A Model-Based Design & Testing Approach for Orion GN&C Flight Software Development

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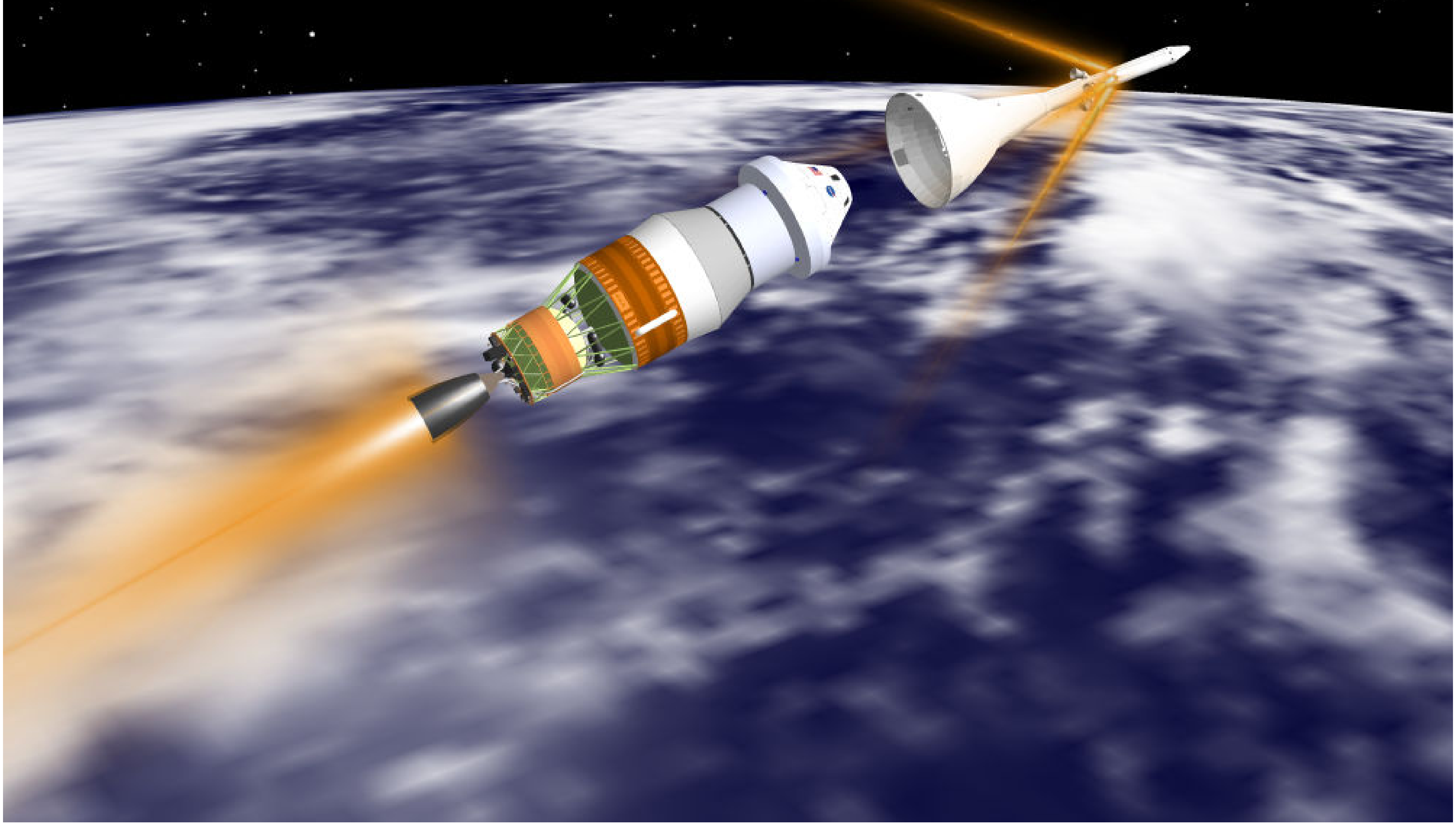


