Integrated and Innovative Design Automation of Mechatronic Systems

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2006 GECCO Evolutionary Computation in Practice Design Track

Outline

- Motivation
- Related Work
- Methodology
  - Unified Representation
  - Evolutionary Synthesis
- Case studies
  - Vehicle Suspension
  - MEMS
- Summary

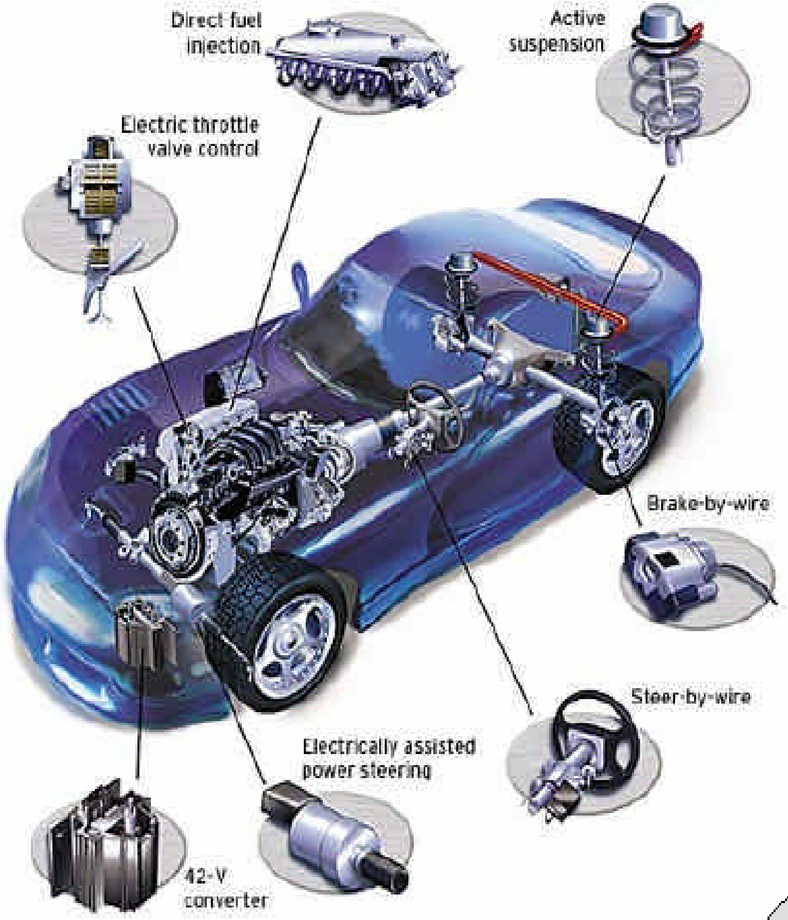
A typical Mechatronic System

Electrical

Controls

Magnetic

Pneumatic



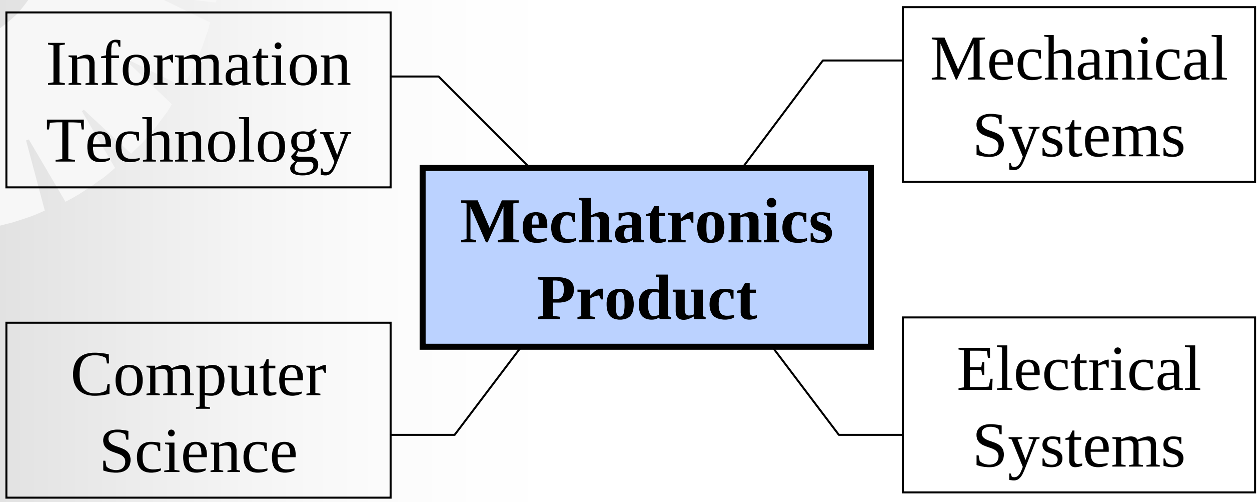
Mechanical

Hydraulic

Thermal

Electro-Chemical

Mechatronics Research



- An evolutionary stage in modern product design
- A synergistic system design philosophy, optimization of the system as a whole simultaneously
- Yet not formally supported in practice

Problem Description

- Lack systematic support for conceptual design
  - Lack horizontal integration: differing representation across engineering domains
  - Lack vertical integration: sequential vs. concurrent design, topological vs. parametric design
- Lack facilities to explore various alternatives
  - Traditional trail-and-error manual synthesis
  - Need for powerful computational search capability
  - Need for innovative design concepts

Research Objectives

- **A**ddress unified representation for multidisciplinary product/system designs.

- **A**utomate the design search process using coevolutionary synthesis mechanism.

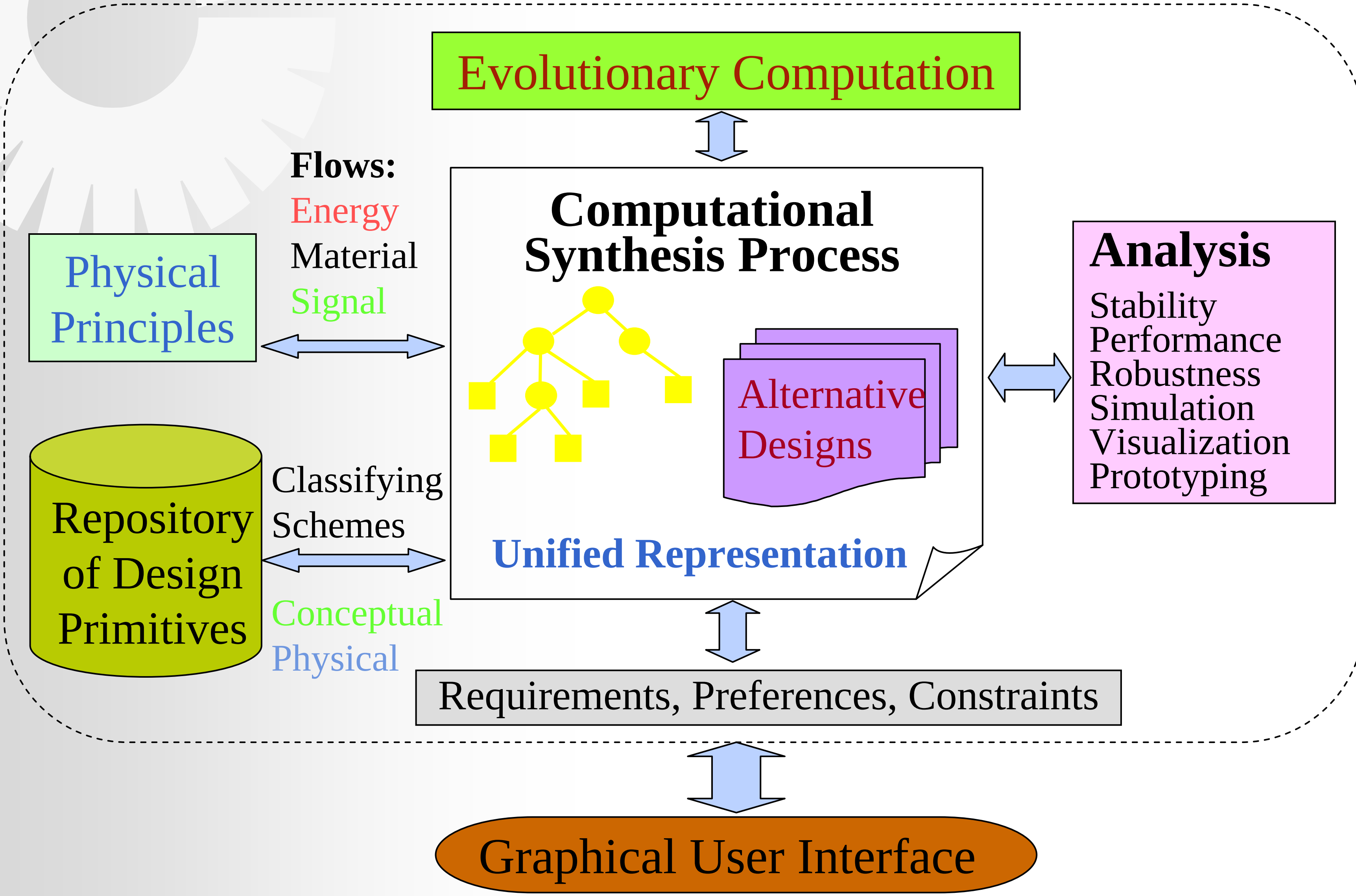
- **A**ssist the rapid investigation of multiple concepts, to give designers more flexibility and insight by exploring a wider range of possible creative and overall optimal design options.

Critical Focus: ***Mechatronics Conceptual Design***

Related Work

- Classical network synthesis of electrical circuits (Foster, Cauer)
- Bond graphs dynamic system manual synthesis (Redfield, Connolly)
- Genetic programming in dynamic system design: Analog electrical circuit synthesis and controller design (John Koza)
- Passive dynamic system design using bond graphs and genetic programming (Erik Goodman).
- “Controller design in the physical domain” philosophy (Neville Hogan)
- Cooperative coevolution (Potter and De Jong)

