Optimal Design of System Architectures

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Outline

- Background

- Past Research
  - Hybrid Electric Powertrain Architecture Design
  - Design of Modular Architectures for Vehicle Fleets
  - Design Using Game Platforms
Background

B.S. Mechatronics Engineering, 2011
Sabanci University, Istanbul

M.S. Mechanical Engineering, 2013
PhD. Mechanical Engineering, 2015
University of Michigan, Ann Arbor

Research Fellow and Adjunct Lecturer
University of Michigan, Ann Arbor
Agenda for Design Research

**Design:** Decision making process

My research interests are in general field of design optimization of complex systems

Examples include:
- Smart products that operate with a controller
- Interconnected system of systems
What is a System Architecture?

Topology / Configuration

Architecture: Topology + Interactions among building blocks

Multiple alternatives for the same task
System Architecture Design

If the building blocks are known:

Parametric design

Topology design

Design of interactions

Interactions can be determined by a controller (e.g., smart products) or management strategies (e.g., systems-of-systems, social systems)

All three design efforts must be combined for successful system operation
Hybrid Electric Powertrain Architecture Design
Types of Hybrid Electric Vehicle Configurations

1. Series Configuration

2. Parallel Configuration

3. Power-spliit Configuration

Planetary Gear
Many HEV Configuration Alternatives Possible

Single-mode configurations
Each design candidate requires a control strategy to evaluate fuel consumption

- Control: distribute power demand to engine and motors

Design and control problems are coupled

- Must be solved together

Fathy et al. (2001)
Problem Overview

Design:

Topology + Component Sizes

Controller

maximize:

fuel economy

subject to:

0-60 mph time \leq k_1
Top speed \geq k_2

Architecture alternatives are usually unknown

Representation \rightarrow Generation \rightarrow Design
**Representation & Generation**

**Bond Graphs**

- **Causal strokes**
- **Bond weights**
- **Junctions**

ρ: Gear ratio  
FR: Final drive ratio

**Quasi-static equations extracted from bond graphs**

\[
\begin{bmatrix}
1 + \rho & -\rho \cdot FR \\
0 & FR \\
\end{bmatrix}
\begin{bmatrix}
\omega_{\text{eng}} \\
\omega_{\text{out}} \\
\end{bmatrix} =
\begin{bmatrix}
\omega_{\text{MG1}} \\
\omega_{\text{MG2}} \\
\end{bmatrix}
\]

**1-PG Feasible Region for ρ ∈ [2,4] and FR ∈ [1,10]**
Decomposition-based Design Optimization

Design \( C_{conf} \)
for Fuel Economy, Performance

Design targets → Design response

Design topology, \( \rho, FR \)
to meet targets,
s.t. (Feasibility & Complexity)

High-level design

Detailed design

The problem is coordinated using Analytical Target Cascading (Kim 2001)
Research Direction: Different Applications

- For a real-life implementation, architecture design must consider cost vs benefits

- Current hybrid architecture design research:
  - Flexible architecture design for evolving market
  - Design for heavy duty applications with diverse mission capabilities

- A generalized architecture design methodology for applications beyond vehicles
Design of Modular Architectures for Vehicle Fleets
Modular Approaches

Family of Vehicles

- Stryker
- Patria Armored Modular Vehicle

Load Handling Systems

- Palletized Load System
- Cameleon

Our Approach

- Plug-and-Play Modularity
- No common platform
- Reconfiguration in theatre

For more details on modularity in practice, see [Dasch, 2015]
Modular Vehicle Fleet Design

Modular Vehicle Fleet

Fleet

Convoy Convoy Convoy Convoy

Vehicle Vehicle Vehicle Vehicle

Module Module Module Module Module

Design evaluation
Operation management
Vehicle configurations
Module design
Module Design

- What modules enable optimal fleet performance?
- Consider modules as clusters of functions (and enabling variables), therefore question becomes:
  - How should functions/variables be grouped in order to maximize system performance? (*module types*)
  - What should *module variants* be in order to maximize the system performance?

