Engineering Creativity: From Design and Inventive Engineering to Evolutionary Designing

Tomasz Arciszewski
Organization

1. Introduction
2. Engineering creativity
3. Design and Inventive Engineering
4. Evolutionary designing
5. Creativity and homeland security
6. Conclusions
1. Introduction
Speaker

- Formal background in structural engineering and mechanics
- Design experience from Poland and Switzerland
- 3 patents (Canada, Poland, USA)
- Interests in:
  - Heuristics (30 years),
  - AI and machine learning (15 years),
  - Evolutionary designing (8 years)
Evolutionary Design Expert

- Rafal Kicinger
- Ph.D. candidate, IT Program, IT&E School, George Mason University
- Research interests:
  - Evolutionary designing
  - Cellular automata
  - Dynamical systems
- Demonstrations:
  - Inventor 2000 - design of steel structural systems in tall buildings
  - TerrorMax/CapitalHill - generation of terrorist scenarios
Presentation Context

- Research on **evolutionary designing**
- NASA-sponsored projects combining research on **evolutionary designing (engineering design)**, **evolutionary computation**, and **complexity-theory (dynamical systems) approaches**
- IT-driven civil engineering research and practice (IT&E School at George Mason University)
Design Concept

...describes a future engineering system in terms of abstract concepts (or primary concepts), that involve symbolic attributes and possibly also relations among design components. It is a **feasible combination of symbolic attributes and their values**.
Concept of a Structural System, Example

A steel truss:

three symbolic attributes of material (steel), of member shape (straight), and of connection type (pinned)
A concept represents a *large class of specific engineering designs* that differ in their detailed descriptions, i.e. in the values of numerical attributes characterizing these descriptions.

A concept of a steel truss describes *thousands* of roof and bridge trusses.
Designs Covered by a Design Concept

No. 1

No. 2

No. 3

No. 4

x4=1 x5=1 x6=1 x7=1

x4=3 x5=1 x6=1 x7=2

x4=1 -> x4=3
x7=1 -> x7=2

x5=1 -> x5=2

x5=3
x6=1 x7=2
Detailed Design (Product)

... a detailed description of a future engineering object, or a system, specifying \textit{values of all numerical attributes} characterizing the design, such as specific dimensions, number of members, etc.
2. Engineering Creativity
Creativity: Industrial Perspectives

• The key to survival

• Driving force behind:
  – Technological progress
  – Maintaining and expanding market share
  – Building a competitive advantage
  – Maintaining intellectual skills
Key to Survival

• The manufacturing industry in this country will not survive because of the low (high?) labor costs
• If it survives, it will be only due to the creativity of people, products, and processes
Creativity: Design Science Perspective

An engineering activity producing unknown yet feasible and potentially patentable design concepts or processes (design, manufacturing, maintenance, etc.)

late Sydney Gregory
Creativity: TRIZ Perspective

• An engineering problem-solving in which one or more technical contradictions are eliminated

• “Every great invention is the result of resolving a contradiction”

Late Henry Altschuller
Technical Contradiction

... is an interrelated pair of technical (abstract) characteristics of an engineering system, when one technical characteristic is improved, the second one is worsened.

*Examples*: rigidity versus weight, reliability versus cost, speed versus volume
Creativity: Pragmatic Perspective

- Creativity level can be quantified and measured
- Examples:
  - Patents: number of claims
  - Morphological distance
  - Logical distance
  - Altschuller’s classes of patentable inventions
Levels of Creativity (Inventions)

• 1st level, STANDARD, or APPARENT INVENTIONS
• 2nd level, IMPROVEMENT, or IMPROVED INVENTIONS
• 3rd level, INNOVATION, OR INVENTION WITHIN PARADIGM
• 4th level, INVENTION, or INVENTION OUTSIDE PARADIGM
• 5th level, DISCOVERY

H. Altschuller
Levels of Creativity (Inventions)

- **APPARENT**, well known and simply selected from a class of known design concepts in a given engineering domain
- **IMPROVED**, a modified concept from a given domain, or obtained as a combination of known concepts from a given domain
- **INVENTION WITHIN PARADIGM**, a combination of known concepts from two different but related domains
- **INVENTION OUTSIDE PARADIGM**, produced using knowledge from at least two much different domains
- **DISCOVERY**, based on a new scientific principle
Creativity: Pragmatic View

