Structural Design Inspired by Nature

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Outline

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Introduction
Motivation

• Growing complexity of structural design problems
• Increased competition and globalization
  • Innovation = competitive advantage
  • Numerical optimization not sufficient
• Progress in Computer Science and Design and Inventive Engineering
• Growing computational resources available to researchers and engineers
Motivation

• Complex design problems require novel methods to address important structural design objectives:
  • Development of novel design concepts
  • Optimization of engineering systems
  • Development of robust engineering systems
• These problems have already been solved by nature
Inspiration from Nature
Inspiration from Nature – Why?

• Nature:
  • Source of inspiration for artists and engineers since the beginning of the civilization
  • Source of most fascinating designs known to humankind
• Today we have better understanding of processes and mechanisms occurring in nature
• We can computationally simulate many of these processes
Levels of Inspiration

• Visual inspiration
  – Earliest, most primitive imitation of forms, shapes, and patterns found in nature

• Conceptual inspiration
  – Results from our improved understanding of the processes occurring in nature

• Computational inspiration
  – Results from our emerging understanding of the computational processes in nature and our ability to simulate them
Inspiration from Nature: Visual

- Relatively well understood and widely used
- Pictures (visuals) of various living organisms, or their systems, are used to create similarly looking engineering systems
Inspiration from Nature: Conceptual

- Occurs when a structural engineer uses a principle found in nature in design
- Requires a solid understanding of both nature and structural engineering
- Cannot be used in a mechanistic way by an automated designing system
Inspiration from Nature: Computational

- Occurs on the level of computational mechanisms inspired by the mechanisms occurring in nature
- **Most promising** from the perspective of automated conceptual design
- **Most intriguing**, still poorly understood and difficult, but has the greatest potential to revolutionize design
Sources of Inspiration
Sources of Inspiration

• Evolution – gradual improvement of living systems in response to environmental conditions

• Coevolution – coadaptation of a species in response to evolution of other species in the ecosystem

• Morphogenesis – evolutionary development, or growth, of an organism or its part
Sources of Inspiration: Evolution

- Living creatures are divided into species
- Species change over time, i.e. they evolve
- Essential components of natural evolution:
  - **Individuals** (plants or animals)
    - They are different within a species
  - **Fitness** determines goodness of individuals
    - Some individuals live longer and are more likely to have children that survive to adulthood – they are *fitter*
  - **Selection**
    - Highly fit individuals have better chances of survival and reproduction
  - **Inheritance** (genetic component)
    - Children inherit genes from their parents. After a number of generations, the proportion of individuals within species with this favorable inheritable characteristic tends to increase
Sources of Inspiration: Coevolution

• …evolution involving successive changes in two or more ecologically interdependent species (as of a plant and its pollinators) that affect their interactions (Merriam-Webster)

• Two major forms:
  • Symbiotic – cooperative coevolution
  • Predator-prey – competitive coevolution
Sources of Inspiration: Morphogenesis

• … is an evolutionary development of the structure of an organism or a part.
• … is an embryological development of the structure of an organism or a part.
• … is the process in complex system-environment exchanges that tends to elaborate a system's given form or structure.
Computational Mechanisms
Computational Mechanisms

- Evolutionary computation
- Coevolutionary computation
- Cellular automata and other generative representations
Evolutionary Computation

• …is based on the use of evolutionary algorithms which utilize a Darwinian notion of survival of the fittest in a computationally useful form
• …utilizes evolutionary processes to solve difficult computational problems

Hence, the name:

Evolutionary Computation
Evolutionary Computation

- Uses a set of solutions called a population of individuals
- Individuals are points in a search space
- Individuals are evaluated for their fitness
- Population dynamics:
  - New individuals (samples) are created from existing high fitness parents using genetic operators like:
    - Crossover
    - Mutation
  - Existing low fitness individuals are deleted
Evolutionary Computation: Representation

Genotype vs. phenotype

Simplified model of a genome

GCCTTAGG

GCCGTAGGG
Evolutionary Computation

Genetic Operators:

- **Mutation**

- **Crossover**
Evolutionary Design

- Topological optimum design problem
- Planar transverse designs of steel skeleton structures in tall buildings
  - 7 types of bracings
  - 2 types of beams
  - 2 types of supports
Evolutionary Design

Wind bracings:

Beams and supports
Evolutionary Design
How? Design Process

Design concept

Application of loads

Structural analysis and sizing optimization

Assign fitness

Detailed design

Total weight

Genome
Evolutionary Design
Coevolutionary Computation

- Multiple populations evolving in parallel
- Fitness of an individual depends on its interactions with individuals from other populations
Coevolutionary Design

• Two competing populations considered:
  • a population of structural designs, and
  • a population of loads

• The fitness of each individual design in the population of designs determined by measuring how well it performs against the loading cases from the population of loads.

• The fitness of each loading case will depend on the number of designs it “defeated,” i.e. how many designs didn’t succeed to satisfy design requirements
Cellular Automata

• One of the simplest mathematical representations of complex systems
• Useful idealizations of the dynamical behavior of various systems
• Models for complex systems and processes consisting of a large number of identical, simple, locally interacting components
• Discrete dynamical system simulators used to study pattern formation and self-organization processes
Cellular Automata

- Motivated by the examples of living organisms:
  - cells containing the same set of genetic instructions
  - complex biological systems consisting of multiple interacting elements
- Modeled as regular arrays of identical elements that can be
  - One-dimensional
  - Two-dimensional
  - Higher-dimensional
Cellular Automata

Simplest cellular automaton

- One-dimensional
- Cell can have only two values (0 and 1, or white and black)
- Neighborhood of size $r=3$ (cell itself plus its two adjacent neighbors)
Cellular Automata

1D cellular automata – the mechanism
Cellular Automata

Chaotic states (rule 30)
Morphogenic Design
Morphogenic Design

Generative representations based on one dimensional cellular automata

Process of generating a wind bracing system from its representation
Morphogenic Design: Evaluation

Generative representation

Growth process

Design concept

Application of loads

Total weight

Assign fitness

SODA

Structural analysis and sizing optimization

Detailed design
Integrated Framework
Integrated Framework

• Currently, computational methods are used separately to address only a single design objective (“1-dimensional design”)
  • Evolutionary computation – optimization of structural designs
  • Coevolutionary computation - generation of robust designs
  • Cellular automata – development of novel designs
• They can be, however, combined and form an integrated design framework inspired by nature
Integrated Framework

“1-dimensional design”:

• individual mechanisms are used separately to achieve corresponding design objectives
• relatively large body of knowledge is available at this level
Integrated Framework

“2-dimensional design”:

• two mechanisms inspired by nature are combined to address two design objectives
• e.g., morphogenic evolutionary design addressing creativity and optimality objectives
Integrated Framework

“3-dimensional” design

- three computational mechanisms combined in an integrated nature-inspired design framework
- direction of future research in engineering design and building future design support tools
Emergent Designer
Emergent Designer Demo

version 1.0
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A design support tool based on models of complex adaptive systems
Other Applications
SecurityMax/Water

- Simulation with EPANet:
- a state of the practice water quantity/quality model for simulating pressurized water networks, developed by US EPA
- capable of steady-state and extended period simulation
SecurityMax/Water

No security scenarios = terrorist scenarios improve

Switching often = constant interaction between terrorist and security scenarios

Switching rarely = terrorist „escape”...
...but we can match their scenarios
Conclusions

• Shifting focus from quantitative/numerical to qualitative aspects of design
• Nature as a source of inspiration
• New era of nature understanding and ability to computationally simulate nature’s processes
• Integrated framework provides “big picture” and research directions
• More questions than answers