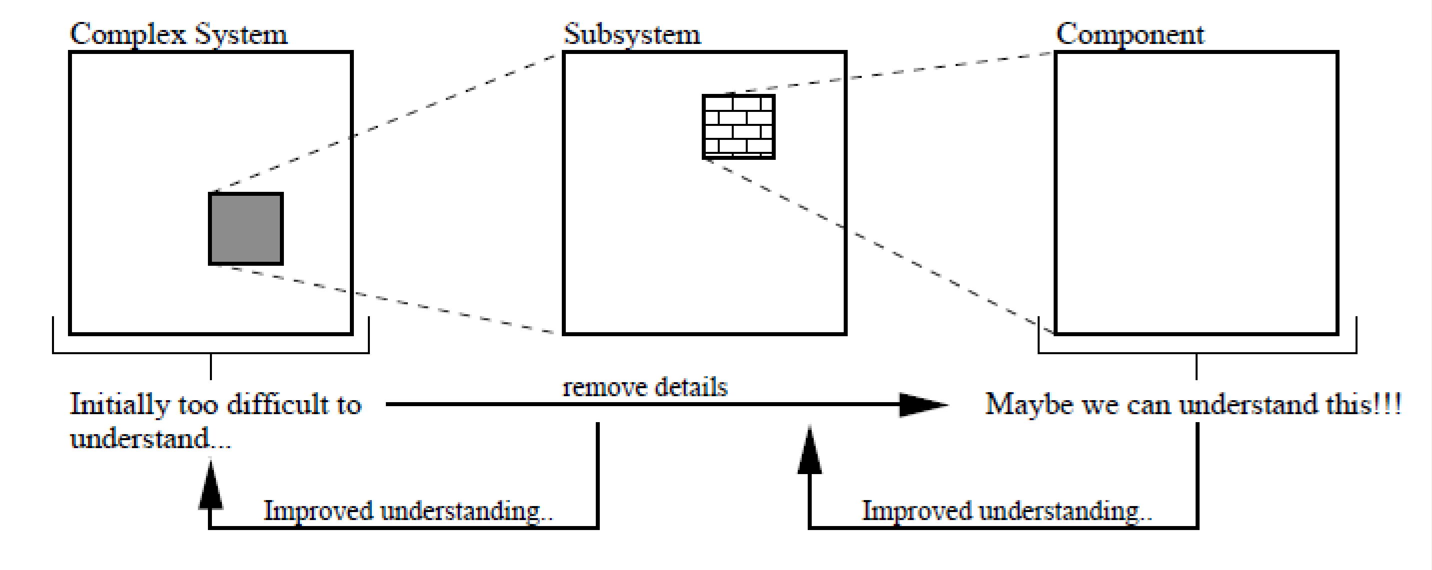
SYSTEMS ENGINEERING GOALS



Systems Engineering Drivers

1. Total integration of system building blocks with a surrounding environment
2. A methodology for systems development that focuses on *objectives*, *measurements*, and *accomplishments*
3. A systematic means of acquiring information and determining tradeoffs in cost, performance, and quality

