Integrated and Innovative Design
Automation of Mechatronic Systems

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Outline

- Motivation
- Related Work
- Methodology
  - Unified Representation
  - Evolutionary Synthesis
- Case studies
  - Vehicle Suspension
  - MEMS
- Summary
A typical Mechatronic System
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

- **Address** unified representation for multidisciplinary product/system designs.

- **Automate** the design search process using coevolutionary synthesis mechanism.

- **Assist** 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

Evolutionary Computation

Physical Principles
- Flows: Energy, Material, Signal

Repository of Design Primitives
- Classifying Schemes: Conceptual, Physical

Unified Representation

Analysis
- Stability, Performance, Robustness, Simulation, Visualization, Prototyping

Requirements, Preferences, Constraints

Graphical User Interface
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 → 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

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

Crossover

Mutation
Genotype-Phenotype Mapping

Genotype

Genetic Programming Tree

Bond Graphs Models Of mechatronic Systems

Intermediate Stage

Phenotype

Physical Realization Of mechatronic Systems
Evolutionary Computation Platform

XML Input Output Object Stream

Bond Graphs Primitives

GA    GP    Coev    Other EC

Generic EC Framework

Object-Oriented Foundations

C++ Standard Template Library (STL)

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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- `<MilestoneWriteOp/>`
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

Evaluation

Reconfiguration

Successful Conceptual Design Candidates

Final Design Realization

Knowledge incorporation

Human-Computer Interaction

Knowledge extraction

Design Repository

Verification

Accumulation

Design Repository

Domain Knowledge incorporation

Guidance
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:
Soft double skyhook

Load disturbance:
Hard double skyhook
Road Disturbance Only

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

\[ K_I(s) = \frac{1992 (s + 4.53)}{s + 7.31} \]
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 = 120000 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 \((Z+Z^*)(j\omega)\) for the desired quarter car model
Co-evolution of Controllers

\[ \text{Fitness}_{\text{norm}} = \frac{1.0}{\sqrt{\frac{\sum_{i=1}^{n}(err_1 + err_2)^2}{n}} + 1.0} \]
Physical Realization

\[ K_{2}(s) \]
\[ K_{11}(s) \]
\[ \Sigma \]
\[ m_s \]
\[ m_u \]
\[ R4 \]
\[ C5 \]
\[ k_t \]
Frequency Domain Performance

Desired and evolved suspension road and load disturbance response

From: $U(1) \quad Z_r$

Road disturbance rejection

From: $U(2) \quad F_s$

Load disturbance rejection

Desired response
Evolved response

Frequency (rad/sec)

Magnitude (dB)

Phase (deg)
Another Coevolved Design
Advantages: less complexity of controllers, more design options, Higher energy efficiency, physical insight for implementations
CO-EC Experimental Analysis

Coevolution average fitness improvement

Coevolution max fitness improvement

Series1  Series2
k1                  k2
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

Top-down design

- high-level objective description
- System-level schematic specification
- component geometry specification
- Three dimensional continuum specification
- process and mask specifications

Bottom-up Verification
High-level Objective Description

Evolved: Mechanical Resonators + Coupling/Bridging Units
System-level MEMS Synthesis

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MEMS Second Level Layout Synthesis

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

$$k_z = \frac{2Ew_ih^3}{L^3}$$
Design Variables and Constraints

15 design variables
8 design constraints, both linear and nonlinear ones.
Robust Design Results – Second Level

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?