<table>
<thead>
<tr>
<th>Module Type</th>
<th>Module Variants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functions: $f_1(v_1, v_2)$, $f_2(v_1)$, $f_3(v_2)$</td>
<td>Functions: $f_1$, $f_2$, $f_3$</td>
</tr>
<tr>
<td>Variables: $v_1$, $v_2$</td>
<td>Variables: $v_1=x_{11}$, $v_2=x_{21}$</td>
</tr>
<tr>
<td>Functions: $f_1$, $f_2$, $f_3$</td>
<td>Functions: $f_1$, $f_2$, $f_3$</td>
</tr>
<tr>
<td>Variables: $v_1=x_{12}$, $v_2=x_{22}$</td>
<td></td>
</tr>
</tbody>
</table>
Design of Modules

- Definition of modules impact the effectiveness of the fleet design
- A function-based approach has potential to generate innovative modular concepts

<table>
<thead>
<tr>
<th>functions</th>
<th>variables</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>v₁</td>
</tr>
<tr>
<td>f₁</td>
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</tr>
<tr>
<td>f₂</td>
<td>1</td>
</tr>
<tr>
<td>f₃</td>
<td></td>
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<tr>
<td>f₄</td>
<td></td>
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<td>f₅</td>
<td></td>
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<tr>
<td>f₆</td>
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Fleet Decomposition

Links to define modules

Submodules partition
Module design is combined with an operation management in a fleet evaluation framework.
Modular Vehicle Fleet Design

Module Design

Operation Scenario

Dynamic Fleet Simulation

Scheduling | Maintenance | Assembly | Resupply

Convoy Optimization

Inventory Management

Personnel Optimization

Demand Prediction

Fleet Readiness
Module Design Problem

Module Definitions

Number of Variants

\[ \begin{align*}
\text{min} & \quad f_{obj1} \\
\text{Total Number of Variants} & \leq N
\end{align*} \]

Module Variables

\[ \begin{align*}
\text{min} & \quad f_{obj1} \\
\text{Design Requirements}
\end{align*} \]

Optimal Module Variables

\[ \begin{align*}
\text{min} & \quad \{f_{obj1}, f_{obj2}\}
\end{align*} \]

Fleet Simulation

Optimal Number of Variants

Mission Scenario
Design with Game Platforms
Design with Game Platforms

- 42% of Americans play games regularly at least three hours a week (Entertainment Software Association)
- Games are based on excessive trial and error that incentivize a player with fun

Research on gaming:
1-) Improve gaming experience
2-) Data collection
3-) Problem solving
4-) Education
Design the final drive ratio to minimize the battery consumption over a track.

Final Drive Ratio: 10
Swipe to tune

Battery usage
Remaining Time

EcoRacer: EV Design and Control Game
Design with Game Platforms

ecoracer.herokuapp.com

EcoRacer (current winner: ikalyoncu)

username

password

LOGIN

REGISTER
Computational Solutions

- Best player score **outperforms** the search algorithm (EGO)
- Using search algorithm is a more **robust approach** than relying on very few experts in the crowd

Best player score: 43.2%  \(\text{(Theoretical upper bound): 43.8\%} \quad \text{Best EGO score: 37.1\%}

![Graph showing scores comparison](image-url)
Research Direction: Urban Planning
Design Teaching with Game Platforms

- Games can also be used for education.
  - NSF, Gates Foundation, Entertainment Software Association supported this idea

- Current applications include:
  - MIT education arcade (middle-high school biology and math education)
  - Karen Markey (Library search game)
  - Aydogan Ozcan (Malaria training game)…

- In design context, games can be used to teach various trade-offs in a system.
  - Games can guide students for their design project
**Summary**

**INTEGRATED SYSTEM DESIGN OPTIMIZATION**

- **Powertrain Architecture Design**
  - MG2
  - Engine
  - MG1

- **Modular System Design**
  - f1
  - f2
  - f3
  - f4
  - f5
  - f6

- **Design with Game Platform**
Thanks!

What questions do you have?