References

- **This presentation is based on the following conference papers:**
  - A Model-Based Design & Testing Approach for Orion GN&C Flight Software Development
    - 2010 IEEE Aerospace Conference, paper #1491
  - Orion GN&C Model Based Development: Experience and Lessons Learned
    - 2012 AIAA GN&C Conference, paper #2012-5036

Overview

- Introduction
- GN&C FSW Development Process
- GN&C Architecture
- Development Tools
- Inspection Process and CSU Memo
- Unit Testing for Models and Autocode
- Rhapsody Architecture
- Process Benefits, Lessons Learned & Challenges

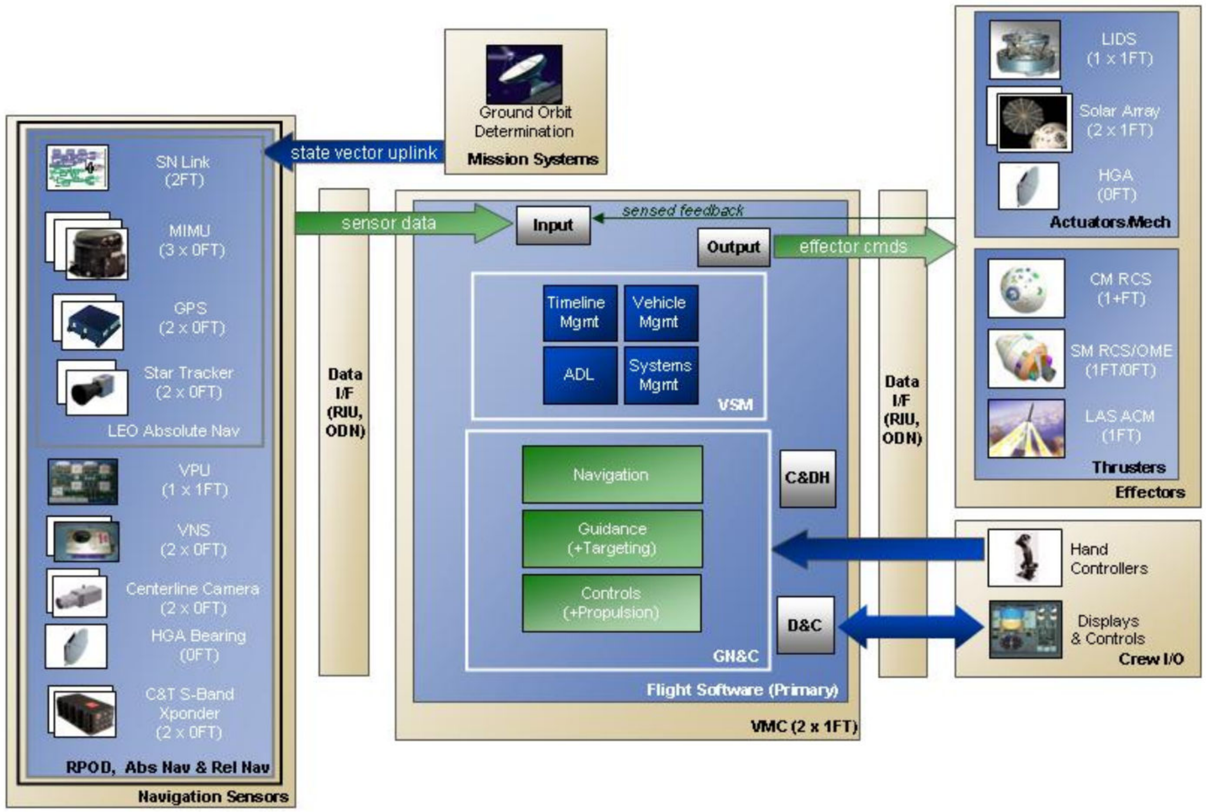
Introduction: Orion GN&C Subsystem

Project Orion

Orion GN&C flight software developed using Model Based Design (MBD)

Original design was for LEO and Lunar Operations (Scaled Back for EFT-1)

Early in the Orion program Matlab/Simulink were selected as GN&C development Tool



- **Complex FSW executes GN&C for multiple mission phases (Ascent, Orbit, Entry)**
  - Interface with multiple sensors, effectors, and crew
  - GN&C FSW executes in an ARINC 653 partition