It is a learnable/teachable ability/skill to:

- Think “outside the box”
- Understand problems in their entire complexity (holistic view)
- Solve problems unsolvable for others
- Generate patentable inventions on demand
Black Box

- **Input**: domain and methodological knowledge
- **Output**: unknown yet feasible and potentially patentable design concepts or engineering processes
- **Transformation**:
  - probability (of ???) less than 1
  - dependent on motivation level
Creativity Crisis

• We teach students analytical numerical/quantitative skills (How to use deterministic analytical procedures)

• We do not teach students qualitative/conceptual skills (How to use heuristic methods and tools to solve qualitative/conceptual problems, How to be creative)
21st Century Engineer: Pragmatic Vision

- The 21st Century engineer must have knowledge and skills necessary and sufficient to deal with both qualitative/conceptual/creative and quantitative aspects of problems.

- Balanced engineering knowledge:
  - Domain knowledge
  - Excellent quantitative/numerical skills
  - Excellent qualitative/creative skills
Creativity Triangle

- Motivation
- Domain knowledge
- Design and Inventive Engineering knowledge
Creativity Types

- **Human approach**: creativity supported by heuristic methods
- **Mechanistic approach**: Artificial intelligence
- **Integrated approach**: human-machine system with a creative engineer using computer tools (our focus)
Human-machine Systems Requirements

- **Paradigm change**: from present one when creativity is at best tolerated to new one when it is considered an integral part of engineering activities
- Design and Inventive Engineering education
- **Fundamental research** integrating heuristics and AI
- Building creativity supporting computer tools
- Development of creativity nurturing and stimulating environments
Combination of human creativity and the use of novel computer tools offer the best hope to produce creative/patentable designs and processes
3. Design and Inventive Engineering
Engineering Design: Science or Art

- **Science Approach**: Design process is governed by formal laws, described by the mathematical models, etc. It can be taught.

- **Art Approach**: Design process is governed by heuristics, described by the descriptive models, important role of intuition (conscious and subconscious meta-rules and rules). It can be learnt by practicing it.
History of D&IE

- **Classical Era**, focus - *prescriptive and descriptive methods*, up to 1960’s
- **Computer Age**, focus - *mathematical models and their computer implementation*, 1960’s - 1980’s
- **IT Age**, focus - *knowledge-based approach*, 1980’s until today,
- **Cyber Age**, focus - *NC in design*, late 1990’s - now
Design Engineering

an engineering interdisciplinary science dealing with the engineering design processes and with the development of design support tools

• recognized as a separate science in the late eighties
• development stimulated by the NSF and ARPA (Design Engineering Program)
Inventive Engineering

a subdomain of Design Engineering dealing with the engineering design processes and the development of design support tools when inventive design concepts are sought

• name proposed only recently
• still not fully recognized as an engineering science
Inventive Engineering

...is an engineering science, a knowledge necessary and sufficient to develop and use a class of design processes, when creative/inventive/patentable design concepts are sought.
Paradigm Change

from *analytical paradigm* to *knowledge paradigm*

**Why?**

- Knowledge revolution, computer revolution, industrial revolution, agrarian revolution.
- Building huge body of knowledge over the last 1036 years
- Availability of computer design support tools
Focus Difference

Analytical Paradigm:
acquiring knowledge about behavior of engineering systems

Knowledge Paradigm:
using accumulated knowledge
Reasoning, conceptual design and inventive design processes are viewed as knowledge processing activities, and can be, at least partially, performed on a computer. Development of computational foundations of design is possible and will lead to building a new class of design support tools!!
Major Sub-domains

- General methodology
- Methodics
- Tool development
Subjects of General Methodology

...are the general methodological issues in design, including:

- design theories
- general models of the design process
- integration of various design methods and tools
- evolution of design processes
- knowledge acquisition
- evaluation of design concepts and of finals designs
- novelty/innovation and its formal measures
- others
Subject of Methodics

...is a study of various design methods, including their:

- formal models
- development of new methods
- mathematical modeling
- experimental verification
- comparison
...is building and testing various computer design tools to support in design
Four Generations of Engineering Creativity

1. Classical heuristics age
2. Mathematical modeling age
3. Knowledge age
4. CyberSpace age
Classical Heuristics Age

- History of our civilization
- *Socrates Dialog* as a heuristic method
- Methods are human designer oriented
- Methods in descriptive and prescriptive form
Mathematical Modeling Age