Integrated Design Environment

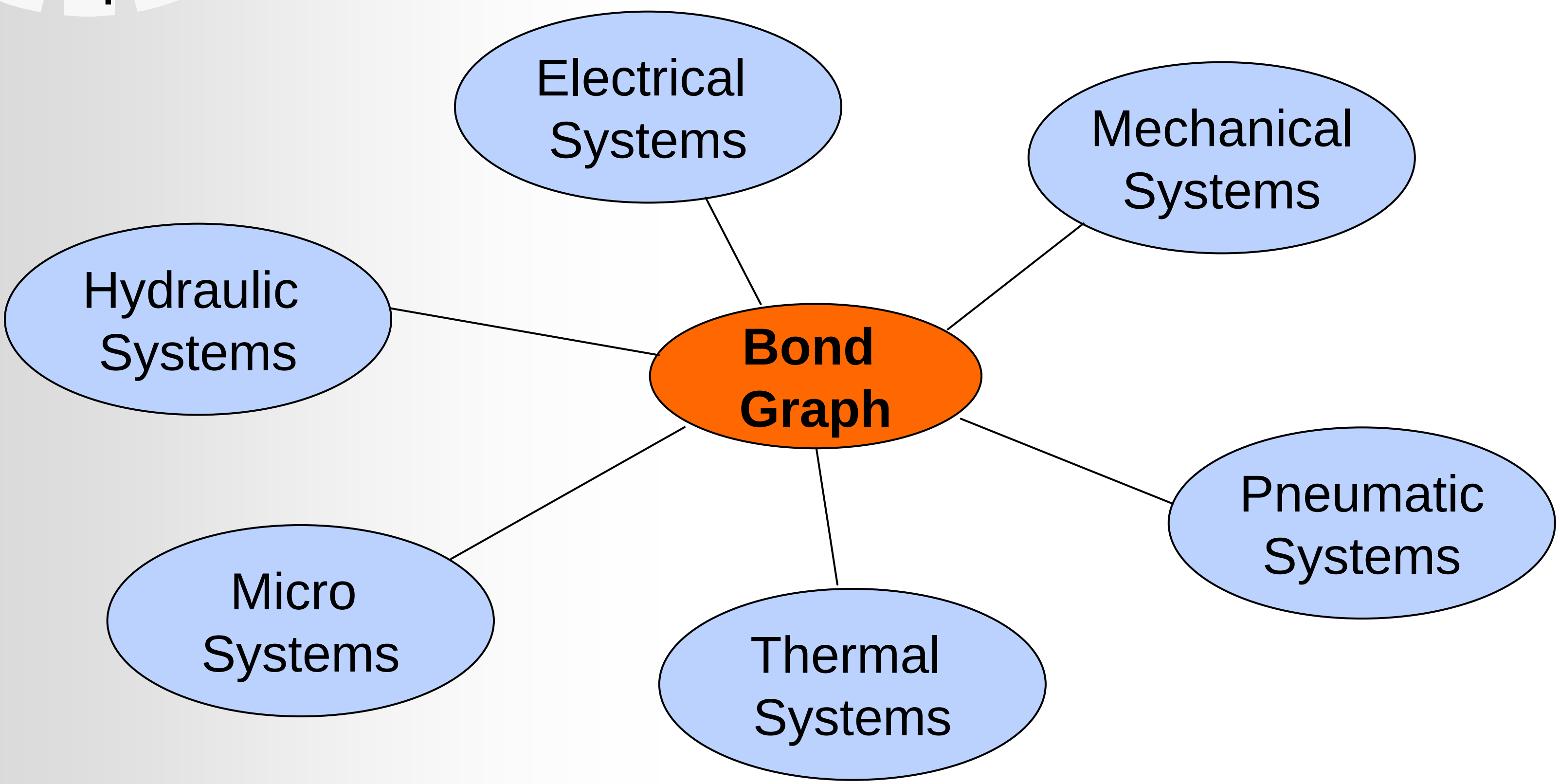


Unified Representation

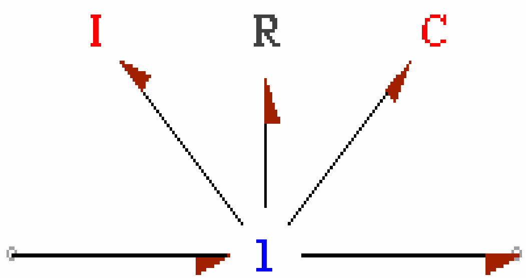
- Bond Graphs: integrate multi-domain physical systems modeling and control
- Consist of a succinct set of elements:
  - Se, Sf – Sources
  - C, I – storage; R – dissipation
  - TF, GY, 0, 1 – Junction structures exchange power
  - Power bonds and signal bonds
- Seamless interfacing with mixed-domain engineering systems through energy interaction

Advantages of Bond Graphs Modeling

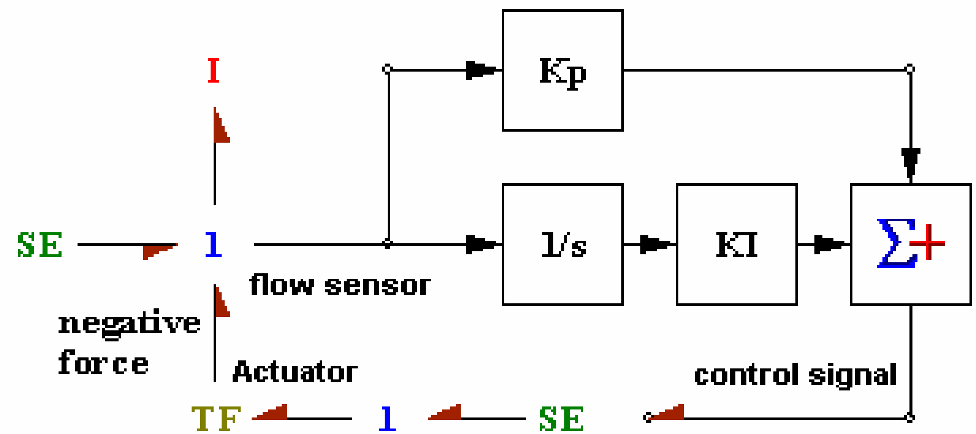
- Using bond graph, models of electrical, mechanical, magnetic, hydraulic, pneumatic, thermal, and other systems can be constructed and linked through common representation



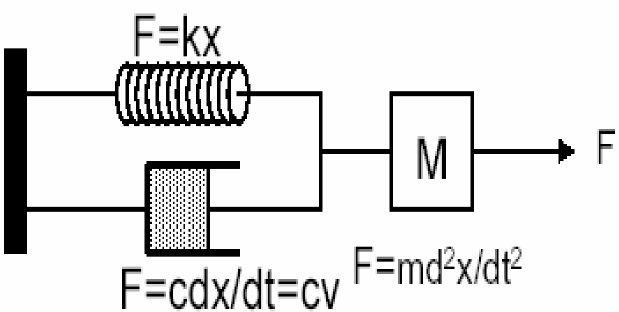
Unified Physical Systems Modeling and Control



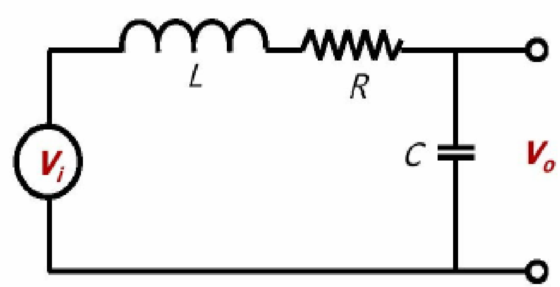
Bond Graphs



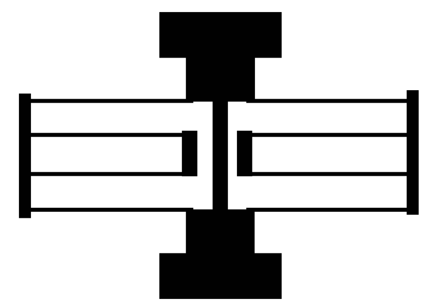
PI Controller



Mechanical Resonator



Electrical Resonator



MEM Resonator

Design in the Physical Domain

- Unify control systems with physical systems design using bond graphs
- Physical equivalence
  - A controlled system can be described as an equivalent physical system, provided that ideal actuators and sensors can be placed at any point in the system.
- IPMs (ideal physical models)
  - Separate representation with implementation
- Physical systems and controller co-design

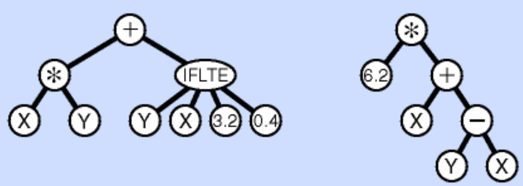
Biology-inspired Design Synthesis

- Experimental biology + computer analysis models = greater understanding of *staggering complexities of living organisms*
  - Pattern formation, morphogenesis
  - Cell signaling and regeneration
  - Synthetic developmental mechanisms

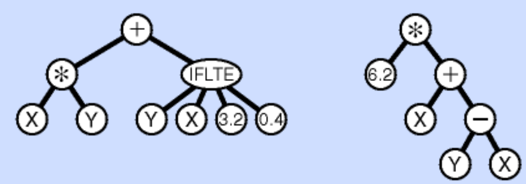
- Engineering computer models + biological developmental processes = *robust engineering design solutions*
  - Population set-based design
  - Combine stochastic and direct search mechanism
  - Various combination and association $\rightarrow$ Innovation
  - Parallel search (coevolution, multi-objective, configuration as well as parameterization)

Evolutionary Synthesis

- Low-lever building blocks ⇒ Given high-lever functionality
- Developmental Genetic Programming: strong capability for topologically open-ended search space



