Adaptive Vehicle Make (AVM)

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Historical schedule trends with complexity

[Graph showing historical schedule trends with complexity, including design, integration, and testing times and costs across different industries like Aerospace Systems, Automobiles, and Integrated Circuits.]
Status quo approach to managing complexity

SWaP used as a proxy metric for cost, and disincentivizes abstraction in design

System decomposed based on arbitrary cleavage lines...

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

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

\[ \text{SWaP} = \text{Size, Weight, and Power} \]
\[ \text{V&V} = \text{Verification & Validation} \]

Desirable interactions (data, power, forces & torques)

Undesirable interactions (thermal, vibrations, EMI)

... and detailed design occurs within these functional stovepipes
The technical problem is in the seams

- Between stages of production →
- Between system components ←
- Between people & organizations →

Source: MIT ESD (deWeck et al., 2008)
Source: DDR&E/SE (Flowe et al., 2009)
Adaptive Vehicle Make vision

**Shorten development times for complex defense systems**  
**[META]**  
- Raise level of abstraction in design of cyber-electromechanical systems  
- Enable correct-by-construction designs through model-based verification  
- Compose designs from component model library that characterizes the “seams”  
- Rapid requirements trade-offs; optimize for complexity & adaptability, not SWaP

**Shift product value chain toward high-value design activities**  
**[iFAB]**  
- Bitstream-configurable foundry-like manufacturing capability for defense systems  
- Rapid switch-over between designs with minimal learning curve  
- “Mass customization” across product variants and families

**Democratize design**  
**[FANG]**  
- Crowd-sourcing infrastructure to enable open-source development of cyber-electromechanical systems [vehicleforge.mil]  
- Prize-based Adaptive Make Challenges culminating in an Infantry Fighting Vehicle for testing alongside a program of record [FANG]  
- Motivate a new generation of designers and manufacturing innovators [MENTOR]
Notional META design flow

Construction Rules → Semantic Definitions → Constraints

Mathematic Representation
Formalized Design Language

System Requirements

Component Model Library

Set of Feasible Architectures

Complexity Assessment

\[ c(n, A) = \sum_{i=1}^{n} \alpha_i + \sum_{i=1}^{n} \sum_{j=1}^{n} \beta_{ij} + \gamma \left( \frac{\log(n)}{\log(7)} \right) \]

Cost vs. Complexity

Abstraction Based Design

Correct-By-Construction

System Structure Assessment

STOCHASTIC FORMAL VERIFICATION
Notional iFAB foundry configuration

Assumptions:
- 100k ft² total space.
- Need not be geographically co-located.
- All custom components in-sourced.
- All unmod COTS components out-sourced.

“Core Manufacturing Science” Insertion

Paint & Finish

Additive/Subtractive Manufacturing

Welding

Sheet Metal Fabrication

Composites

Tape Laying

Autoclave

CNC Brake

3D Printer

Laser Cutter

CNC Mill 5-Axis

6-Axis Robots

Swaging Press

Fuel Cell Test Set

Articulating CMM

CNC CMM

Automated Harness Loom

Electronics Fabrication

Harness Buildup

Drill & fill

Wire bundles

Robotic assembly

Machine Instructions

(STEP-NC, OpenPDK)

iFAB Foundry Configuration

Logistics

Hydraulics & Pneumatics

Tube Bending

QA / QC

Product Meta-Representation

Notional iFAB foundry configuration

Assumptions:
- 100k ft² total space.
- Need not be geographically co-located.
- All custom components in-sourced.
- All unmod COTS components out-sourced.
Crowd-sourcing infrastructure: vehicleforge.mil

Estimated Size of Component Model Library

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Unique Parts (upper limit)</th>
<th>Total Parts (lower limit)</th>
<th>Library Parts (unique x 5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drivetrain</td>
<td>3,000</td>
<td>8,000</td>
<td>15,000</td>
</tr>
<tr>
<td>Chassis/Armor</td>
<td>5,000</td>
<td>12,000</td>
<td>25,000</td>
</tr>
<tr>
<td>Other</td>
<td>7,500</td>
<td>10,000</td>
<td>37,500</td>
</tr>
</tbody>
</table>

| Total          | 15,500                      | 30,000                    | 72,500                    |

Note: Estimates are at the numbered part level. Cables and circuit boards counted as single part. Excludes variable mission equipment, software.