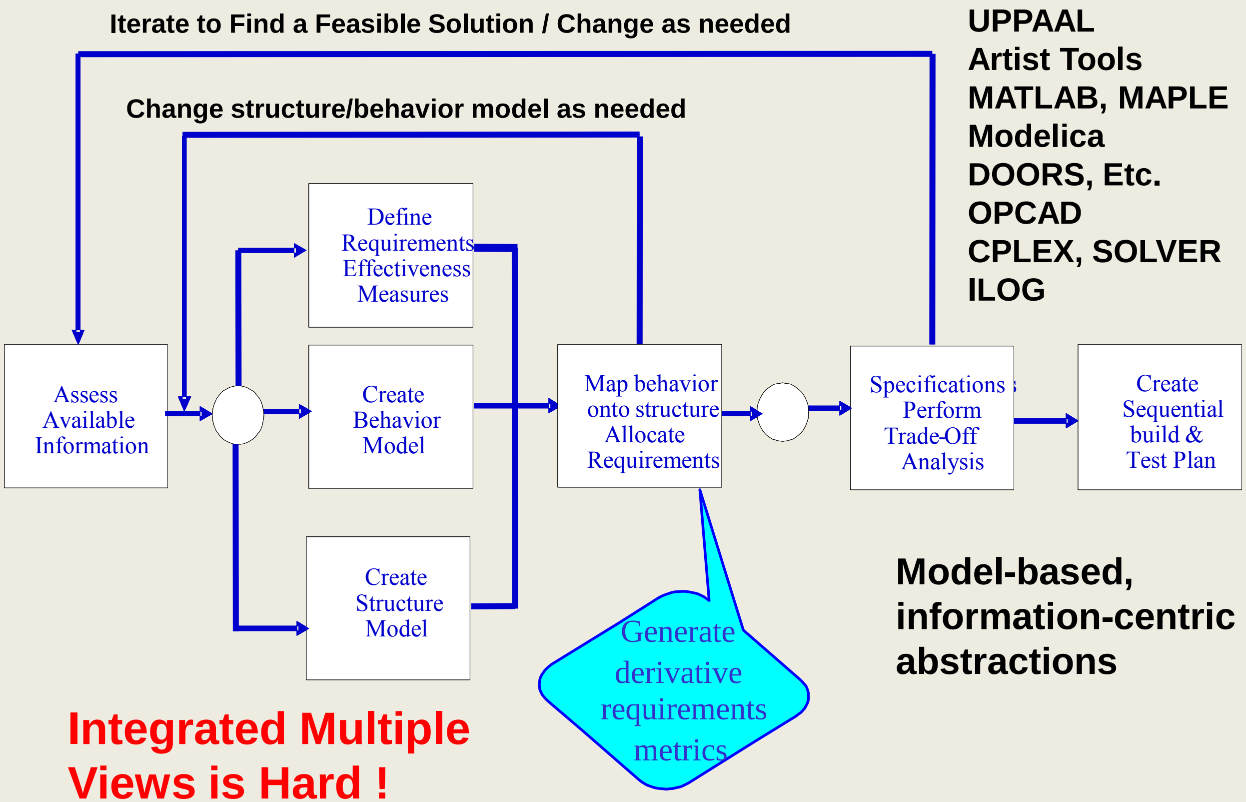
SYSTEMS HIERARCHY



- It is difficult to envision a final product/device during the initial stages of development
- By decomposing a project in a systematic way, we can logically progress towards a final device
- Designing from a system perspective increases overall understanding of the system and can help avert design faults

MODEL-BASED SYSTEMS ENGINEERING PROCESS

Integrated System Synthesis - Tools & Environments missing



Integrated Multiple Views is Hard !

Model-based
UML-SysML
Rhapsody
UPPAAL
Artist Tools
MATLAB, MAPLE
Modelica
DOORS, Etc.
OPCAD
CPLEX, SOLVER
ILOG

Model-based, information-centric abstractions

CORE MBSE TOPICS

- Object Oriented modeling and beyond
- Automata, languages, design rules
- Trade-off analysis and multi-objective optimization
- Testing, validation, behaviors
- Logic programming and optimization
- Performance over time, hybrid systems
- Simulation and performance analysis

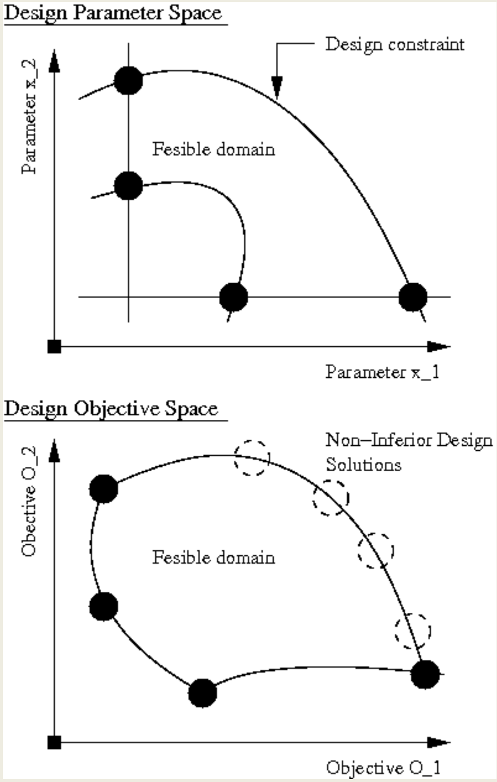
Why it is harder for MEMS and NANOS?
Non-traditional "Design Variables" : Multiple Physics, Materials and Geometry

SYNTHESIS AND SYSTEM-LEVEL DESIGN OF MEMS/NANO SYSTEMS

Systems Engineering Drivers

Challenges include:

- Nonlinear multi-physics behavior.
- Geometry details matter.
- Design problems are highly multi-dimensional involving many potentially good material types.
- Design parameters are mixtures of logical (choice) and numerical values.
- Many nonlinear / physical constraints.
- Multiple design criteria: cost, time-to-market, reliability, agility.



Systems Engineering Solutions

Formal methodologies and tools for:

- Synthesis and system-level design of MEMS/NANO systems.
- Efficient exploration of design spaces.
- Multi-objective tradeoff analysis.

THANKS!

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