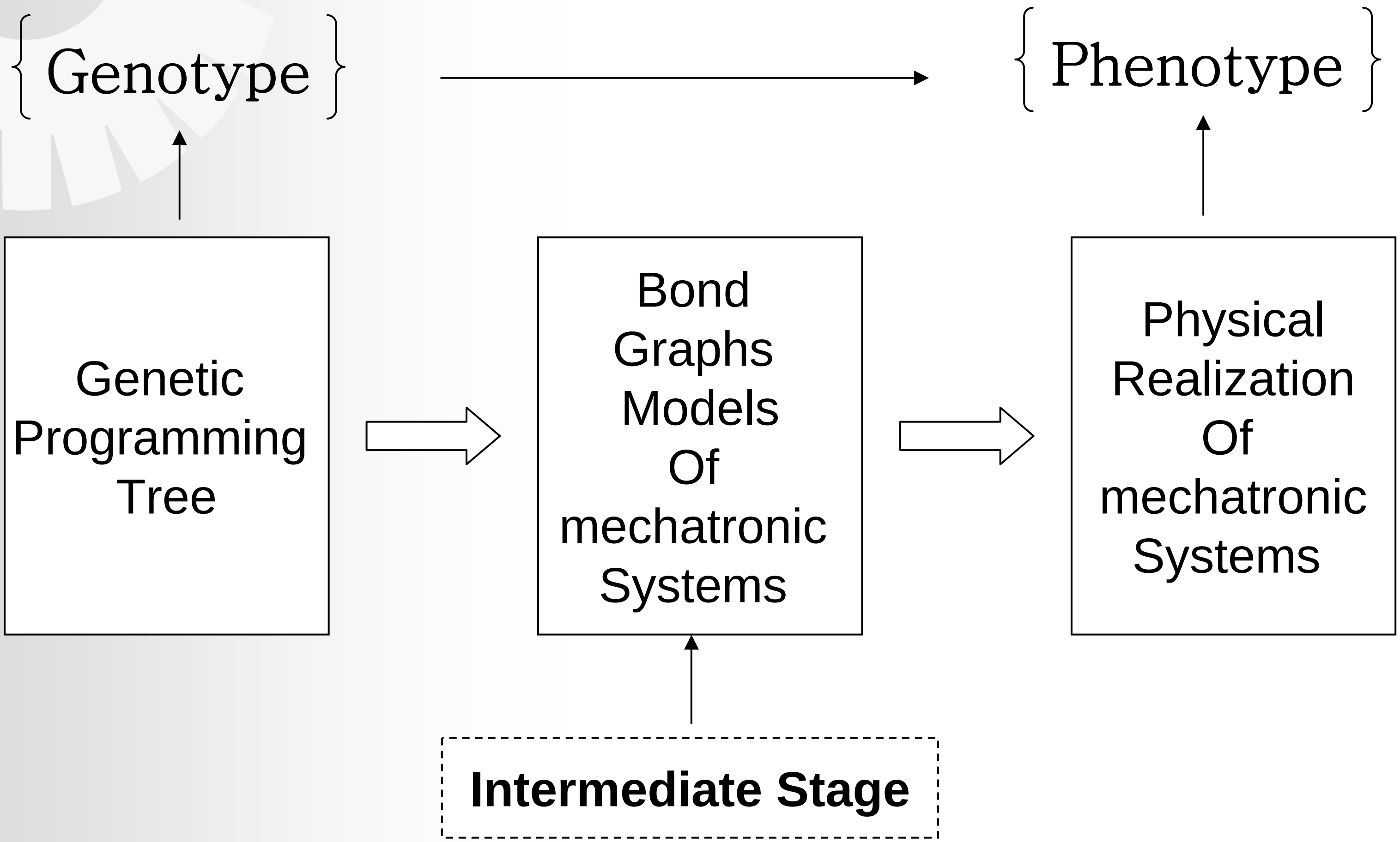
Crossover



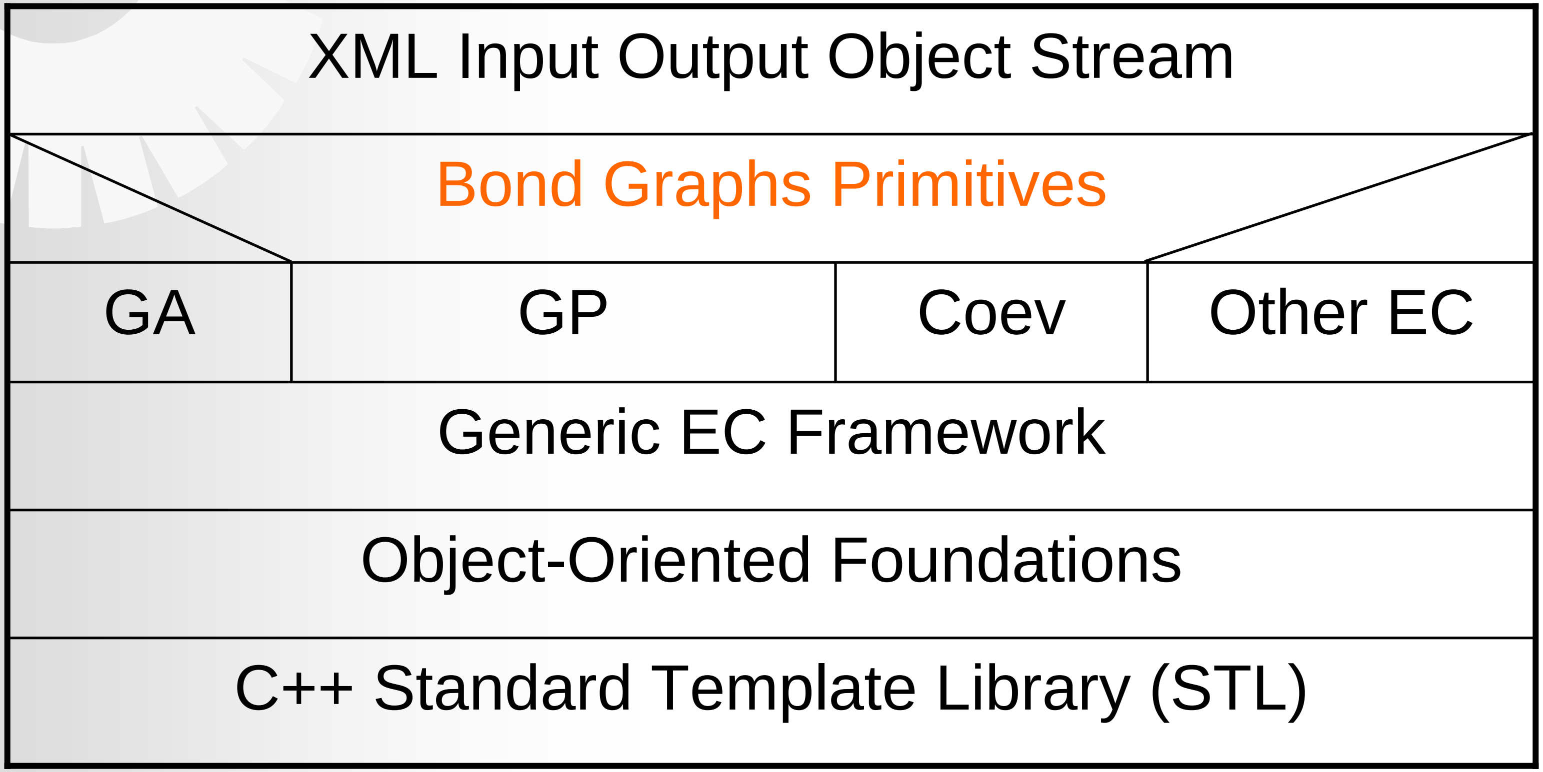
Mutation

- Encode bond graphs in GP tree to represent basic and modular building blocks

Genotype-Phenotype Mapping



Evolutionary Computation Platform



Open BEAGLE Evolutionary Computation Framework

Coevolutionary Model

GA Evolver
<SelectTournamentOp/>
<GA-MutationFlipBitStrOp/>
<GaEvalOp/>
<MigrationRandomRingOp/>
<StatsCalcFitnessSimpleOp/>
<TermMaxFitnessOp/>
<Coev-TermBroadcastOp/>
<MilestoneWriteOp/>

GP Evolver
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<GP-CrossoverConstrainedOp/>
<GP-MutationStandardConstrainedOp/>
<GP-MutationShrinkConstrainedOp/>
<GP-MutationSwapConstrainedOp/>
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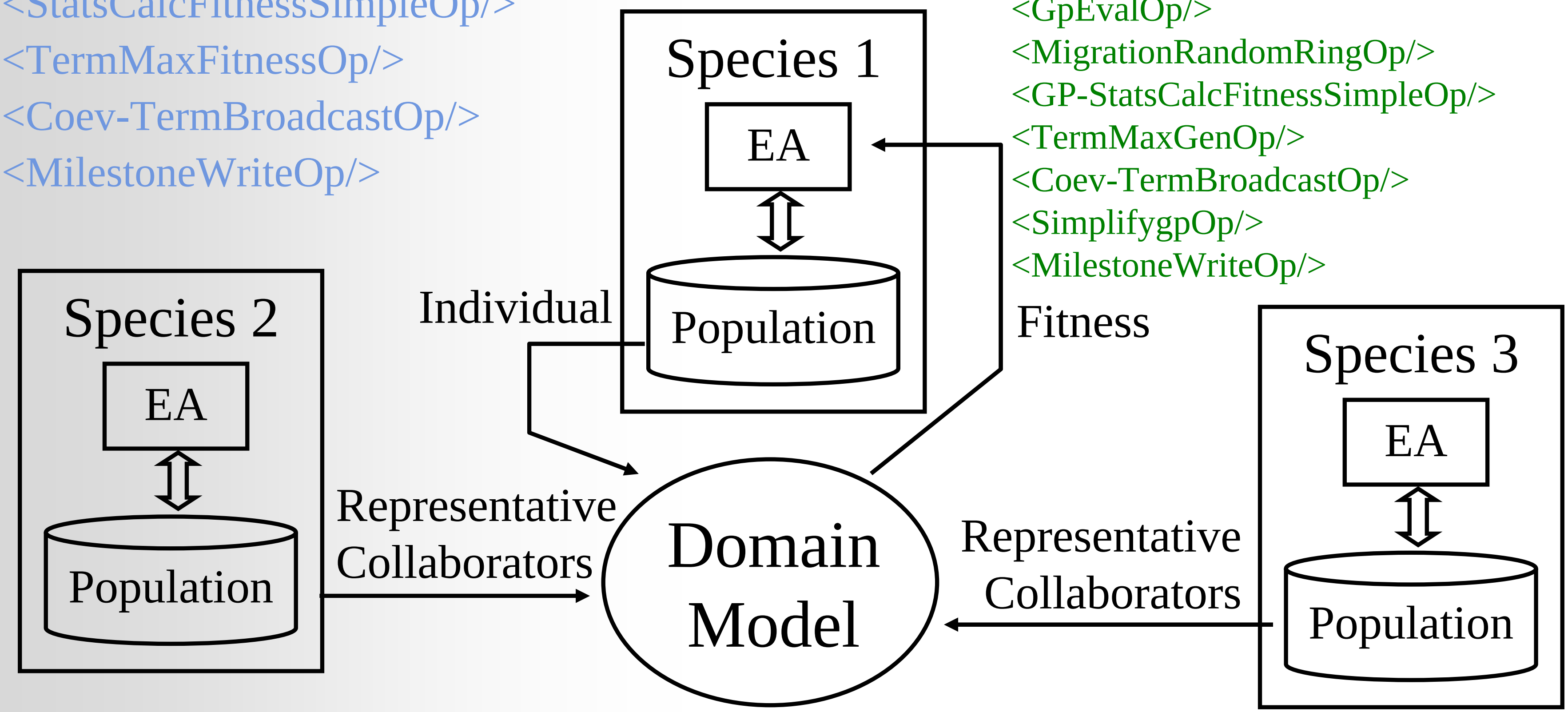
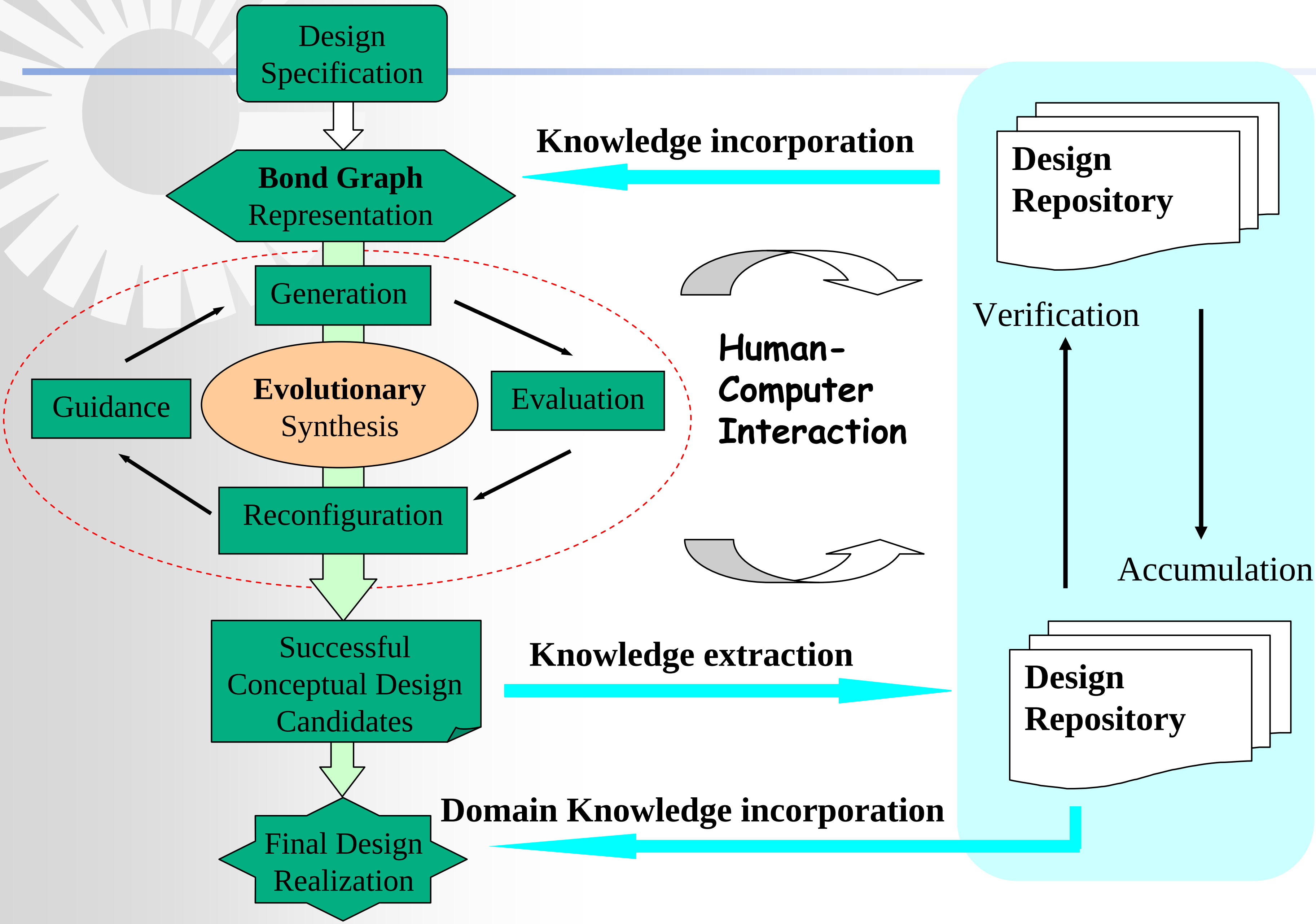


Design Process

- Customer needs → target design specification
  - QFD, curve fitting
- Design specification → concept generation
  - Problem decomposition, evolutionary synthesis (BG/GP)
  - Map GP tree to bond graphs
- Concept generation → concept selection
  - Map bond graphs to domain systems
  - Multi-engineering modeling and simulation
    - Dymola (Modelica), MATLAB, …
  - Current state of technology, feasibility, cost
- Rapid prototyping


Design Specification
Bond Graph Representation
Generation
Evolutionary Synthesis
Guidance
Evaluation
Reconfiguration
Successful Conceptual Design Candidates
Final Design Realization
Knowledge incorporation
Human-Computer Interaction
Knowledge extraction
Domain Knowledge incorporation
Design Repository
Verification
Accumulation
Design Repository

Case Studies

- **Vehicle Suspension**
  - Target: soft and hard double sky-hook physical system
  - Initial conditions: sprung mass, unsprung mass, tires, etc.
  - Goal: suspension system with choices of passive and active implementation

- **Micro-Electromechanical Systems (MEMS)**
  - Given a predefined high-level design specification
  - First step: automatically obtain a system-level description of a MEMS from an existing library of components
  - Second step: robust design optimization for layout synthesis