- Begins in the late seventies
- Focus on building mathematical models of problem solving processes
- Methods are computer oriented
Knowledge Age

- Begins in the late eighties
- Focus on using knowledge in the process of problem solving
- Methods are computer-oriented
CyberSpace Age

- Begins in the late nineties
- Focus on using network computing in problem solving
- Methods are computer network-oriented
Education

• Discovery, Design & Innovation Graduate Certificate Program at GMU

• Core graduate courses:
  – Design and Inventive Engineering
  – Process of Discovery and its Enhancement in Engineering Applications
  – Systems Design and Integration

• Undergraduate course:
  – Introduction to Design and Inventive Engineering
4. Evolutionary Designing
Why Evolutionary Computation in Engineering?

- Emergence of IT as driving force in design computations
- Growing sophistication of computer tools
- “Natural” need to evolve designs utilizing SOTA and to produce many comparable designs
- Progress in computer science
- Promising initial results, 20 years of efforts
Evolutionary Computation (EC)

- ...is based on the use of evolutionary algorithms (EAs), 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
Engineering Perspective

...it is a computational process in which a solution, or solutions, undergoes gradual changes

Objective:

to transform a given problem, provided as a representation space with constraints and requirements, into a class of solutions
CS versus Engineering

- **Computer Science:**
  Genetic manipulation of strings, sequences of genes, or of genotypes

- **Engineering:**
  Conceptual design, or inventive problem solving, using semantic interpretation of genotypes as design concepts
Evolutionary Algorithm (EA)

• ...is based on Darwinian notion of an evolutionary system

• Basic elements:
  – A population of “individuals”
  – A notion of “fitness”
  – A birth/death cycle biased by fitness
  – A notion of “inheritance”
Simple EA

1. Randomly generate an initial population
2. Do until some stopping criterion is met:
   • Select individuals to be parents (biased by fitness)
   • Produce offspring
   • Select individuals to die (biased by fitness)
   • End do
3. Return a result
Simple EA: Black Box Approach

Constraints and Requirements

Representation Space

Initial population generation

Parent Selection

Reproduction

Survival Selection

Final Population
Representation, Example

• **Symbolic Attributes:**
  1. **Shape**: triangle, circle, square
  2. **Material**: steel, concrete, wood
  3. **Color**: brown, green, yellow

• **Numerical Attributes:**
  1. **Length**: 6 m, 7 m, etc.
  2. **Depth**: 2 m, 3 m, etc.
  3. **Weight**: 5 pounds, 6 pounds, etc.
## Representation as Binary String

<table>
<thead>
<tr>
<th>Design 1:</th>
<th>Design 2:</th>
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<tbody>
<tr>
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<tr>
<td>A9 = 0</td>
<td>A9 = 0</td>
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</table>
## Mutation of Design 1

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<th>Mutated:</th>
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<tbody>
<tr>
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<td>A8 = 1</td>
</tr>
<tr>
<td>A9 = 0</td>
<td>A9 = 0</td>
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</tbody>
</table>
## Crossover: New Design

<table>
<thead>
<tr>
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<th>Design 2</th>
<th>New Design</th>
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</thead>
<tbody>
<tr>
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<tr>
<td>$A_9 = 0$</td>
<td>$A_9 = 0$</td>
<td>$A_9 = 0$</td>
</tr>
</tbody>
</table>
Evolutionary Designing History

- Early 1970, Germany, Rechenberg, optimization of steel trusses
- Mid-80, USA, Goldberg, optimization of gas pipe lines
- Late 1980, USA, Hajela, structural optimization
- Late 1980, England, Parmee, engineering design, conceptual and detailed
- Late 1990, Canada, Grierson, Pareto optimization of building design
Paradigm Change

- **Dominant practice**: *Creationistic Designing*
  - One or very few design concepts are selected or generated
  - No formal conceptual design methods and tools are used
  - Focus is on the detailed design: analysis, dimensioning, and optimization

- **Emerging practice**: *Evolutionary Designing*
  - A large number of design concepts is automatically generated and evolved
  - A conceptual design method and tool are used, utilizing the evolutionary process
  - Focus is on the conceptual design: on the generation and evolution of design concepts
Evolutionary Designing

• A multistage process in which a line of designs (a trajectory) is gradually evolved

• Evolution may include evolving:
  – Designs
  – Constraints
  – Requirements
  – Fitness function
  – Project definition, etc.

