Advancing Model-based Engineering through Improved Integration of Domain-Specific Simulation and Analysis using SysML-based Models for Unmanned Aerial Vehicles

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Introduction

• With an increasing reliance on unmanned aircraft vehicles (UAVs) for a large variety of military missions, the capability to design them for customized requirements is highly desirable

• An agile and speedy design process is, therefore, integral to a robust modeling, simulation, analysis, and design capability as it allows for efficient identification of new solutions

• Architecture-centric (and model-centric) approaches can be considered a potential solution to address this challenge

• There has been growing interest in adopting the Systems Modeling Language (SysML)\textsuperscript{1} and other similar MBSE tools for simulation-based engineering activities including the references below\textsuperscript{2}

• However, these do not focus on the challenges regarding variant-based design (a critical system architecture decision)

\textsuperscript{1} Object Management Group 2017; Friedenthal, Moore, and Steiner 2015 \textsuperscript{2} Zhang et al. 2021; Ciampa and Nagel 2020; Ciampa, Rocca, and Nagel 2020; McKean, Moreland, and Doskey 2019; Vaneman, Carlson, and Parker 2021; Lu 2019
Variant-based Integrated (Simulink) Model

- In this work on aircraft design, the four subsystems are 1) Aerodynamics, 2) Engine, 3) Thermal Management System (TMS), 4) and Electrical Power System (EPS)

- A critical aspect considered in this work is when multiple different modeling options (termed variants) are available for a given piece of a system

- As an example, consider the following sets of variants for the four subsystems:

\[ \{\text{Aero}\} \times \{\text{Engine-A, Engine-B}\} \times \{\text{TMS-A, TMS-B, TMS-C}\} \times \{\text{EPS-A, EPS-B}\} \]

which has 12 unique complete variant architectures using the Cartesian product\(^1\) with one specific architecture being \{Aero, Engine-A, TMS-C, EPS-B\}

- Here, the external analysis tool, Simulink, supports variant systems\(^2\)

- We change the variant selections through the SysML-based model by passing values to a Matlab script that performs the programmatic change

- Specific information on the physics models used in each of these subsystems can be found in the paper

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\(^1\) The variant-based approach is an instance of the combining pattern (Selva, Cameron, and Crawley 2016)

\(^2\) MathWorks 2022c
Software Architecture Components

- There are several key components that define the composition of the software architecture
  
  1. *SysML modeling tool* that supports the desired SysML version and other modeling capabilities\(^1\)
     - Cameo Systems Modeler (CSM) v19.0 SP4\(^2\) supporting SysML v1.5
  
  2. *Executable SysML model capabilities* that supports the desired interfacing and execution with the desired domain analysis tool(s)
     - Cameo Simulation Toolkit (CST) v19.0 SP4\(^3\) as it supports integration with Matlab
  
  3. *External analysis tool(s)* for simulations that are desired to be integrated into the SysML model — compatibility between the executable SysML model capabilities and external tools is required
     - Matlab/Simulink R2020b\(^4\) as it is the supported version for the existing aircraft subsystem simulation models

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\(^1\) Object Management Group 2017  \(^2\) No Magic 2020a  \(^3\) No Magic 2020b  \(^4\) MathWorks 2020
**Approach Overview**

- **System Requirements**
  - Aircraft definition with values, constraints, and requirements
  - Subsystem
    - Requirements
      - Requirement
  - Subsystem
    - Requirement

- **Aircraft**
  - Requirement Analysis
  - Run Simulation

- **System context**
  - Analysis

- **Variant-based Simulink Model**
  - Tool-specific implementation running a simulation with aircraft and context inputs

- **Requirements Context**
  - Mission, Requirement Values, Requirement Analysis Parameters, etc.
  - Data File
Thermal Management Subsystem (TMS) Definition with its Variants

Model Name = VCS_3

«interfaceBlock»
TMS Simulink Interface
proxy ports
FromEngine
FromAFTMS
FromEFTMS
FromAero
FromEPS
ToEngine
ToAFTMS
ToEFTMS
ToAero
ToDataOut

Get values from data file

Evaluate and visualize requirements

Simulation result value properties

Variable names in Matlab context

Selected variant name from variants list

«AFRL Simulink»
VCS_3 : Thermal Management
[Matlab Version = "r2020b",
Point of Contact = Dominic Dierker,
Reviewer = Soumya Patnaik,
Status = Complete,
Version Number = "1.2"]

Model Name = VCS_3
Simulation Executable with Links to the Requirements Context and Aircraft