Quarter-car Suspension System Design

Immittance Matrix:

$$\begin{bmatrix} F_r \\ \dot{z}_s \end{bmatrix} = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix} \begin{bmatrix} \dot{z}_r \\ F_s \end{bmatrix}$$

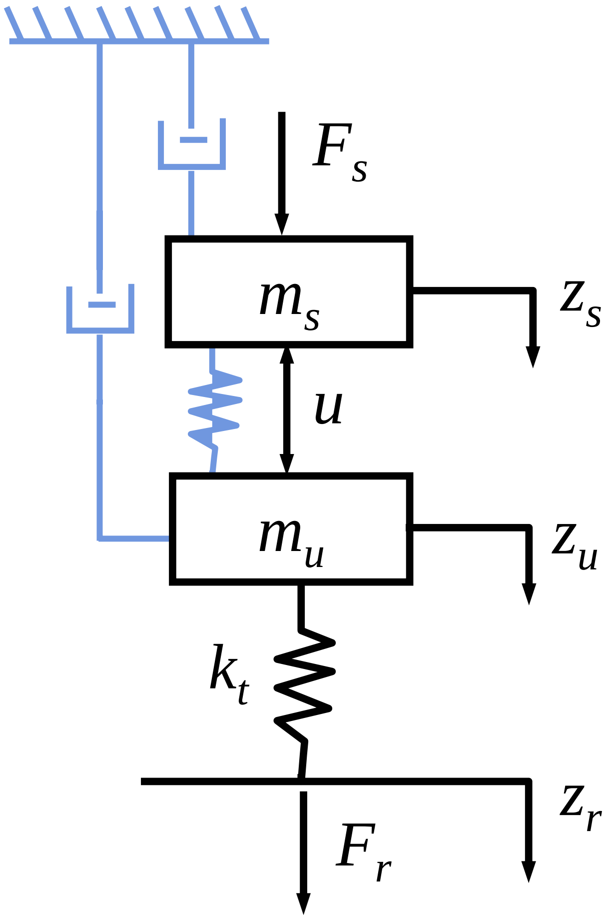
Target Specification:

Road disturbance: $\dot{Z}_s / \dot{Z}_r$

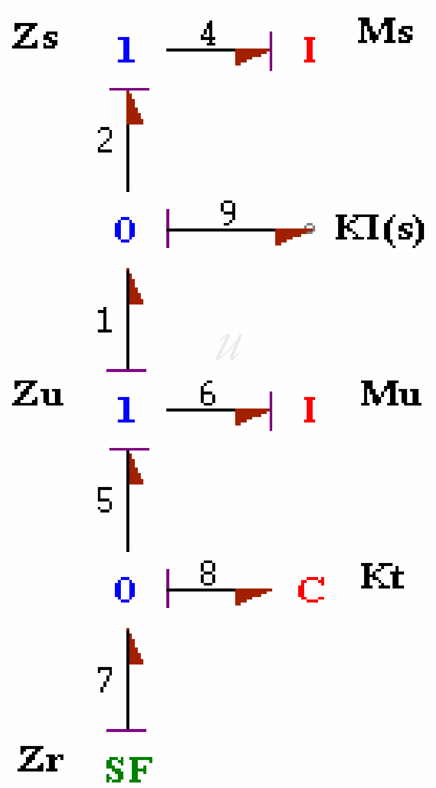
Soft double skyhook

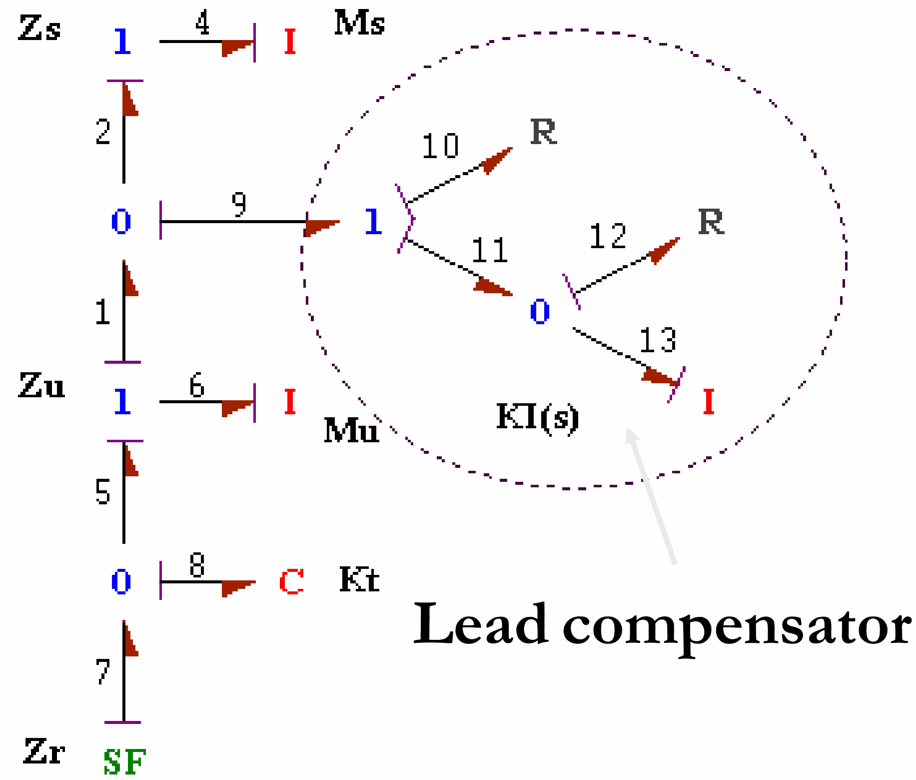
Load disturbance: $\dot{Z}_s / F_s$

Hard double skyhook



Road Disturbance Only





$$K_I(s) = \frac{u}{\dot{z}_u - \dot{z}_s}$$

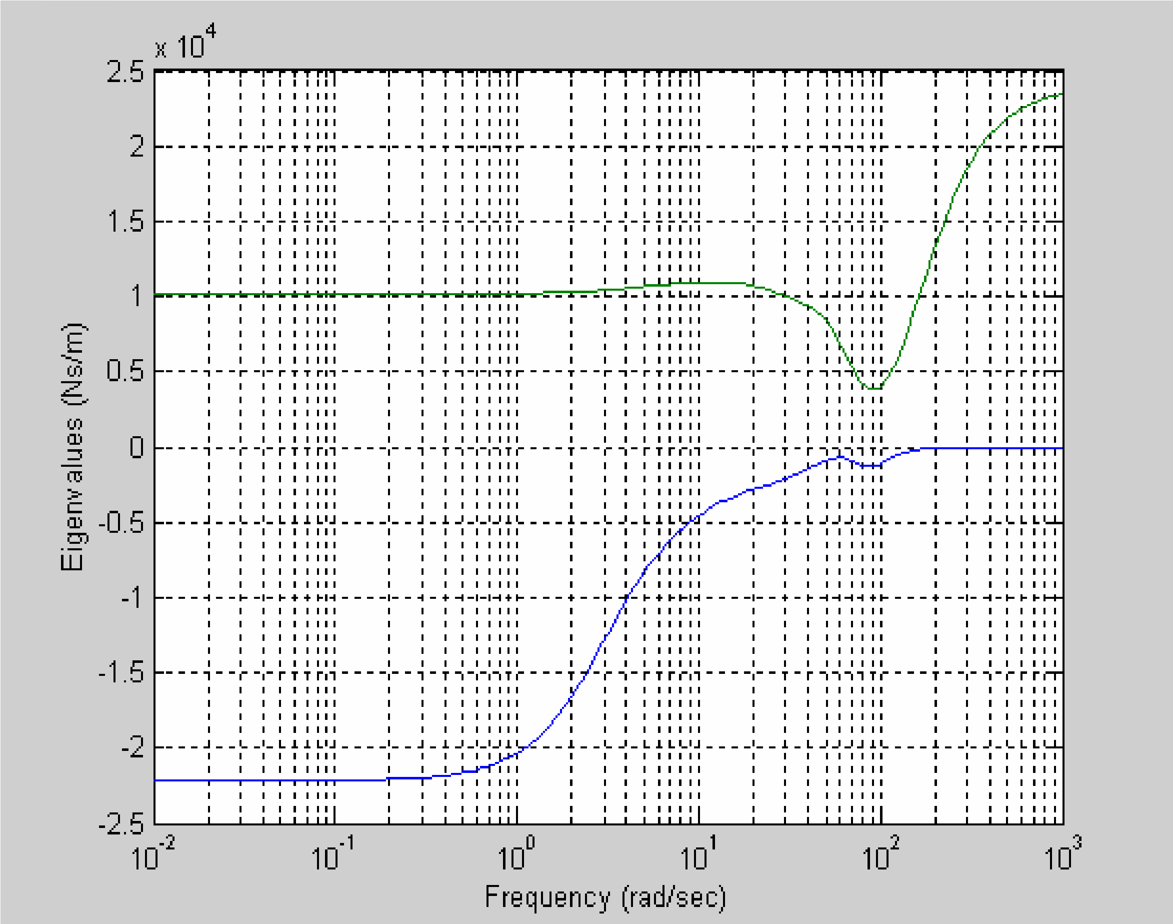
$$K_I(s) = \frac{1992\,(s + 4.53)}{s + 7.31}$$

Road and Load Disturbance - Specification

Soft specification:
ks=10000N/m
cs=4000 Nm/s
cu=2000 Nm/s

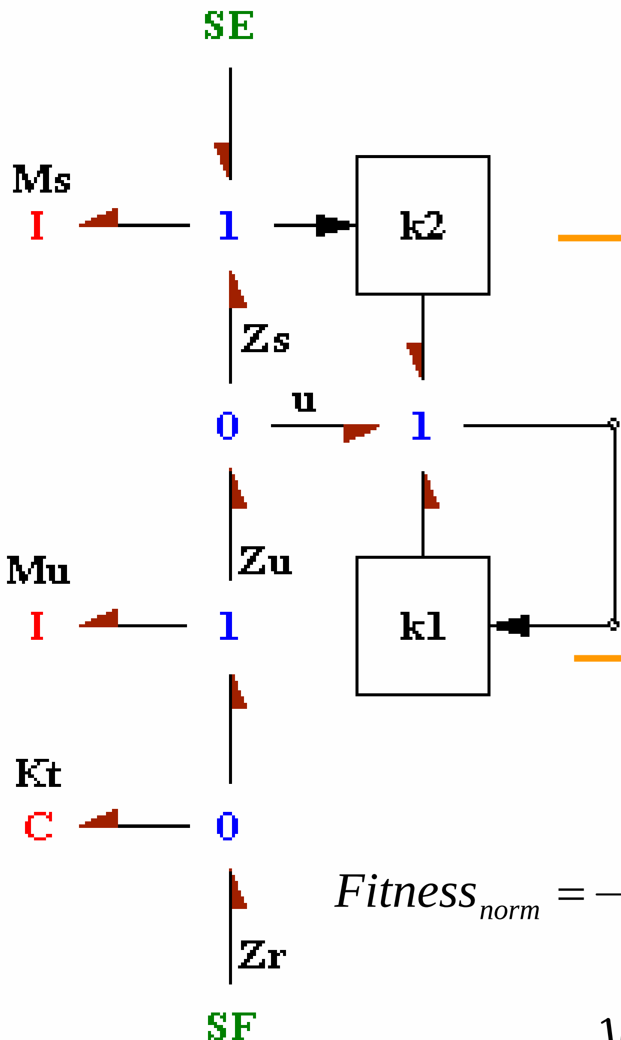
Hard specification:
ks = 150000 N/m
cs = 12000 Nm/s
cu = 6000 Nm/s