Introduction: Exploration Flight Test One

- **Orion will be the first human spacecraft built by NASA in 3 decades**
- **New flight-test based approach is now being used, so first mission for GN&C software on Orion avionics will be Exploration Flight Test One (EFT-1)**
  - Previous Pad Abort One flight test also used MBD but a somewhat different process
  - The EFT-1 mission includes an elliptical orbit designed to increase entry velocities to test thermal components – commercial booster used for launch system
  - FSW modes for EFT-1 include: Pad align, ascent navigation, orbit coast, CM translation burn, guided direct entry, drogue rate damping, touchdown roll control

Development Process: Traditional vs Model Based Development

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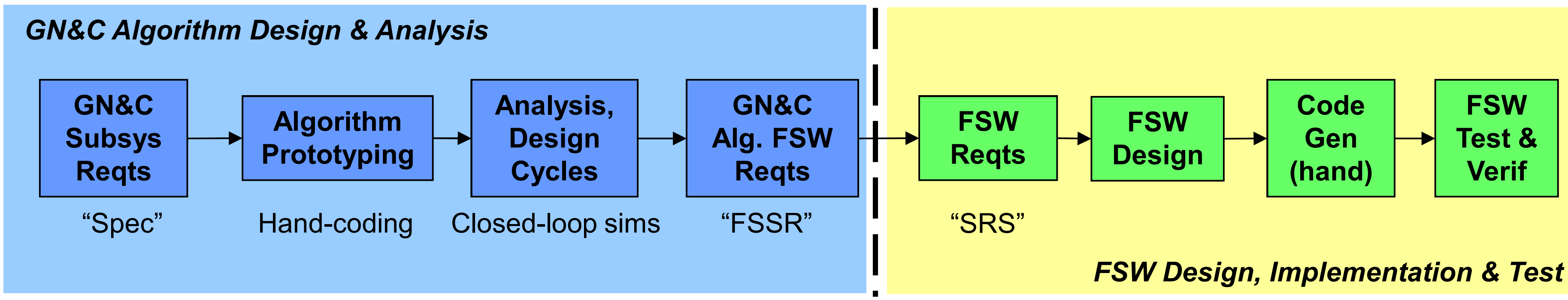
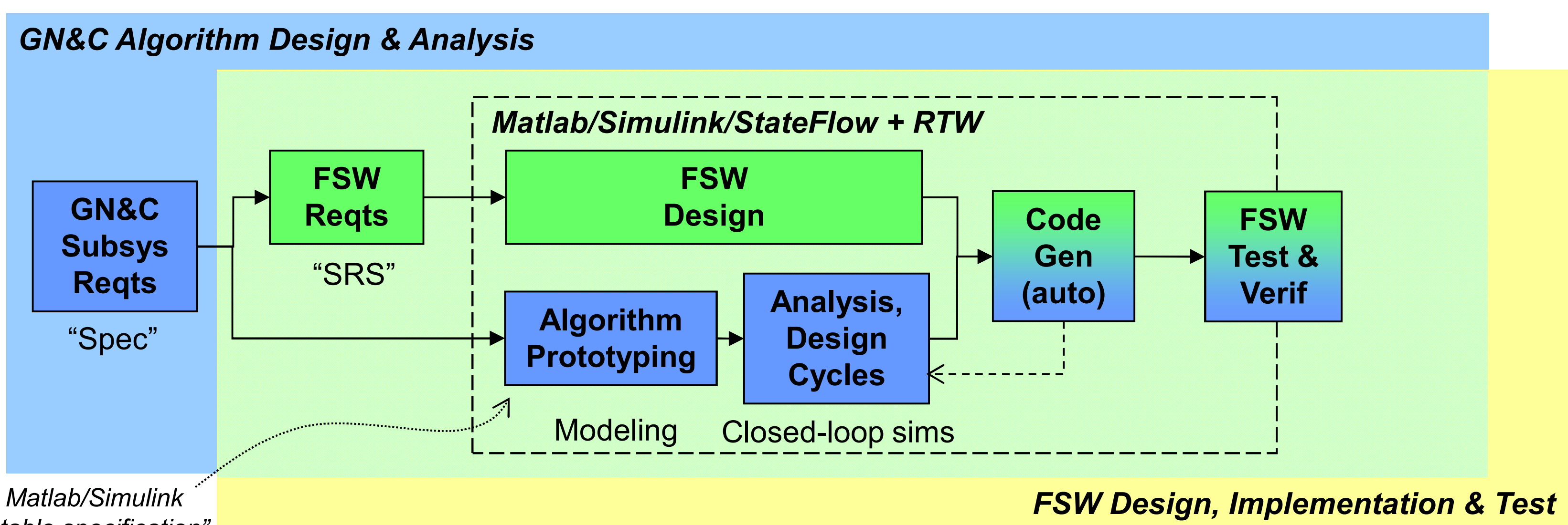
Responsibility
GNC Team
FSW Team

