Computational Design Synthesis Across Disciplines

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Drivers for Computer-Aided Product Development

• shorter design cycle time and reduced time-to-market
• reduced total cost
• improved quality

• increased market segments and design variants
• increased product complexity (multidisciplinarity, scale, …)
• increased importance of innovation

➢ Develop new tools to help engineers produce better designs faster.
➢ Use methods and tools to better understand engineering design synthesis.
Outline

Introduction and Motivation

A Computational Synthesis Framework

Structural Synthesis

MEMS (Microsystems) Synthesis

Mechanical Synthesis

Future Challenges
Synthesis and Analysis

Synthesis

The combination of fundamental components, or building blocks, to produce a unified and often complex system that efficiently exhibits at least the required behavior, in a novel way.

Analysis / Simulation

Resolution of a system into its elements and the study of these elements and their interrelationships.

The construction of a mathematical model to reproduce the effects (behavior) of a phenomenon, system, or process, using a computer.
Computers in Product Development

CAD  

Analysis  

Computational Optimization  

Computational Synthesis

design space

performance space

design space

performance space

design space

performance space

design space

performance space
Current Approaches to Design Automation

- **parametric and associative modeling**
  - automated geometry modification
  - use of “masterparts” and design tables to quickly switch between design alternatives

- **scripting**
  - automated geometry generation from scratch of design alternatives

- **knowledge-based engineering (KBE)**
  - model experts knowledge as design rules to generate parts
  - fully automate, routine, repetitive and time consuming tasks
  - roots in AI and problem solving
Computational Design Synthesis Goals

- computationally describe design spaces and languages
- reason from fundamental engineering knowledge and physics-based simulation
- generate a range of both known and new design alternatives
- generate “good” and optimal designs
- expand perceived design and performance limits
- spark creativity and innovation

structural systems  MEMS (microsystems)  mechanical systems
Computational Design Synthesis Framework

1. **Design Requirements**
2. **Model (CAD/CAE)**
3. **Generate**
4. **Select + Direct**
5. **Evaluate**
6. **Alternative Solutions**
Engineering Design Grammars

- analogy to natural languages
- uses building blocks (vocabulary)
- encodes “logic” of design (rules), e.g. fundamental principles, design rules, strategies and best-practice
- bottom-up design generation
- many types of representations
  - shape grammars
  - graph grammars…
- also capable of design validation
- engineering design requires simulation of the physical world to establish design function and behavior

shape grammar using Froebel blocks (Stiny, 1980)

**Engineering Design Languages**

- **design language**
  - the set of all valid designs produced by the grammar
  - encode a class of designs, style or domain

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Finding Optimal Designs in a Design Language

- pose a synthesis task as a design optimization problem
- metrics provide semantics (understanding) of a design language

\[
\begin{align*}
\min & \quad \{f_1(x), f_2(x)\} \quad \text{(objectives)} \\
\text{subject to:} & \quad g(x) \leq 0 \quad \text{(inequalities)} \\
& \quad h(x) = 0 \quad \text{(equalities)}
\end{align*}
\]
**eifForm - structural generation and optimization system**

- **Initial design**
- **Intermediate design**
- **Final design**
- **Structural grammar rules**
eifForm - Example Results

Class I (1995)

Class III/IV (2003)

Class V (1997)

Class VI (1999)
Design Brief

Noon Mark
Proposal for King Edward Court, Building 2, Paternoster Square, City of London

South Elevation to Paternoster Square
Structural Grammar - Class III truss-beams

generate a series of tetrahedrons

generate a planar truss (class I)

copy + geometrically transform brace
Design Synthesis Process using eifForm

- generate optimised design alternatives
- select 1-2 designs
- analyze full set of 13 load combinations
- re-optimize section sizes and one joint position for
  - wider and taller support; reduced skew
  - reduced section OD < 90 mm
  - vertical wind load down
- select 1-2 designs
- full check according to BS and Eurocode
Structural Synthesis - Characteristics

- **scale** - applications range from 10s to 1000s components
- **spatial complexity** – often very high!
- **functional complexity** – typically only one or two functional elements
- **behavior complexity** – typically known behavior; multidisciplinary
- **solution spaces** - extremely large! (10^{100s})
- **aesthetic requirements** - often high considering architectural goals
- **design tasks** – most benefits seen on highly complex projects
**Synthesis of MEMS (Microsystems)**

- design of devices is still often by trial and error, offering potential for using a computational synthesis tool to guide designers
- a small but growing number of functionally different elements can be incorporated in MEMS devices
- simulation of the complex multiphysics involved is required to generate realistic devices

micro resonators
**CNS Design Representation**

- use basic building blocks, called primitives, and nodes to build systems and subsystems of interconnected primitives
- primitives are defined by a set of internal parameters, port nodes (connectivity) and constraints
- design modification operators add, remove and modify primitives while checking both local (primitive) and global constraints

![Diagram of CNS Design Representation](image)

- **Special Node** (e.g. anchor/support)
- **Standard Node**

**KEY**
- Primitive Type 1
- Primitive Type 2
- Primitive Type 3
- Primitive Type 4
Case Study - Meandering Resonator

- center mass supported by four springs
- synthesis of beam topology, shape and beam sizes
- minimize error in frequency and device area subject to stiffness and fabrication constraints

![Graph showing the relationship between area and error in resonant frequency](image)

**Performance trade-off**

![Graphs illustrating different aspects of the resonator](images)
MEMS Synthesis - Characteristics

• scale - small in size and typically 10s components
• spatial complexity – 2.5D geometry
• behavior complexity – very complex multi-physics simulation required
• functional complexity – potential for a larger number of different functional elements
• aesthetic requirements - none
• design tasks - currently routine → non-routine and innovative
Challenges of Mechanical Design Synthesis

- a large number of functional elements
- complex 3D geometry and geometric constraints
- strong dependencies between form and function
- no common language for description of function
- strong dependency between design and fabrication process
A Virtual Mechanical Clock

• Can we automate the synthesis of mechanical gear systems?

• **initial task:** generate a mechanical clock with minute and hour hands given a bounding box in which the clock must fit

• **method components:**
  – function grammar using graphs
  – structure grammar using 3D parametric solids
    • vocabulary - spindle, gear, base plate, power source
Function-Behavior-Structure Representation

Function
(connectivity)

Structure
(form)

Behaviour
(constraints)
A Virtual Mechanical Clock

Task: generate a mechanical clock with minute and hour hands within a given space

Function

- applied rules:
  - add first vertex
  - create new vertex

Structure

- applied rules:
  - add first shaft
  - add new shaft
  - insert gear pair
  - add a power source
  - create escapement
Application to Vehicle Gearbox Design

Source of images on left: Romax Technology
**Mechanical Synthesis - Characteristics**

- **scale** - applications range from 10s to 1000s components
- **spatial complexity** – very high; 3D
- **behavior complexity** – typically known; complex interactions
- **functional complexity** – potentially large number of different elements
- **aesthetic requirements** – typically none
- **design task** – currently routine → non-routine and innovative

![5-noded](image1.png) ![10-noded](image2.png)

generated optimal camera winding mechanism alternatives
Future Directions

• **key benefits of computational synthesis tools**
  – formalization and integration of fundamental engineering knowledge
  – definition of design languages and generation of design alternatives
  – integrated, early-stage simulation (CAD/CAE)
  – early-stage concept optimization and design exploration

• **increasing task complexity**
  – larger subsystems and systems
  – multi-domain grammars (mechatronics)
  – networked grammars

• **integration and customization**
  – with current tools and industry processes
  – making tools that enhance designer capabilities and provide competitive advantage!
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