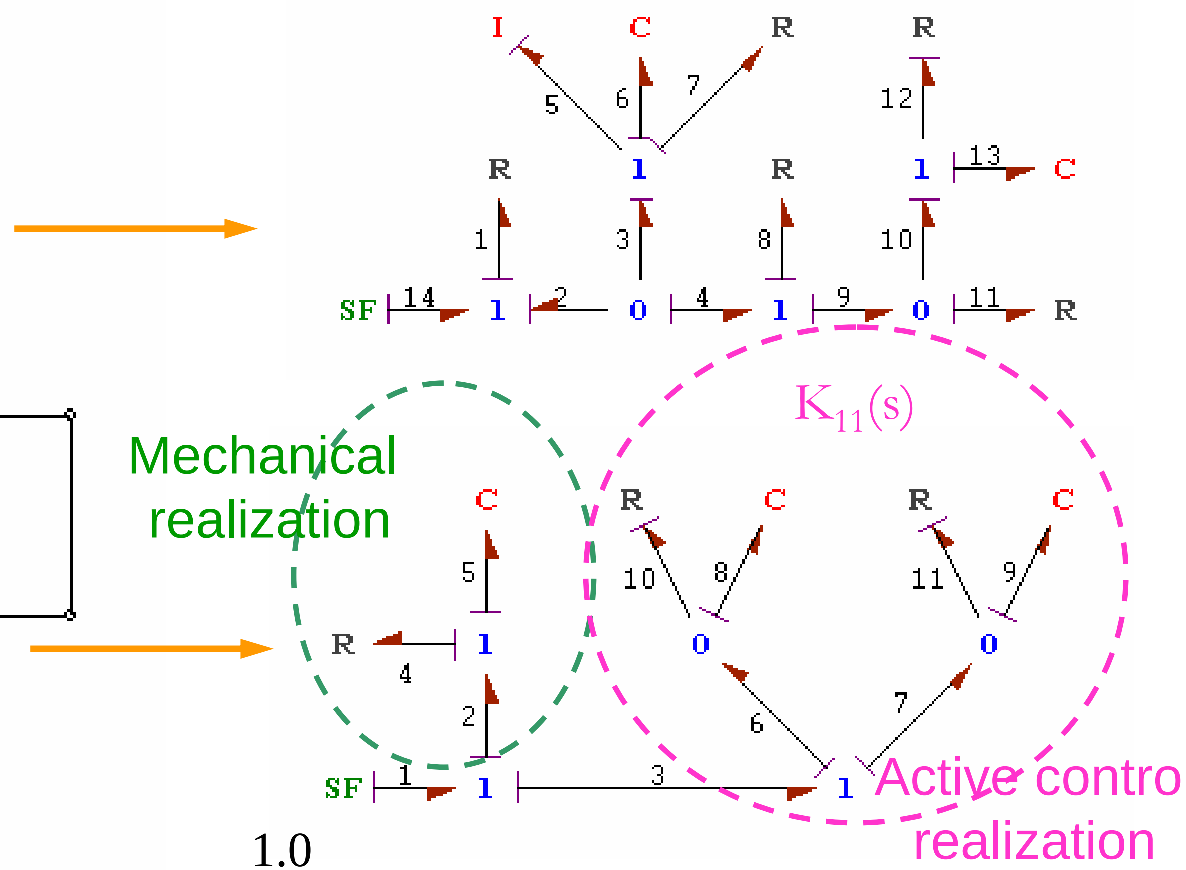
$$\begin{bmatrix} F_r \\ F_s \end{bmatrix} = \begin{bmatrix} Z_{11}(s) & Z_{12}(s) \\ Z_{21}(s) & Z_{22}(s) \end{bmatrix} \begin{bmatrix} \dot{z}_r \\ \dot{z}_s \end{bmatrix}$$



Eigenvalues of *(Z+Z*)(jω)* for the desired quarter car model

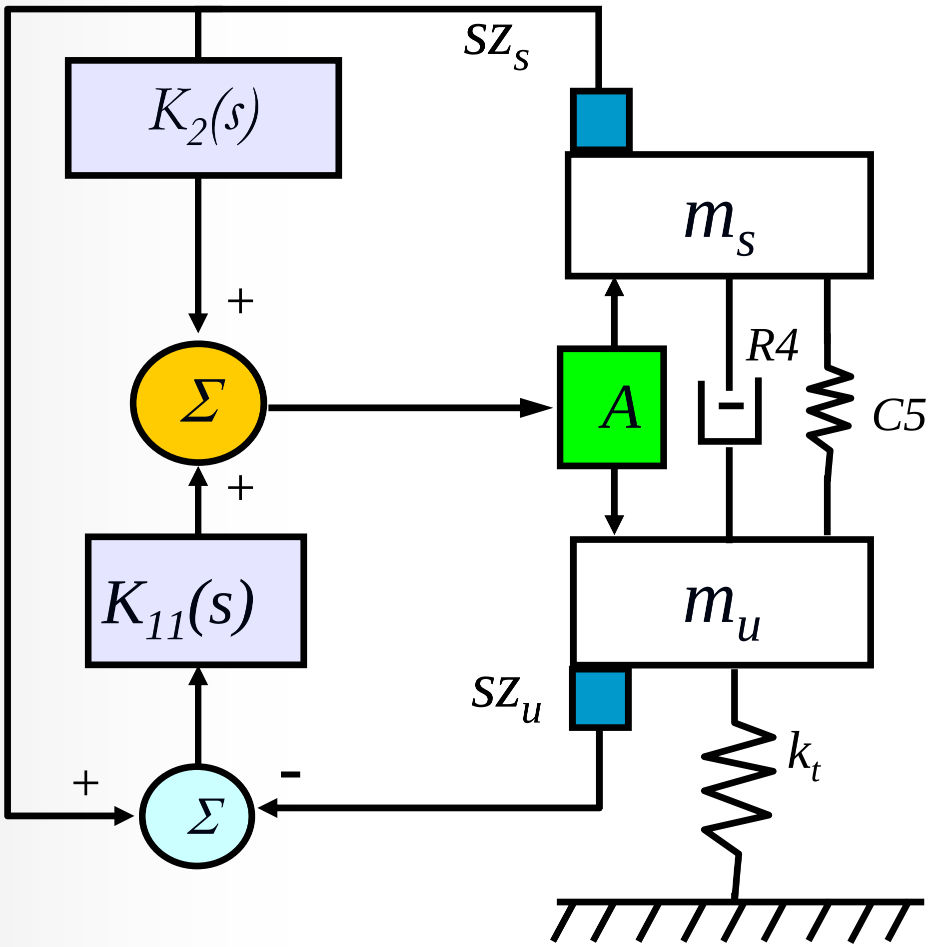
Co-evolution of Controllers



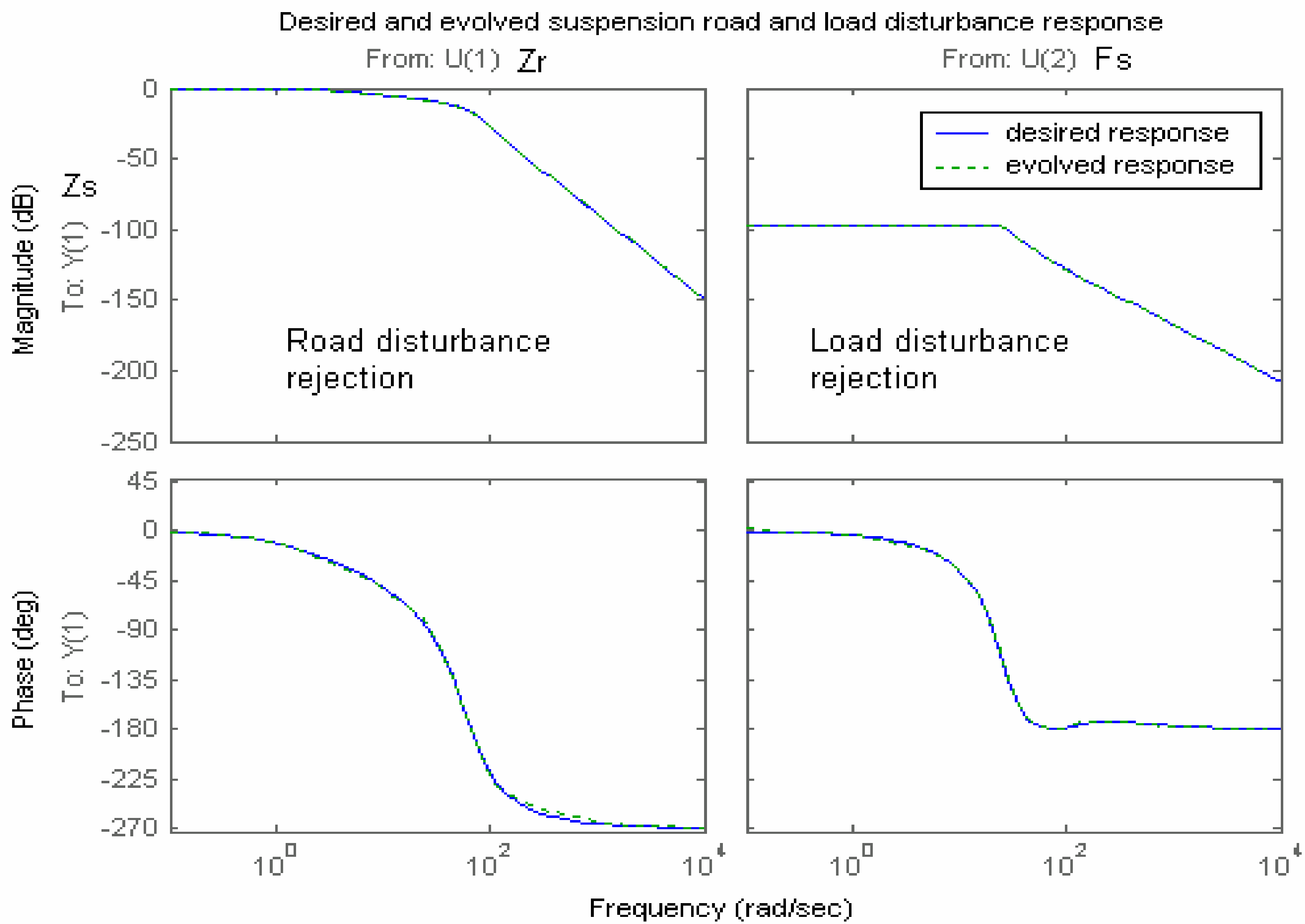


$$Fitness_{norm} = \frac{1.0}{\sqrt{\frac{\sum_{i=1}^{n}(err_1 + err_2)^2}{n}} + 1.0}$$