• It is a reflection of holistic understanding of engineering design within the context of the changing world even during the design process (several years)
Evolutionary Designing: Major Stages

1. Realization of needs
2. Needs and SOTA analysis
3. Formulation of requirements and constraints
4. Building design representation space
5. Selection/random generation of initial design concepts
6. Integrated design process
7. Evaluation of the final designs
Evolutionary Designing: Search Perspective

...is a search process through the symbolic part of the design knowledge representation space to find a concept or concepts of an engineering system.
Integrated Evolutionary Design

- Both the conceptual and detailed design are sequentially conducted at the same time
- Conceptual design (process) deals with abstract design aspects described by symbolic attributes
- Detailed design (process) deals with numerical design aspects described by numerical attributes
Inventor 2001

- Evolutionary design and research tool for designing steel skeleton structures in tall buildings
- Produces both design concepts and detailed designs
- Uses evolutionary computation to search through the design space
Major Features

1. Produces complete designs
2. Allows the development of inventive designs through the evolution of known designs
3. Contains several major components: evolutionary computation module, SODA, wind forces analysis module, etc.
Concept is a vector with 220 attributes:
108 attributes with 7 values
108 attributes with 4 values
4 attributes with 2 values

Information Flow

From Design and Inventive Engineering to Evolutionary Designing
Example: Parents, Generation No. 7
Interesting Result
Emergence of A Belt Truss System
Inventor 2003

- Generic system to be customized for various applications
- Both single and multi-population evolutionary computation
- Internet & computer network oriented
- Initial design and planning applications:
  - Steel structural systems in tall buildings
  - Concrete structural systems in tall buildings
  - Mars mission: landing of a probe
5. Creativity and Homeland Security
Challenges

• Asymmetric threat against nation’s vulnerabilities and weakness while ignoring its strengths

• Infrastructure professionals are NOT known for their ability to think “out of the box”
  – Not properly trained
  – Against the culture
Our Advantage

- Information Technology
- Design and Inventive Engineering
- Evolutionary designing technology, including proactive approaches to homeland security
- Education
Proactive Approaches to Homeland Security

- Competitive co-evolutionary models
- A population of evolving terrorist scenarios to maximize impact of an attack
- A population of evolving security scenarios to minimize impact of an attack
- A simulation package allowing assessment of terrorist and security scenarios
Proactive Approach: Initial Step

- TerrorMax/Generic
- A multi-population evolutionary computation tool for the generation of terrorist scenarios
- Developed for Internet applications
- To be integrated with various simulation packages
Education

• A powerful anti-terrorist weapon
• A paradigm change must occur: from following instructions to creative thinking to respond to unexpected situations
• Design and Inventive Engineering Education is a potential solution
TerrorMax/CapitolHill
Research Team

- Tomasz Arciszewski
- Kenneth DeJong
- Michael Goode
- Andrew Sage
- Rafal Kicinger
- Zbigniew Skolicki
Assumptions

- 7 attack locations
- 5 types of attack
- Up to 4 locations attacked at the same time
- Up to 3 attack types at one location
Attack Locations

- Capitol Hill
- Pennsylvania Avenue
- NASA Headquarters
- FEMA Headquarters
- Smithsonian Station
- Washington Monument
- Memorial Bridge
Attack Types

- Fire
- Explosion
- Radioactive
- Biological
- Chemical
Terrorist Scenario

- A combination of terrorist’s decisions regarding the locations and types of attacks
- Example: Attack on the Capitol Hill using chemical and biological weapons combined with an attack on the NASA Headquarters using a bomb
Fitness Assessment

- Fitness within [0, 200]
- Some combinations of attack had their fitness assigned manually in an external tool created
Generated Scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Type</th>
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<tbody>
<tr>
<td>Capitol Hill</td>
<td>Radiation chemical</td>
</tr>
<tr>
<td>Pennsylvania Avenue</td>
<td>Fire explosion</td>
</tr>
<tr>
<td>NASA Headquarters</td>
<td>Explosion</td>
</tr>
<tr>
<td>FEMA Headquarters</td>
<td></td>
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<tr>
<td>Smithsonian Station</td>
<td></td>
</tr>
<tr>
<td>Washington Monument</td>
<td></td>
</tr>
<tr>
<td>Memorial Bridge</td>
<td>Fire chemical</td>
</tr>
</tbody>
</table>