- Model Name: Engine Variants
- Extract Engine Values
- Constraint
- Aerodynamics
- Model Name: Aero Variants
- Extract Aero Values
- Constraint
- Thermal Management
- Model Name: TMS Variants
- Extract TMS Values
- Constraint
- EPS
- Model Name: EPS Variants
- Extract EPS Values
- Constraint
- Run Simulation
- IsSimulated [1]
- ResultFile: String
- ResultFile[1]
- ResultFile[1]
- ResultFile[1]
- ResultFile[1]
Management and Other Activities through the SysML-based Model

- There are a variety of realizable advantages when deploying SysML-based models as the pillar for system development activities.
- Some of these advantages are described in the literature\(^1\).
- In the paper, we discuss some of the specific existing and new use cases realized in this work that better support the integration of analysis/simulation/design-focused teams, including:
  - Standardization of organizational practices
  - Documentation
  - Stakeholder dialog and artifacts

\(^{1}\) Borky and Bradley 2019; Friedenthal, Moore, and Steiner 2015
Customized Stereotypes for Improved Standardization and Documentation

For defining the metadata for any element that is managed like a diagram or model.

For capturing external artifacts like presentations, reports, etc.
Activity Diagram Showing the Workflow for Running a Simulation

Diagram info can be customized (and standardized). Uses AFRL Actors

- Aero Variants Library
- Engine Variants Library
- EPS Variants Library
- TMS Variants Library

Select Subsystem Variants

Select Requirements Context

Linked model elements

Run Simulation Configuration

- Run Single System
  - Run Simulation
  - Run_Simulation

«centralBuffer» Data File (.mat)

Hyperlinked to the Matlab script (so will open Matlab when double clicked)

Run Requirements Analysis

- Aero Variodynamics Constraints
- Engine Constraints
- TMS Constraints
- Requirements

Context

Requirement Parameters

Aero Variants Library

Engine Variants Library

EPS Variants Library

TMS Variants Library

Modification date 11/27/22 10:56 PM
Point of Contact Dan Herber
Reviewer Dominic Dierker, Soumya Patnaik
Version Number 1.0
Status Needs Review
Definition and Usage of Actors for Managing Various Model Elements

<table>
<thead>
<tr>
<th>Model</th>
<th>Actors [Model::AF]</th>
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<tbody>
<tr>
<td>1 Aircraft [Requirements]</td>
<td>Dan Herber</td>
</tr>
<tr>
<td>1.2 Engine</td>
<td>Dominic Dierker</td>
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<tr>
<td>Analysis_Workflow [Analysis::Run Single System]</td>
<td>Soumya Patnaik</td>
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Legend:
- Point of Contact
- Reviewer

Legend:
- Model
- Aircraft [Requirements]
- Analysis_Workflow [Analysis::Run Single System]
- TMS Variants Library [Structure]
- Ram_ACS_3 : Thermal Management
- Ram_3 : Thermal Management
- VCS_3 : Thermal Management
Results Summary

- Here we show technical feasibility of the proposed approach combining an integrated variant-based Simulink model with a SysML-based model for various engineering activities

- The 16 combinations simulated are a product of the 4 different TMS subsystem variants, 2 different EPS variants (an empty and a specific nonempty case), and 2 different flight missions

<table>
<thead>
<tr>
<th>Looking Ahead</th>
</tr>
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<tbody>
<tr>
<td>Anecdotally, the SysML model has enabled better communication and a more rapid generation of artifacts for various reviews and presentations. Still, future work remains to explore the added value of the SysML-informed development process formally.</td>
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</tbody>
</table>
Various Trajectories for the 16 Different Configurations Simulated (1)
Various Trajectories for the 16 Different Configurations Simulated (2)
Conclusion and Future Work

- We have explored how modern MBE and MBSE activities will be better supported with integration with SysML-based modeling techniques and tools.
- The demonstration application using SysML in Cameo Systems Modeler linked with detailed physics-based Simulink models focused on UAVs.
- Supported the definition and simulation of 16 distinct configurations (with the potential of 100+ configurations soon).
- Also enabled other typical management and engineering activities.

Looking Ahead

Potential future work items include:

- Effective combined version control
- Integration physical test data
- Design and optimization capabilities (perhaps with other tools\(^1\))
- Consideration of tools like the Requirements Toolbox\(^2\) and Simulink Test\(^3\)
- Functional Mock-Up Unit (FMU)-based approach\(^4\)

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1. Ko, Keel, and Beale 2022  
2. MathWorks 2022a  
3. MathWorks 2022b  
4. Blockwitz et al. 2012; Modelica Association 2022


References (continued)

Y. Zhang et al. (2021). “Towards holistic system models including domain-specific simulation models based on SysML”. *Systems* 9.4. DOI: 10.3390/systems9040076
Thanks!

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