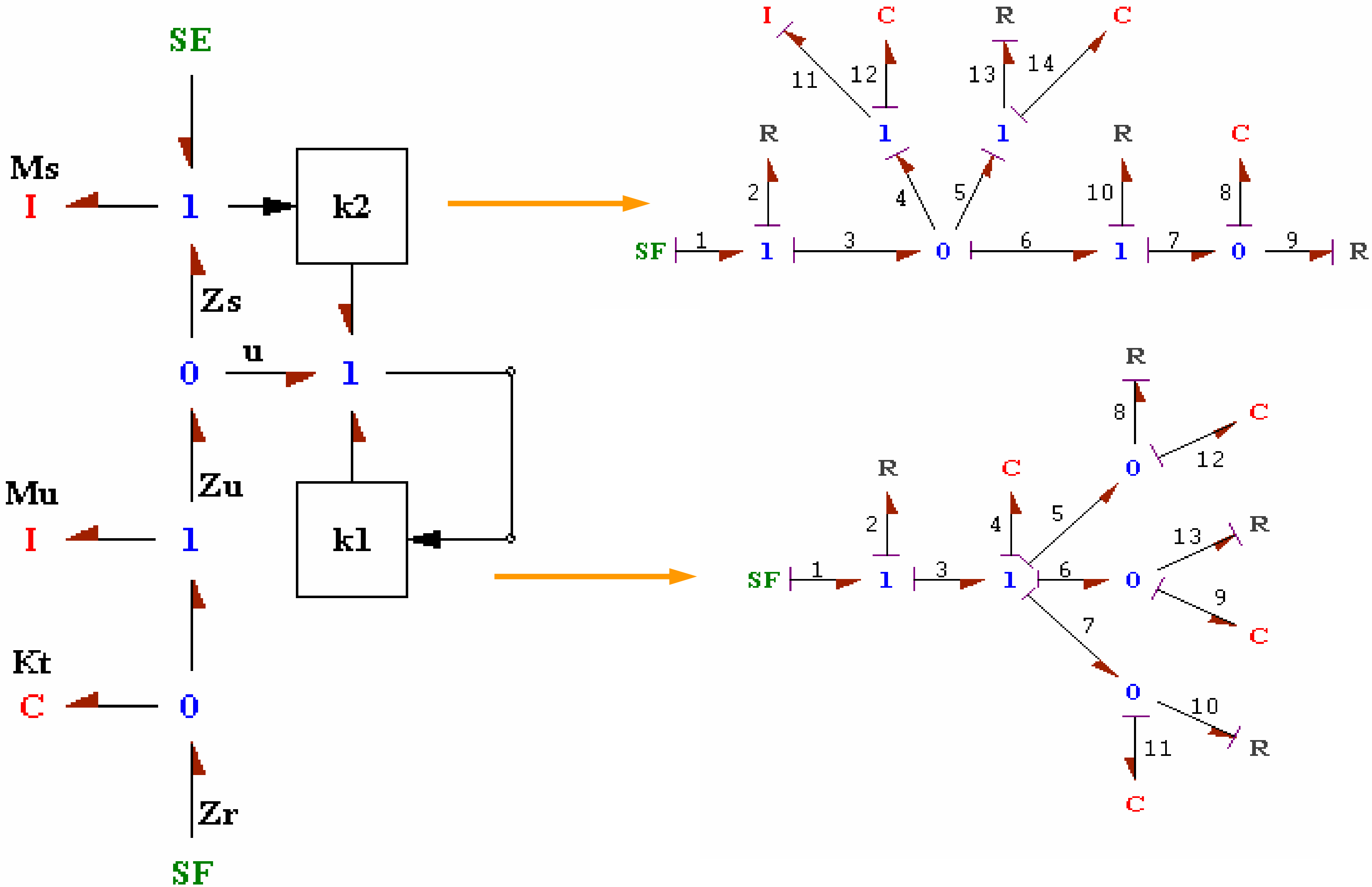
Physical Realization



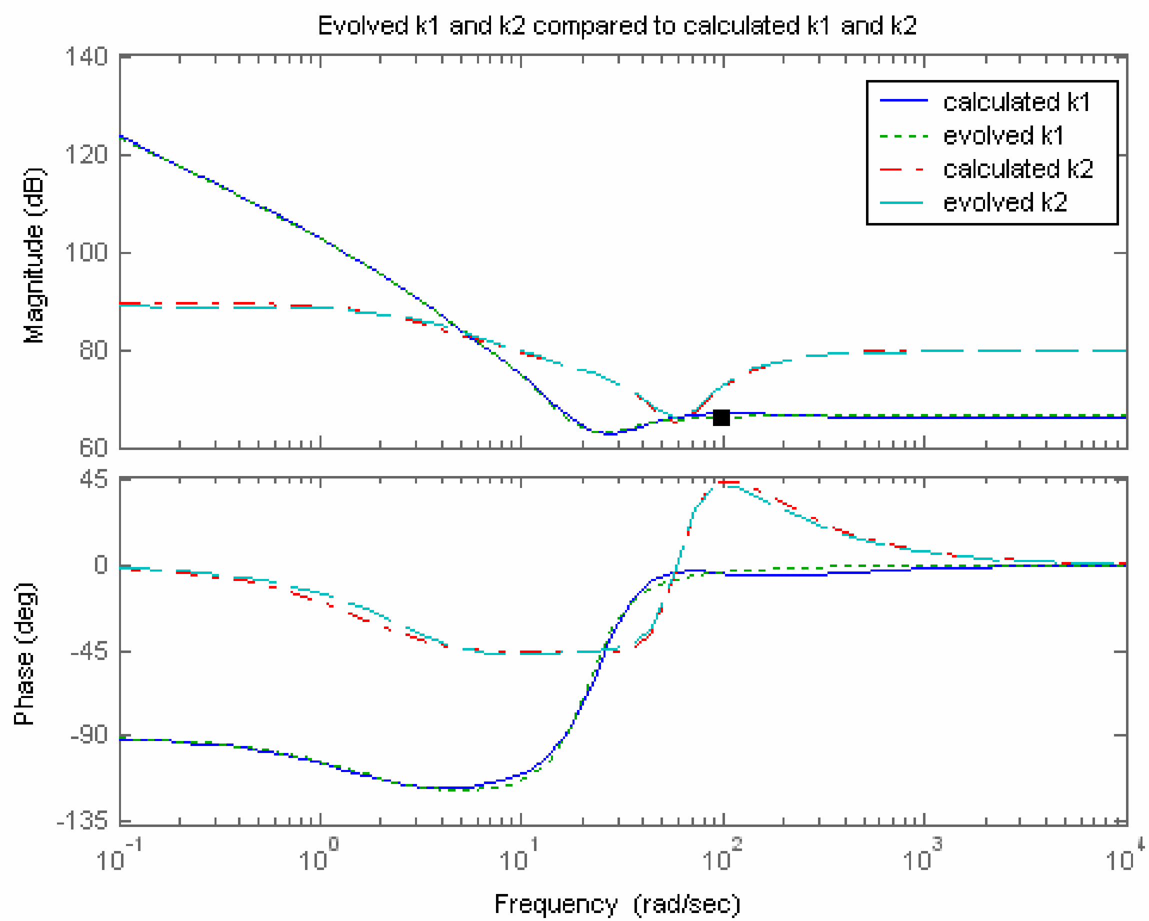
Frequency Domain Performance



Another Coevolved Design

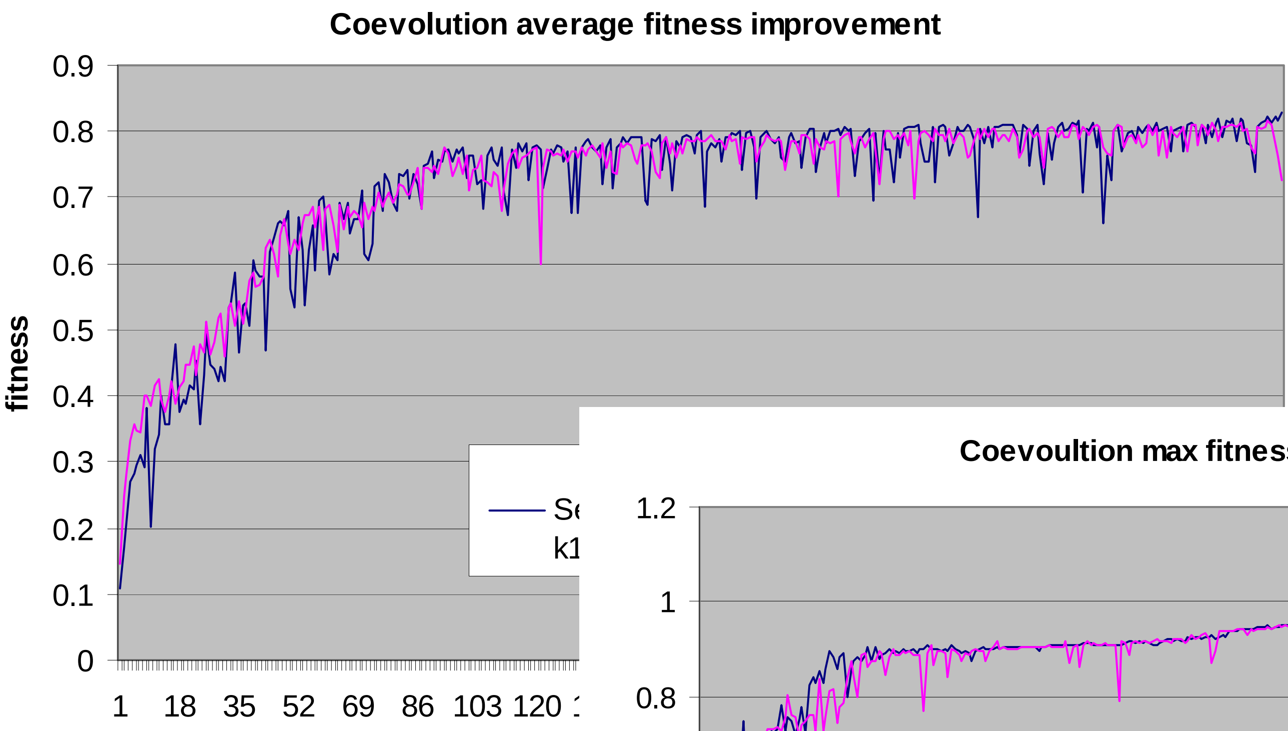


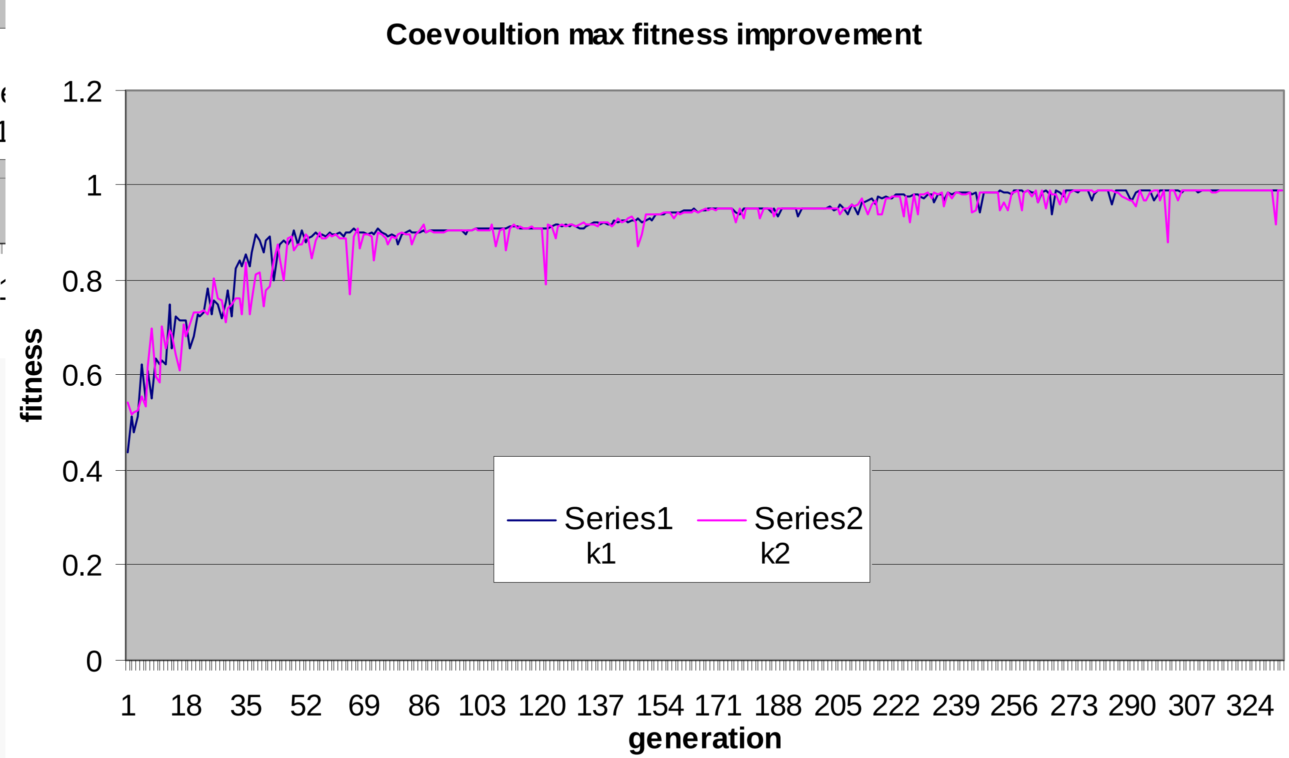
Compare with Manual Calculation



Advantages: less complexity of controllers, more design options,
Higher energy efficiency, physical insight for implementations

