Model Based Design Tools for Cyber Physical Systems

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Trends in Complex Design
Traditional System Design

- SWaP used as a proxy metric for cost, and disincentivizes abstraction in design.
- System decomposed based on arbitrary cleavage lines.
- Conventional V&V techniques do not scale to highly complex or adaptable systems—with large or infinite numbers of possible states/configurations.
- Resulting architectures are fragile point designs.
- Unmodeled and undesired interactions lead to emergent behaviors during integration.

MIL-STD-499A (1969) systems engineering process: as employed today

- Cost Optimization
- System Functional Specification
- System Layout
- Verification & Validation
- Subsystem Design
- Subsystem Testing
- Component Design
- Component Testing

SWaP = Size, Weight, and Power
Desirable interactions (data, power, forces & torques)
Adaptive Vehicle Make Vision

• **Speed:** Design a system in 1/5 the time of traditional design methods

• **Functional:** *Probabilistic Prediction of Performance*

• **Manufacturing:** Designs can be built

• **Adaptive** to requirements and new tech.

• **Accessible:** Lower the barrier to entry
The META Approach

Component Based Design
- Design Reuse, Distribute Workload
- Leverage cross-domain Component Libraries

Design Space Exploration
- Explore, Evaluate, Understand Tradeoffs
- Maintain Design Flexibility/Agility

Executable Requirements
- Auto-compose models/invoke domain analysis tools
- Minimize repetitive engineering labor

Meta Programmable Tools and Semantic Backplane

Support integration of new tools and analysis
Applicable across new domains and engineering processes

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The META Design Flow

Design Space and Design Modeling

- Cyber Physical Modeling Language (CyPhy/GME)
- CAD Tool (PTC/Creo – currently)
- META Link
- Synchronized 2D-3D Design Environment
- Testbenches

Requirements

- Stakeholders/End-Users
- Derived Reqts.

Component/Subsystem Libraries

- Multi-Domain Component Model Libraries
- (Sub)System Libraries
- Custom Components/Subsystems

Static Constraint based DSE

- Performance Analysis
- Low Fidelity Manufacturability
- CAD Geometry Analysis
- Structural Analysis
- CFD Analysis
- Blast/Penetration Analysis

Dynamics Simulation based Performance Analysis

- Detailed Manufacturing Analysis

Design Space

- Design Detail/Analysis Fidelity
- Design Space

Data Visualization

MAUF Trades Exploration

Computed Design Metrics

MAUF Weights/Prefs
Component Models

- Represent Behavior Across Domains
  - Electrical, Mechanical, Fluids, Thermal ...
- Support Multiple Tools
  - Dynamics
  - CAD
  - Procurement & Cost
  - Cyber
- Levels of Abstraction
  - Multiple Fidelity
  - Tradeoff Speed and Accuracy
- Conforms to Ontology
  - Interchangeable Components
- Composition
  - Components plug together to make systems
  - Properties of components maintained in systems
  - Semantics Maintained

Caterpillar C9 Diesel Engine: AVM Component

- Weight: 680 kg
- Height: 1070 mm
- Number of Cylinders: 6
- Maximum Power: 330 kW
- Maximum RPM: 2300 rpm
- Minimum RPM: 600 rpm

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<thead>
<tr>
<th>Parameter/property</th>
<th>Interface Type</th>
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<tbody>
<tr>
<td>Weight</td>
<td>FEA Geometry</td>
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<tr>
<td>Height</td>
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<tr>
<td>Maximum Power</td>
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<td>Bond Graph Dynamics Model</td>
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<tr>
<td>Minimum RPM</td>
<td>Detailed Geometry Model</td>
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- Low-Fidelity Dynamics
- Detailed Geometry
- FEA Geometry
Design Spaces Construction & Exploration

Architectures:
- Mobility
  - # Wheels/Legs/Tracks
  - Wheel Articulation
- Power Sources
  - Diesel, Electric, Solar
- Manipulators
- ...
Test Benches to Evaluate FANG Requirements

Simple Test Benches

Complex/Sequenced Test Benches
Dynamic Performance Evaluation: Composition and Execution of Multi-Fidelity Ordinary Diff Equations

Simulation Testbench for Behavioral Properties

Uncertainty Propagation & Estimation

Design Architectures

Multiple Fidelity Behavior Models

Multiple Physics Domains
Geometric Reasoning: CAD Assembly Composition

META Model of Structural Connections

CAD-Independent Assembly

CAD Tool Specific Drivers

BOM, Assembly, GD&T, …

iFAB Interface (partial)
Vehicle 3D Model

Composed Vehicle Geometry as Designed
Finite Element Analysis

**Underpinnings**
- Annotated 3D Models
- Semantics of 3D Physical
- TouchPoints in Test Bench
- Automated Composition

**Challenges**
- Scalability
- Stability of Analysis
  - (Production & Detection)
- Portability

**End State:**
Abaqus, ProE, Open Source
Probabilistic Certificate of Correctness

Qualitative Reasoning

Probabilistic Model Checking

Relational Abstraction

- Hybrid system --> Discrete system
- Model check the (infinite state) discrete system
  - infinite bounded model checking
  - k-induction
- Find: Safe/Unsafe/Goal States
Data Visualization & Trade Space Exploration (Dashboard)

Requirements Analysis

Multi Attribute Utility Function

Design Space Analysis
• Open / Extensible Tool Architecture
• Formal Meta-Models and Interchange formats
• Dual Cloud-based & Local Analysis Execution Infrastructure
• 300 Design Teams, 20+ Finalists
• 9 Amphibious Infantry Combat Vehicle Designs
• Takeaways:
  – AVM Software/Models Used by Uninitiated Group
  – Small Teams designed complex systems quickly
  – Teams pushed the limits of design space, despite narrow component selection
  – Result being built for validation
New/Ongoing Development For 2013-14

- Geometry Focus
  - Interactive CyPhy/CAD Coupling
- PDE Tools
  - CFD, Thermal, Dynamic Stress
- Fault and Reliability Modeling
- Mission Computing and RTOS Integration
- Composition
- Multi-Simulation Integration (HLA)
Transition of AVM Technology

• Application to New Domains
  – Understand various design requirements
  – Define Components
  – Leverage existing tool resources

• Prove Out META Processes In Situ
  – Immediate vs Gradual transition
  – Leverage NRE and Tools
  – Leverage assets (components)