Modeling & Simulation of CubeSat Mission

Model-Based Systems Engineering (MBSE) Behavioral Modeling and Execution Integration of MagicDraw, Cameo Simulation Toolkit, STK, and Matlab using ModelCenter



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System Engineering Challenges

Conventional approaches:

- Focus on subset of subsystems
 - Over-simplified, low fidelity
 - Neglect subsystem interactions
- Requirements verification using average/best/worst-cases
 - Fail to capture realistic "dynamic" nature of missions
- Models and simulations are not integrated!
 - "Hacked" together for one-off cases
 - Not modular, extensible, reusable





System Engineering Challenges

Particularly an issue for CubeSats¹ because:

- Physical components physically integrated
- Extremely constrained:
 - Limited ability to collect and store energy (e.g. batteries)
- Operational constraints/ decisions coupled
 - When to collect data versus download data?
- Obits are unknown/ dynamic
 - Little/ no control over launch orbit
 - Experience variation in eclipse duration, may de-orbit
- Operate in inefficient/ stochastic environments





Integrated models and tools are critical to design and plan for these missions!

¹Type of miniature spacecraft (1U = 10cm³, <1 kg)



Image Credit: www.cubesatkit.com

Model-Based Systems Engineering (MBSE¹)

Why MBSE?

- 1) Enables system-level model capture
 - Formal, accurate, authoritative single source
 - Contains elements, relationships, interactions
 - Multiple compatible views, e.g. physical/ functional
 - Requirements verification and traceability



¹ "Formal" model to support requirements, design, analysis, verification





Model-Based Systems Engineering (MBSE)

Why MBSE?

2) Enables integration of models and simulations

- Connect system-level model to analytical tools (STK, Matlab)
- Execute dynamic simulation of end-to-end mission •
- Identify failure to satisfy requirements, sub-optimal designs •
- Accommodates re-evaluation when design changes occur
- Enables co-simulation: simultaneous vehicle/ mission design •







Motivation Overview Modeling Simulating Design Trades Reflections Future Work





Motivating Mission Example

- Radio Aurora Explorer (RAX) CubeSat mission
- Science target: plasma irregularities in ionosphere
- Experimental zone in Poker Flat, Alaska
- Global ground station network
- Vehicle constraints: solar panels, battery, data buffer



RAX Ground Network footprints

Motivating Mission Example

Systems engineering questions:

- How do satellite states evolve throughout mission?
- Does the vehicle design/operations meet all mission requirements?
- How do changes in spacecraft mission parameters impact performance and requirements satisfaction?





Motivation

Overview

Modeling

Simulating

Reflections

Future Work

Design Trades



Project: "Model" Operational CubeSat Mission goals....

Goal #1: Develop fundamental systems model of CubeSat mission

Capture structure, function, relationships, requirements, traceability. *Pretty clear-cut if you know what you're modeling. Accomplished by SSWG*^{1,2}.

Goal #2: Execute realistic behavioral CubeSat scenarios

Capture operational opportunities, state evolution, mission performance. *No clear way to do this in March 2013.*

Potential tools: MagicDraw? Simulation Tool Kit (STK)? Matlab? Phoenix ModelCenter? Cameo Simulation Toolkit?

[1] S. Spangelo, D. Kaslow, C. Delp, L. Anderson, B. Cole, E. Foyse, L. Cheng, R. Yntema, M. Bajaj, G. Soremekum, and J. Cutler, "<u>Model Based Systems Engineering (MBSE) Applied to Radio Aurora Explorer (RAX) CubeSat Mission Operational</u> <u>Scenarios</u>", Accepted for IEEE Aerospace Conference, 2013, Big Sky, MT, March 2013.

[1] S. Spangelo, D. Kaslow, C. Delp, B. Cole, L. Anderson, E. Fosse, L. Hartman, B. Gilbert, and J. Cutler, "<u>Applying Model Based</u> <u>Systems Engineering (MBSE) to a Standard CubeSat</u>", IEEE Aerospace Conference, 2012, Big Sky, MT, March 2012.





Project: "Model" Operational CubeSat Mission accomplished...

Project Deliverables:

- Systems-level SysML model (in MagicDraw)
 - Structure of mission architecture and vehicle
 - Requirements definition and traceability
 - Parametric diagrams to capture analytical relationships
 - Evaluated using MBSE Analyzer
 - Behavioral diagrams to capture dynamic operations
 - Executed using Cameo Simulation Toolkit and MBSE Analyzer¹
 - Analytical models for describing behavior
 - STK, Matlab, Java
 - ModelCenter enabled integration with SysML and automated execution of dynamic scenarios

Image Generated with STK





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Modeling Philosophies

For usability/ extensibility:



- *Patterning*: re-use of modeling patterns *e.g. common pattern in Power and Data Management subsystems*
- *Nomenclature*: simple and sufficiently descriptive *e.g. subsystem naming codes used for data rate and power values*





CubeSat System Model Architecture



PHOENIX

The system model captures requirements, structure, behavior, and parametrics.