Elements of a Component Model

<table>
<thead>
<tr>
<th>Physical attributes</th>
<th>Undesirable emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>• size and shape</td>
<td>• thermal</td>
</tr>
<tr>
<td>• mass properties</td>
<td>• electro-magnetic</td>
</tr>
<tr>
<td>• elastodynamics</td>
<td>• vibrational</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Interfaces</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>• data</td>
<td>• blackbox model</td>
</tr>
<tr>
<td>• power</td>
<td>• failure modes</td>
</tr>
<tr>
<td>• mechanical</td>
<td></td>
</tr>
</tbody>
</table>

Performance

Fast, Adaptable Next-generation Ground vehicle (FANG)

**Mobility/Drivetrain Challenge**

**SCOPE**
- Vehicle drivetrain to meet IFV speed, efficiency, terrain, reliability objective
- Available model library to include:
  - Hybrid-electric systems
  - Novel ground interfaces

**PARTICIPANT POOL**
- Global

**INCENTIVE**
- Prize $1M for winning design
- Winner(s) judged based on multi-objective weighting function

**DESIGN AGGREGATION**
- Use of META metalanguage required
- Use of vehicleforge.mil optional

**BUILD APPROACH**
- iFAB foundry build for top design(s)

**Chassis/Integrated Survivability Challenge**

**SCOPE**
- Chassis and armor design to meet principal IFV-like survivability objectives
- Available model library to include:
  - Advanced armor concepts
  - Novel configs (monocoque, v-hulls)

**PARTICIPANT POOL**
- Global

**INCENTIVE**
- Prize $1M for winning design
- Winner(s) judged based on multi-objective weighting function

**DESIGN AGGREGATION**
- Use of META metalanguage required
- Use of vehicleforge.mil optional

**BUILD APPROACH**
- iFAB foundry build for top design(s)

**Total Platform Challenge**

**SCOPE**
- Complete IFV based on core Army objectives and distilled requirements

**PARTICIPANT POOL**
- Global

**INCENTIVE**
- Prize $2M
- Winner judged based on satisfaction of constraints and multi-attribute preference function (i.e., entirely objective approach)

**DESIGN AGGREGATION**
- Use of META metalanguage required
- Use of vehicleforge.mil optional

**BUILD APPROACH**
- iFAB foundry build for top design(s)
Goal

• Educate, motivate, and inspire a next-generation cadre of designers and manufacturing innovators
• Inculcate AVM-type design methods such that they become pervasive in subsequent generations of engineers

Approach

• Design collaboration using modern CAD tools and conventional social networking media
• Distributed manufacturing across networks of schools equipped with various digital manufacturing equipment
• Run competitive prize challenges for design and build of moderately complex systems (e.g. go-carts, mobile robots, small UAVs, etc.)
• Outreach Objectives:
  • 10 schools in CY12
  • 100 schools in CY13
  • 1,000 schools in CY14
• Participation by domestic and foreign schools
Experimental Crowd-derived Combat support Vehicle (XC2V)

Goal
• Experiment in crowd-sourced design
• Militarily-relevant application
• Existing (simple) commercial infrastructure

Approach
• Utilize existing social network of ~20,000 from Local Motors (increased by ~3,000)
• Crowd-source design of a combat support vehicle
• $10k in prizes
• Build in existing micro-factory

Results
• 159 final designs submitted
• 100 of “high caliber” according to DARPA Service Chiefs Fellows
• 4 week design period
• 14 week build period
AVM Portfolio Schedule

<table>
<thead>
<tr>
<th>CY09</th>
<th>CY10</th>
<th>CY11</th>
<th>CY12</th>
<th>CY13</th>
<th>CY14</th>
<th>CY15</th>
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<td>FY11</td>
<td>FY12</td>
<td>FY13</td>
<td>FY14</td>
<td>FY15</td>
<td></td>
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</tbody>
</table>

- META
  - Tools & Metalanguage
- META-X
  - Tools Maturation
- C2M2L-1
  - Mobility Drivetrain Library
- C2M2L-2
  - Chassis & Surv Library
- C2M2L-3
  - Full IFV Model Library
- iFAB
  - Tools & Model Library
- iFAB-F
  - Configure, Build, and Operate Foundry
- vehicleforge.mil
  - Crowd Source Design Infrastructure Development and Maintenance
- XC2V
  - CS Pilot
- FANG
  - Execute Adaptive Make Challenges
- MENTOR
  - Distributed Manufacturing High School Outreach
- SBIR Portfolio
  - Large-Scale Manufacturing in Quantities of One
- META-X
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### META