"Traditional" GN&C FSW Development



Orion GN&C FSW Development



Modeling in Matlab/Simulink is the "exeutable specification", and essentially replaces the "FSSR"

Development Process: GN&C/FSW Team Interface

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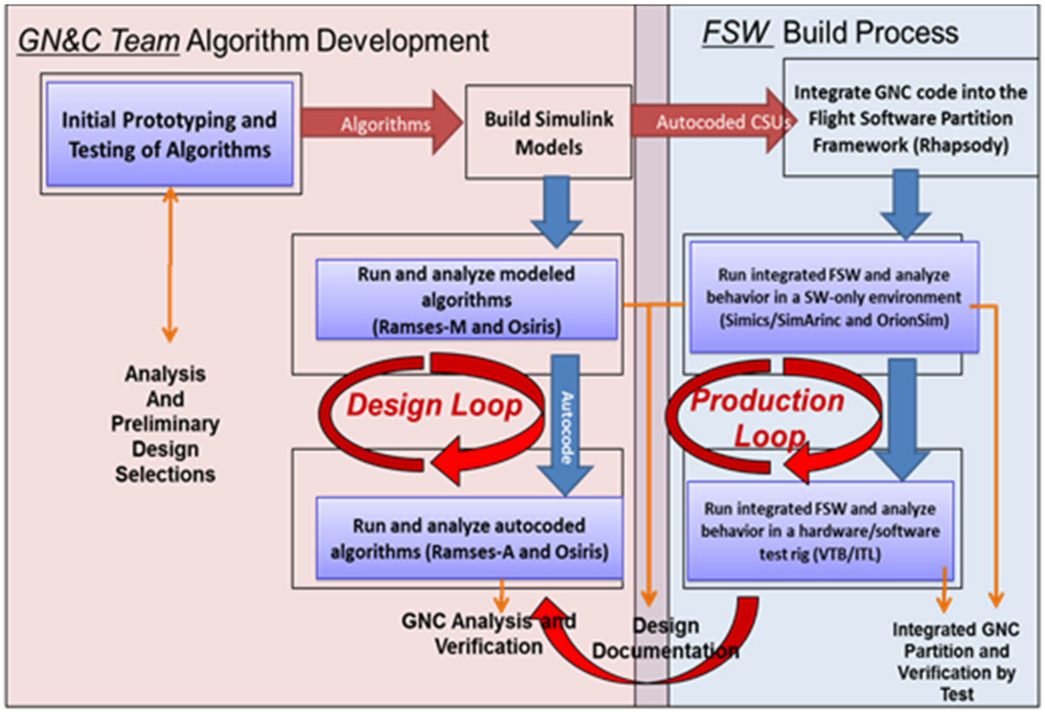
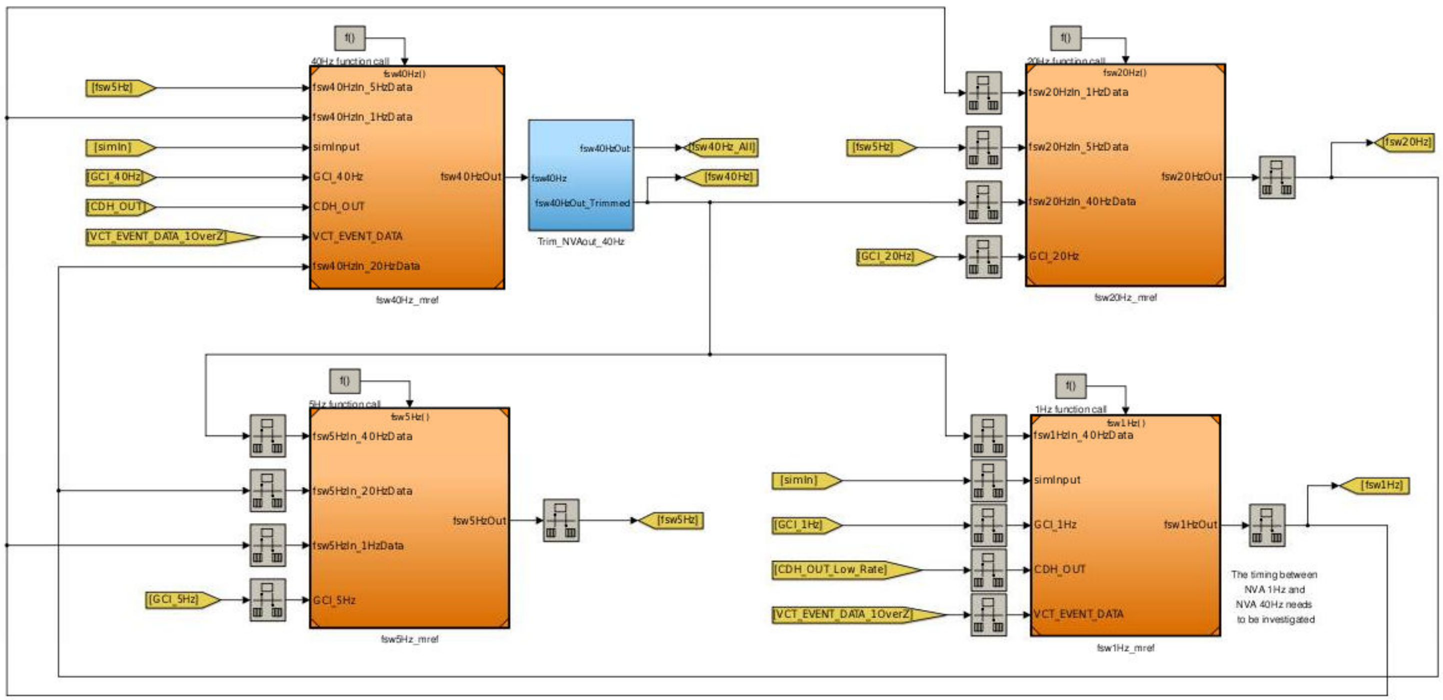
GN&C algorithm and FSW development cycle