11

Structural Diagrams

Motivation Overview Modeling Simulating Design Trades Reflections Future Work







Mission Level

Vehicle Level

Defines constraint on lowest battery level throughout mission

Mission Requirements Drive systems design

Defines constraint on minimum download

Motivation Overview Modeling Simulating Design Trades Reflections Future Work





Defines constraint on lowest data storage level throughout mission



Parametric Diagram

Constraint blocks defines opportunities

Motivation Overview Modeling Simulating Design Trades Reflections Future Work





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Pointing to a ModelCenter model with STK and Matlab



ModelCenter Model STK and Matlab Plug-Ins

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- Analysis models (STK, Matlab) wrapped and integrated with ModelCenter •
- ModelCenter models imported into SysML model constraint blocks with **MBSE** Analyzer



Systems Tool Kit (STK)

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Analytic simulation tool used to propagate obit & compute:

- Solar state: sun/eclipse, solar panel angles
- Access to experimental zone
- Access to ground stations











Parametric Diagrams Constraint blocks computes total power





Parametric Diagrams

Constraint blocks update satellite states

- Compute energy level at the next time step
- Similar parametric diagrams for experiment data and data download

MBSE Analyzer: Parametric Diagram Solver

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- Solves linked parametric diagrams (all 3) simultaneously
- Automated requirements verification (green: pass, red: fail)

Bringing the Model to Life Main State Machine Diagram

- Entry point of Cameo Simulation Toolkit (CST) behavioral simulation
- Starts "RunOperation" activity diagram that steps through mission simulation
 - Updates solar, experiment, and download states according to signals

Main Simulation Loop

How are Mission Simulations Performed?

Mission Simulation Results

Motivation Overview Modeling Simulating Design Trades Reflections Future Work 2

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- During CST simulation, MBSE Analyzer is called at each time step
- Data Explorer automatically stores time history of the simulation data

Mission Simulation Results

Motivation Overview Modeling Simulating Design Trades Reflections Future Work

energy_level (J)

- Combined simulation SysML behavioral diagrams to STK, Matlab using MBSE Analyzer
- MBSE Analyzer is called at each time step during CST simulation
- Time history of energy level, experiments, and data download is stored

Final Step: Requirements Verification Full end-to-end (dynamic) scenario

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	Analyzer Edit View Tools Help					
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Future Work						
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- Post-CST simulation: final state stored in an instance specification
- Use MBSE Analyzer to verify requirements with visual tool!

Mission and Design Trade-Offs Battery Capacity

Mission and Design Trade-Offs Orbit Altitudes

Nominal: semi-major axis = 7012km, apogee altitude = 811.69 km, perigee altitude=457.57 km High: semi-major axis = 7500 km, apogee altitude = 1311.22 km, perigee altitude = 932.50 km Low: semi-major axis = 6800 km, apogee altitude =593.55 km, perigee altitude=250.18 km

Motivation Overview Modeling Simulating Design Trades Reflections Future Work

28

Mission and Design Trade-Offs Ground Station Locations

Location And Description Of Ground Stations In Network

Name	State	Latitude (degrees)	Longitude (degrees)	Altitude (km)	Minimum Elevation (degrees)	Efficiency
AnnArbor	MI	42.271	-83.73	0.256	5	0.8
Fairbanks	AK	64.88	-147.5	0	0	1
MenloPark	CA	37.457	-122.2	0.022	0	0.95

Reflecting on Project Experience

How did MBSE enable us to overcome challenges?

- Coupled analytic models with simulation capabilities
- Demonstrated dynamic behavioral modeling
- Achieved requirements verification for full end-to-end missions
- Extensible by use of standards, libraries, patterns, etc.

Lessons Learned

- Working with many tools is challenging (license, versions, etc.)
- STK has a lot of flexibility: exploit use vectors/ angles
- Best to automate repeated tasks
- Working with vendors is necessary/advantageous
- Always ask: "Am I using the right modeling/simulation tool?"

Motivation

Overview

Modeling

Simulating

Reflections

Future Work

Design Trades

30

Future Work

- Extend the system-level model
 - Higher fidelity models of the spacecraft subsystems
 - Include communication and experimental link budgets
- Extend and refine the behavioral and analysis models
 - Add spacecraft scheduling for optimal use of resources
 - Improve approach for data extraction at specific time (e.g. from STK)
- Automate system and mission parameters trade-offs
 - Extend MBSE Analyzer to drive simulations by CST
 - Enable sensitivity analysis and design optimization
- Generalize the model for applicability to a variety of mission concepts

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- CubeSat and Amateur Radio Communities
- Dr. Derek Dalle (graphics)