![Image](image_url)
Fitness Function
Scenario Example
TerrorMax/Water Distribution System
Research Team

- Moe Wadda
- Tomasz Arciszewski
- Zbigniew Skolicki
Area Considered

Water utility service areas in the Washington metropolitan area, year 2000

Service areas:
- Loudoun Co. Sanitation Auth.
- DC Water and Sewer Authority
- Rockville DPW
- Prince William Co. Sanitation Auth.
- Washington Suburban Sanitary Commission
- Vienna DPW
- Virginia American: Dale City
- Fewa wholesale cust.shp
- Falls Church DPW
- Arlington County DPW
- Virginia American: City of Alexandria
• A water system is attacked
• Biological or chemical contamination is placed is a water system
• Large number of system’s nodes is affected (and a number of people who receive poisoned water)
• Terrorists want to maximize the impact measured by the number of nodes affected (terrorist’s fitness function)
Terrorist Scenario

• A combination of terrorist’s decisions regarding the placements of the biological or chemical contamination and locations of the fire hydrants to be opened
• Example: tanks 2 and 3 attacked, and fire hydrants 134 & 190 opened
Integrated Tool

- Integrated computer tool for the optimization of terrorist scenarios

- Major Components:
  - Terrorist scenario generation tool: Inventor 2003
  - Simulation&fitness evaluation tool: EPANet system developed by EPA
Initial Parents
(Dangerous Terrorist Scenarios)

1. Largest tank attacked plus 5 hydrants opened
2. 2 large tanks attacked plus 3 hydrants opened
3. 1 large Tank attacked plus 10, or more, hydrants opened (annual flushing program)
Poison Flow

- Tracing of poisoned water flow
- Colors represent various poison level
Preliminary Findings

- Tanks are potential problems.
- Flushing operations need to be coordinated carefully to minimize widespread propagation of contaminated water.
- Fire hydrants need to be protected.
Urban Poisonous Gas Attack
Research Team

- **Infrastructure Security:**
  Tomasz Arciszewski

- **Poison Gas Flow Modeling:**
  Rainald Lohner and Fernando Camelli

- **Evolutionary Computation:**
  Kenneth DeJong and Elena Popovici
Objective

To determine the feasibility of using evolutionary computation in the generation of terrorist scenarios related to a poisonous gas attack in an urban area
Background

- Intentional or unintentional release of poisonous gas can lead to devastating consequences
- Proactive infrastructure security means the determination of the worst case terrorist scenario
- The worst case terrorist scenario: maximum impact on a given urban area
Impact Measure

Integral of people-occupied volume in which concentration is above assumed safety threshold times probable density of people in this volume
Evolutionary Computation

- The worst case terrorist scenario determination means finding the maximum impact location, or impact locations, in the search space.
- The search space contains all feasible locations of poisonous gas containers in a given urban area.
- Evolutionary Computation is used for finding the maximum impact point, or points.
Poisonous Gas Flow Simulation

• Conducting high-resolution 3-D runs with up to a million elements on PC platforms in about 60 minutes

• Software developed at the Computational Fluid Dynamics Laboratory, School of Computational Sciences, GMU

• Authors: F. Camelli & R. Lohner
Types of Poisonous Gas Release

• Continuous or plume
• Instantaneous or puff (used for current experiments)
Urban Area Considered

Grey areas denote where releases can occur.

Preliminary tests conducted in this area.
Urban Area Considered: Bird View
Evolutionary Computation

- Evolutionary Computation tool used: *Inventor* – domain independent Evolutionary Computation shell developed at the Evolutionary Computation Laboratory, GMU

- Used to evolve best location (x,y coordinates) for maximizing terrorist effects
Fitness Curves for 1st Experiment
Fitness Landscape: Main Street
Poisonous Gas Flow: Main Street

Click on the above to play

From Design and Inventive Engineering to Evolutionary Designing
Conclusions

• Feasibility demonstrated

• Poisonous Gas Flow Modeling software integrated with Inventor

• Strong potential for using Evolutionary Computation in Generation of Terrorist Scenarios for Urban Poisonous Gas Attack