CO-EC Experimental Analysis





MEMS Design Automation

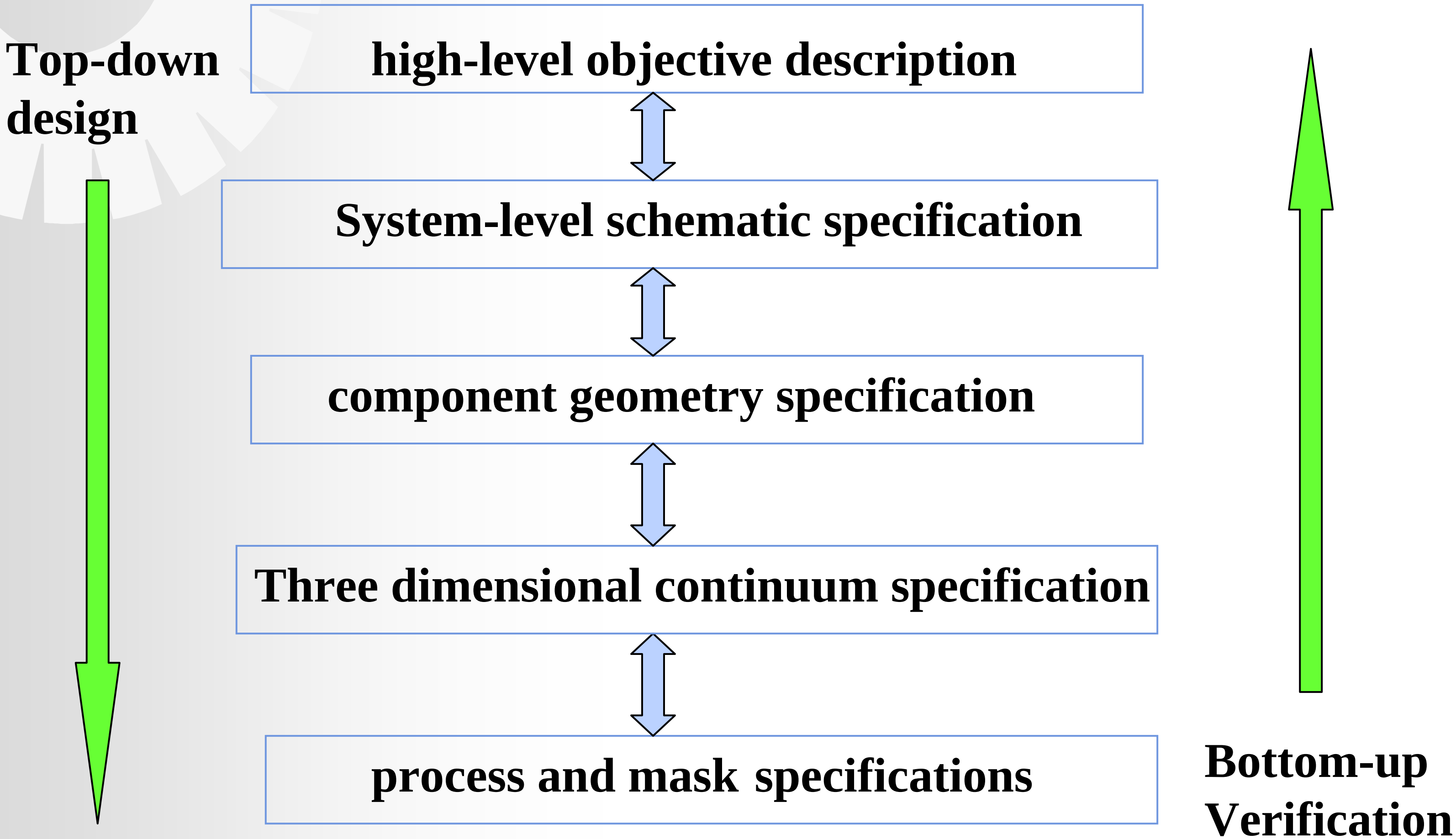
Promises:

- MEMS evolves from microelectronics
- Strong relationship exists between Microsystems and very large scale integration (VLSI)
- VLSI has highly structured automated design synthesis methods (EDA)
- This strongly encourage research on structured design methods for MEMS

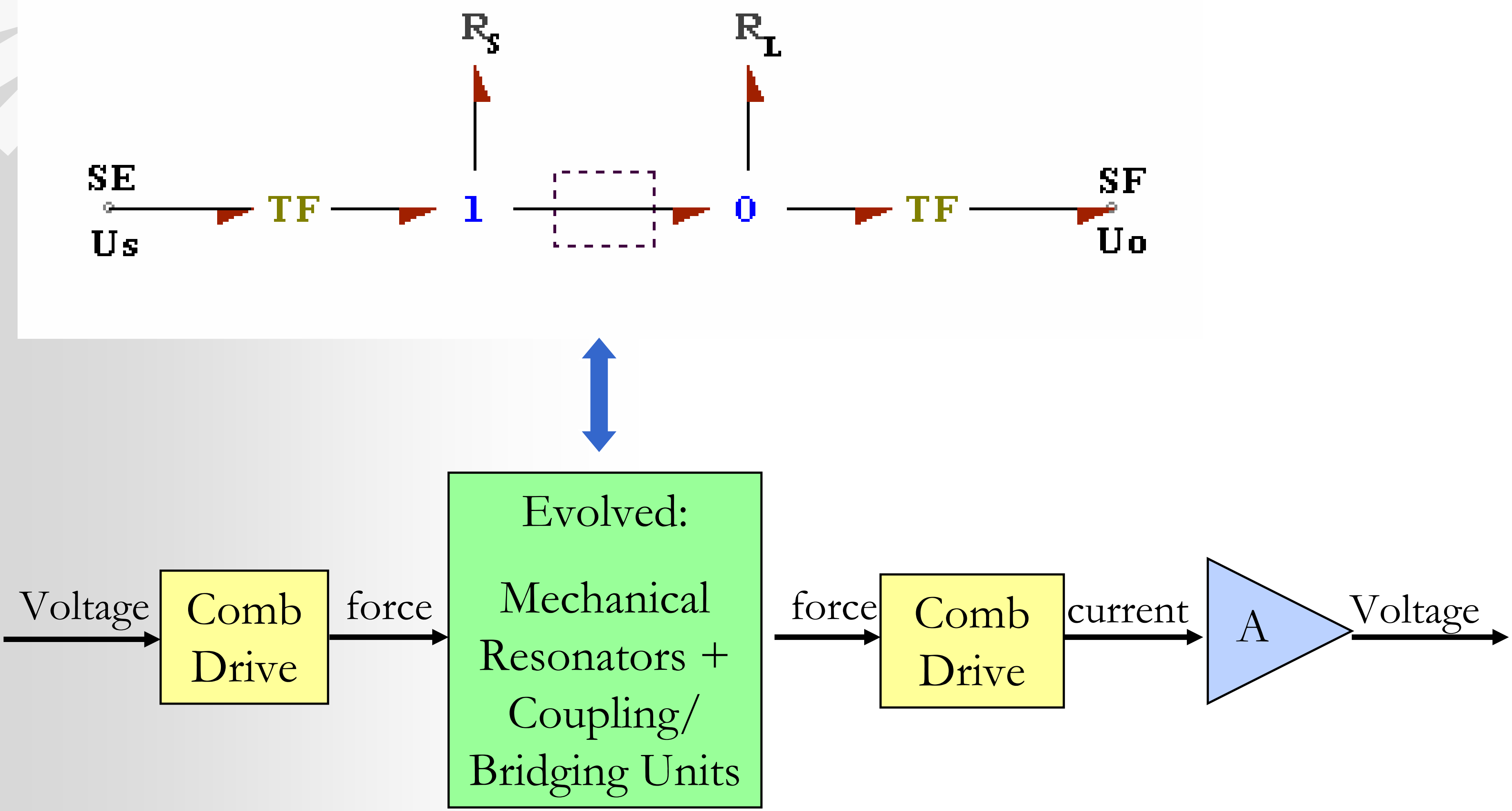
Challenges:

- Operates in multiple coupled energy domains
- Impose many design constraints that are not well-defined
- Diverse in function/design and fabrication/process

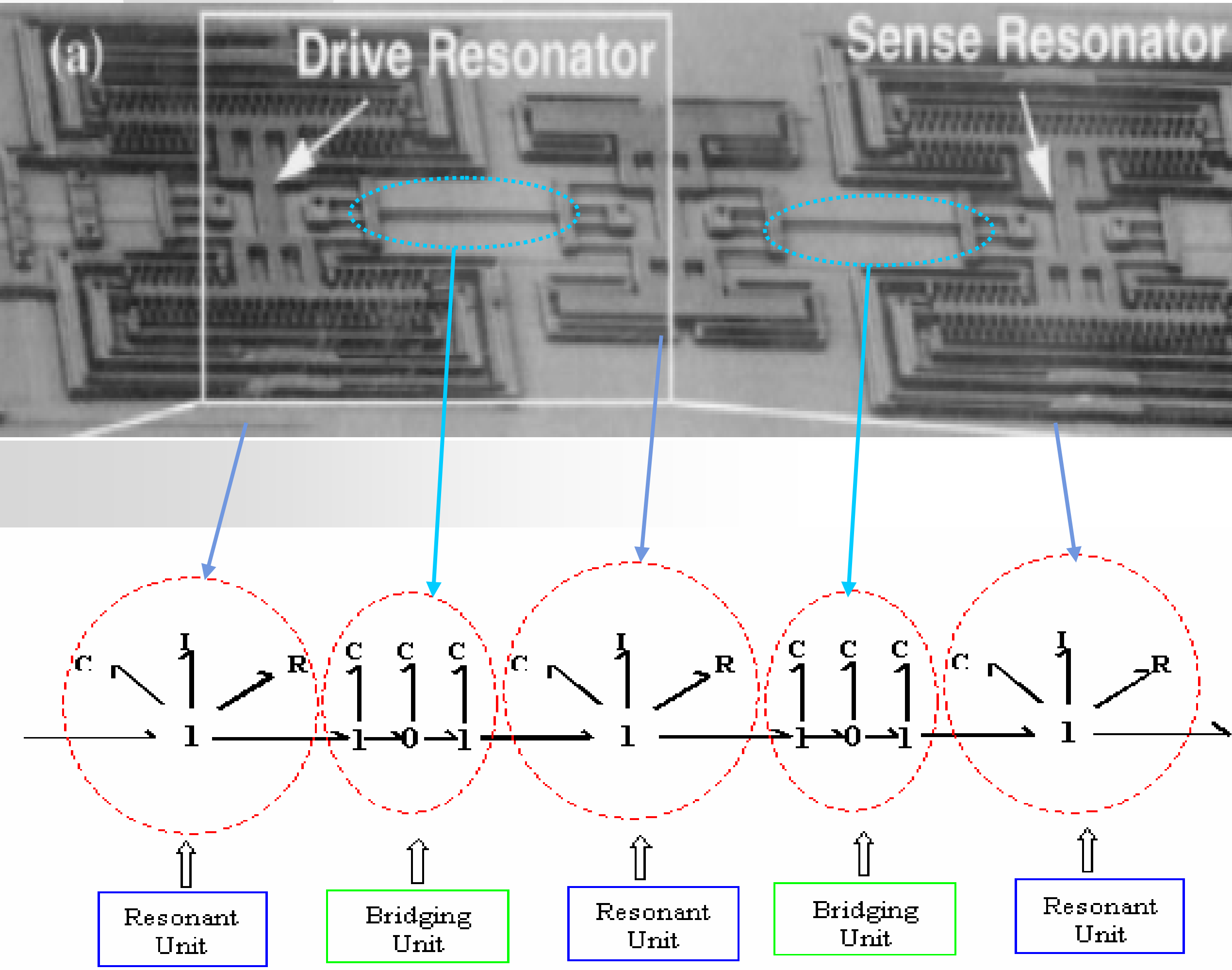
Evolutionary Hierarchical Synthesis of MEMS