<table>
<thead>
<tr>
<th>Organization</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dassault Systèmes</td>
<td>Extension of commercial CATIA/DELMIA PLM suite to enable formal verification</td>
</tr>
<tr>
<td>Vanderbilt Univ (Dr. Bapty)</td>
<td>Compositional cross-domain tool-chain analysis templates that support deep domain analysis</td>
</tr>
<tr>
<td>Vanderbilt Univ (Dr. Neema)</td>
<td>Rich model-based approaches developed for software and VLSI into the CPS world</td>
</tr>
<tr>
<td>Xerox PARC / CyDesign</td>
<td>Function-based framework for co-verification assessment and reasoning at early stages of design</td>
</tr>
</tbody>
</table>

### iFAB

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<thead>
<tr>
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</tr>
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<tbody>
<tr>
<td>Boeing/General Motors</td>
<td>Manufacturing capability and process model library with describing foundry resources &amp; human actors</td>
</tr>
<tr>
<td>Carnegie Mellon Univ</td>
<td>Distributed agents/process model approach for two-way interface between CAD and CAM systems</td>
</tr>
<tr>
<td>Intentional Software</td>
<td>Formal “meta meta” language to enable multi-domain co-design of artifact &amp; manufacturing</td>
</tr>
<tr>
<td>Penn State ARL</td>
<td>Agent-based foundry configuration and trade space visualization</td>
</tr>
<tr>
<td>Univ of Delaware</td>
<td>Developing compositional cross-domain tool-chain analysis templates for composites manufacturing</td>
</tr>
<tr>
<td>Xerox PARC</td>
<td>Rapid construction and search of feasible manufacturability spaces and metrics for such spaces</td>
</tr>
<tr>
<td>Georgia Tech GTRC</td>
<td>Creating adaptable software libraries of manufacturing processes pertinent to the fabrication of electro-mechanical components and/or assemblies</td>
</tr>
</tbody>
</table>

### vehicleforge.mil

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<th>Organization</th>
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<tbody>
<tr>
<td>GE Research/MIT</td>
<td>Custom collaboration site linking to MIT DOME model repository and social network challenge platform</td>
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<tr>
<td>Georgia Tech GTRI</td>
<td>Collaboration site based on open source distributed version control system; teamed with RedHat</td>
</tr>
<tr>
<td>Vanderbilt University</td>
<td>Collaboration site derived from KForge software and information forge site platform</td>
</tr>
<tr>
<td>Univ of Pennsylvania</td>
<td>Credentialing users and contributions utilizing reputation-based quantitative trust management</td>
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### MENTO

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<tbody>
<tr>
<td>Georgia Tech/Dassault</td>
<td>Sophisticated distributed manufacturing front-end based on Dassault CAD, low-cost 3D printer network</td>
</tr>
<tr>
<td>O’Reilly Media</td>
<td>Novel approach to assembly of complex 3D shapes from 2D media, use of MAKE Magazine, Maker Faires</td>
</tr>
</tbody>
</table>
### Example elements of a component model

<table>
<thead>
<tr>
<th>Physical attributes</th>
<th>Component</th>
<th>Subassembly</th>
<th>Assembly</th>
<th>Structure</th>
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<tr>
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<td><img src="image" alt="Component" /></td>
<td><img src="image" alt="Subassembly" /></td>
<td><img src="image" alt="Assembly" /></td>
<td><img src="image" alt="Structure" /></td>
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<tr>
<td>- mass properties</td>
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<td><img src="image" alt="Data" /></td>
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<td><img src="image" alt="Interface" /></td>
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<td><img src="image" alt="Power" /></td>
<td><img src="image" alt="Mechanical" /></td>
<td><img src="image" alt="Interface" /></td>
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<tr>
<th>Undesirable emissions</th>
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<th><img src="image" alt="EM" /></th>
<th><img src="image" alt="Vibrational" /></th>
<th><img src="image" alt="Undesirable" /></th>
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<tbody>
<tr>
<td>- thermal</td>
<td><img src="image" alt="Thermal" /></td>
<td><img src="image" alt="EM" /></td>
<td><img src="image" alt="Vibrational" /></td>
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<tr>
<td>- vibrational</td>
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