High-level Objective Description

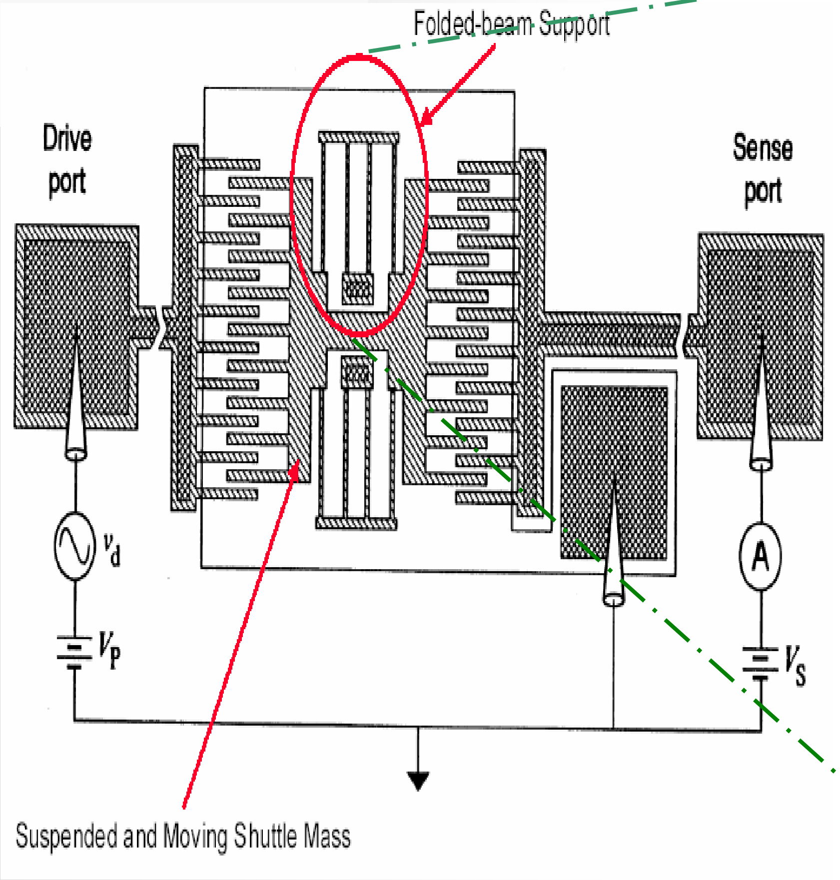


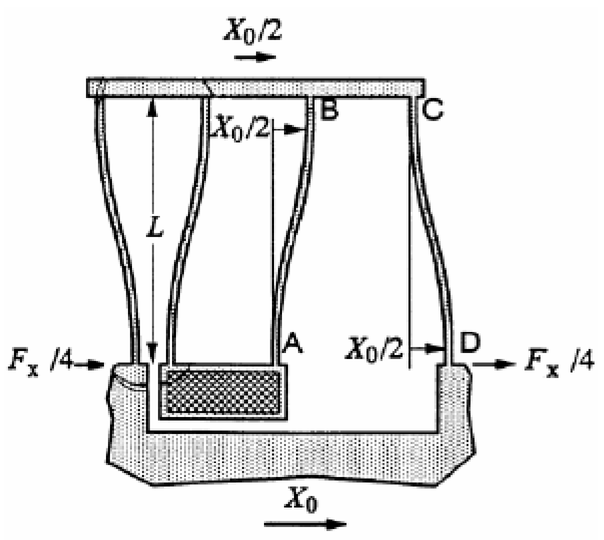
System-level MEMS Synthesis



Parameter	Value	Unit
C_{x1}	0.0081	F
L_{x1}	0.652	H
R_{x1}	0.139	Ω
C_{ox1}	0.00002737	F
C_{x2}	0.0046	F
L_{x2}	1.589	H
R_{x2}	169.6447	Ω
C_{ox2}	10	F
C_{x3}	0.0024	F
L_{x3}	0.007	H
R_{x3}	0.049	Ω

MEMS Second Level Layout Synthesis

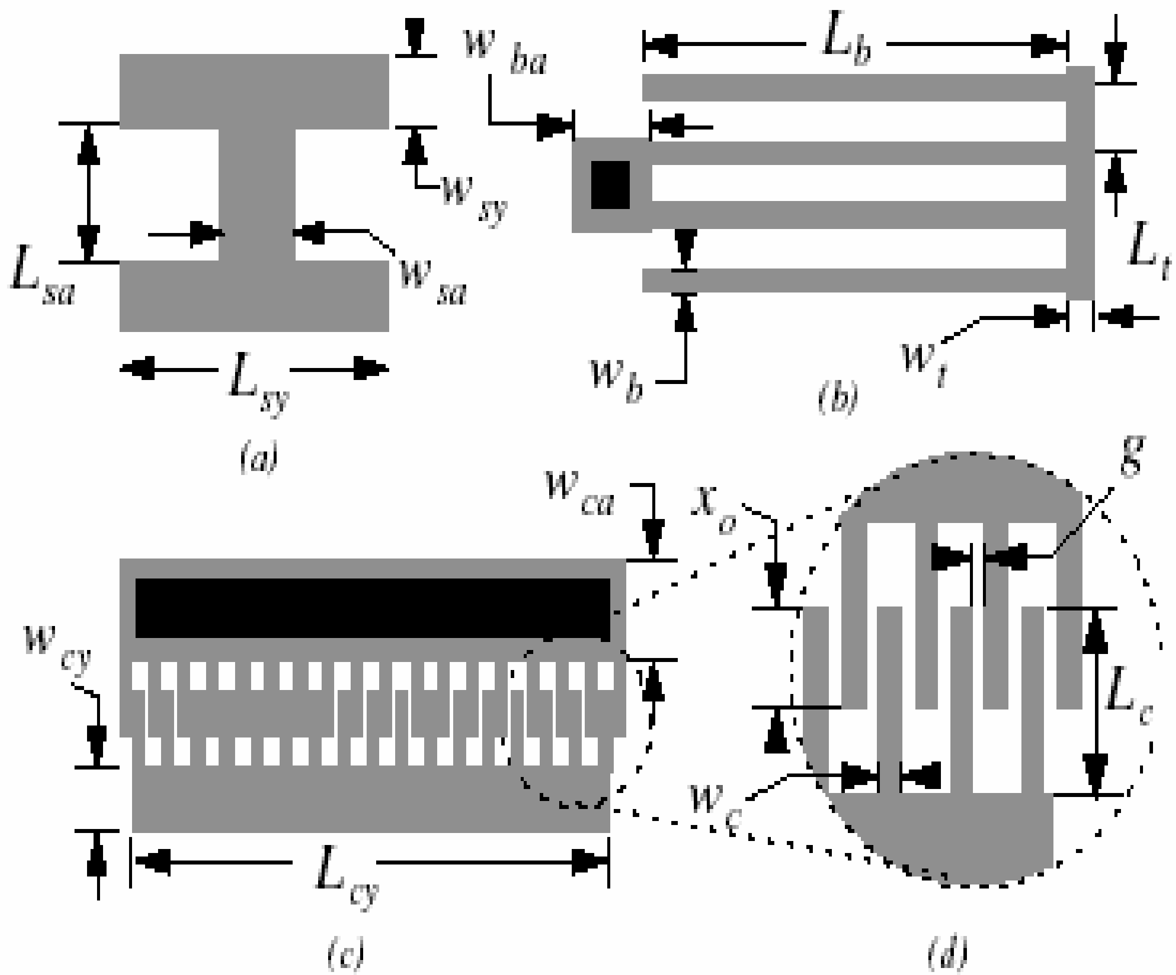




$$k_x = \frac{2Ehw^3}{L^3}$$

$$k_z = \frac{2Ewh^3}{L^3}$$

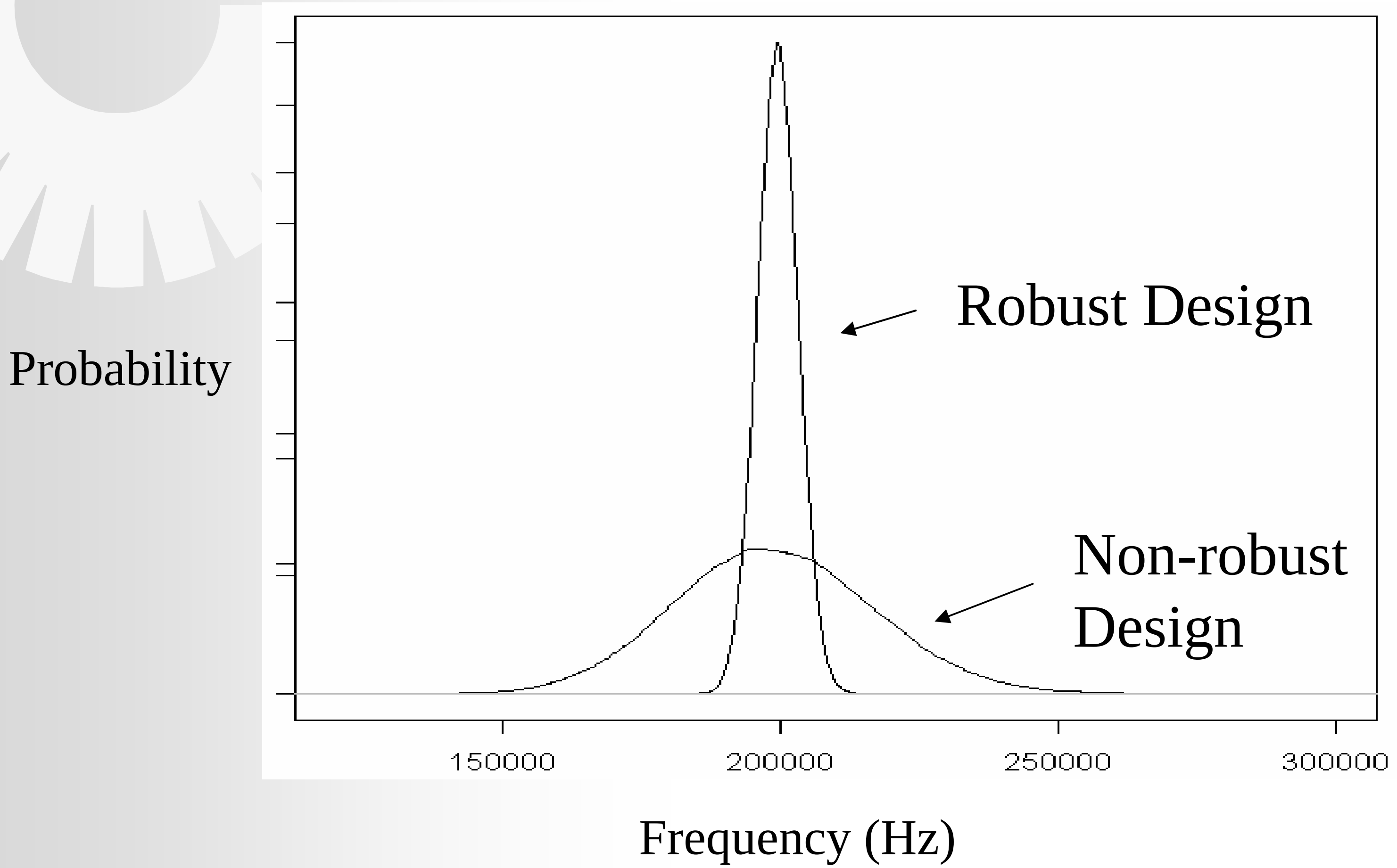
Design Variables and Constraints



15 design variables

8 design constraints, both linear and nonlinear ones.

Robust Design Results – Second Level



Fan, Z., Wang, J., Goodman, E. D. (2005) “An Evolutionary Approach for Robust Layout Synthesis of MEMS,” 2005 IEEE / ASME International Conference on Advanced Intelligent Mechatronics, Monterey, California, USA. July 24-28, 2005.

Summary

- An integrated, cross-domain, and open-ended mechatronics design automation methodology with BG / GP
- Horizontal integration: at the higher design level, use bond graphs modeling to integrate design representation across domains, integrate control systems with physical systems design.
- Vertical integration: design in the physical domain, consider physical system configurations and controller strategies simultaneously.
- Creative and alternative solutions: combine low-level building blocks or features to achieve given high-level functionality by evolutionary computation to balance exploration and exploitation.

Collaborating With Industry

"*If you can touch the sky, yet stand firmly on the ground, you are a giant*."

– Shuzi Yang

- Touch the sky
  - Explore aggressively the academic frontier
  - Challenge courageously research issues that are of great novelty, inspiration, significance, and even great risk
- Stand on the ground
  - Make sure that research results are applicable to industry and/or have beneficial impacts on society

Future Prospect

- Concurrent hierarchical product design
  - hardware and software co-design
  - body and brain co-evolution
  - Modular plug-n-play, self-organization
- Computational efficiency
  - Parallel and distributed computing
  - Mixed optimization techniques
- Applications
  - Automotive
  - Robotics
  - MEMS, NEMS

Questions?