- **Algorithms developed as Computer Software Units (CSU) using Simulink**
- **Integrated and matured using RAMSES-M and tested using RAMSES-M and RAMSES-A**

- **After iterating and maturing algorithms in the "design loop" the autocoded CSU's were delivered to GN&C FSW, where they were integrated into the ARINC 653 GN&C partition**
  - The GN&C partition may be executed either on target hardware (real-time only) or by using software emulators. Partition development and test is referred to as the "production loop"
  - Problems encountered during hardware integration that affect the Simulink models are fed back to the GN&C team for rapid fixes. No manual modification of the autocode is allowed.

GN&C Architecture

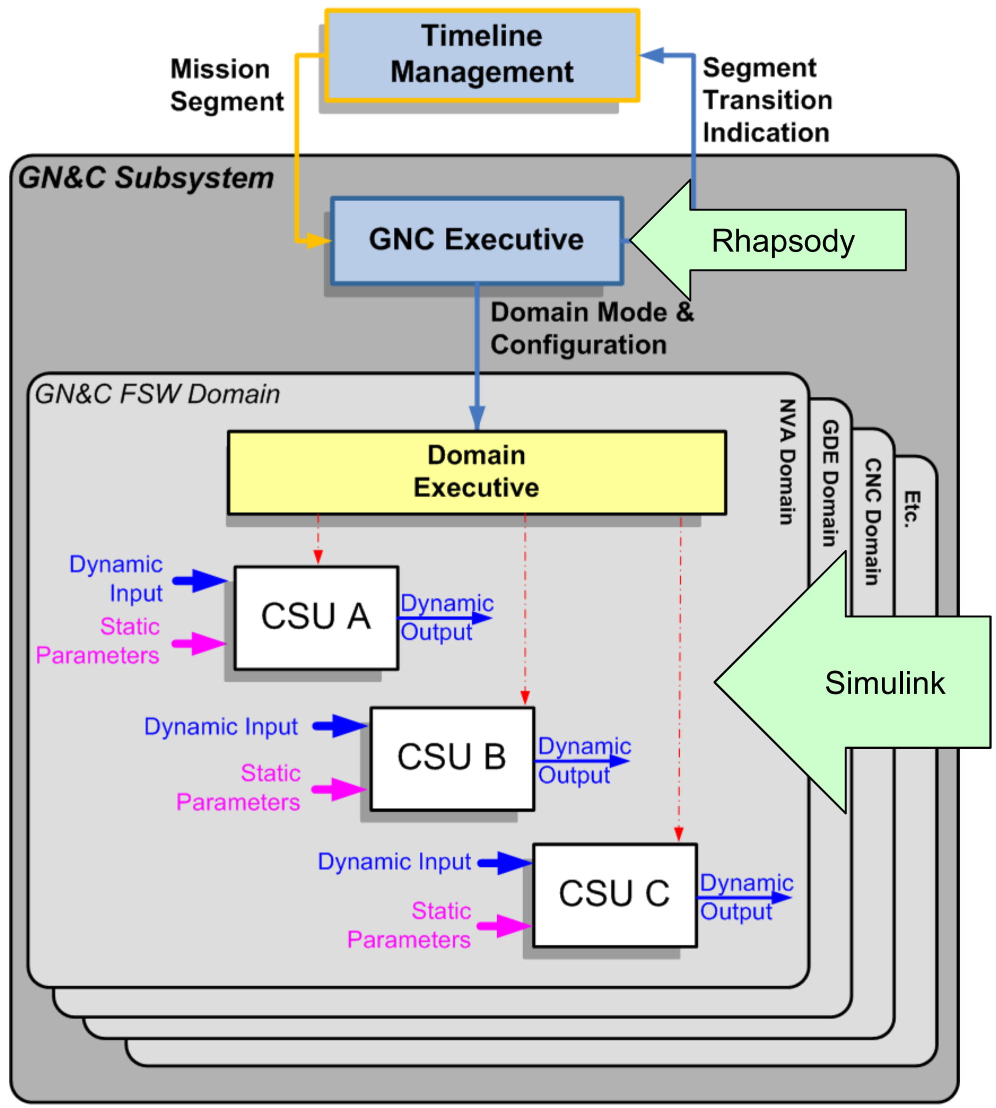


- **CSU's are collected into rate groups (1 Hz, 5 Hz, 20 Hz and 40 Hz) and then into domains (guidance, navigation, control) – this simplifies the emulation of rate group interaction within Simulink**
- **Figure shows the top level RAMSES-M diagram with each rate group**

GN&C Architecture

- GNC design is a hierarchical decomposition of flight software by flight phase & function
- Centralized GNC Executive coordinates via GNC Activities
- Data Driven Lists, Modes, Configs

GN&C Domain	GN&C Domain Functionality
GCI	*GN&C Command Interface*
NVA	Absolute Navigation
NVR	Relative Navigation (Rendezvous)
NVE	Ephemeris Processing
NHM	*Navigation Health Manager*
GMP	Vehicle Mass Properties
GDA	Ascent Guidance
GDE	Entry Guidance
GDO	On-Orbit Guidance
GHM	*Guidance Health Manager*
CNC	Command-Module (CM) Control (Entry)
CNS	Service-Module (SM) Control (Ascent, Orbit)
CNL	Launch Abort System (LAS) Control (Ascent)
CNE	Propulsion Engine Control
CNP	Propulsion Systems Control
CHM	*Control Health Manager*

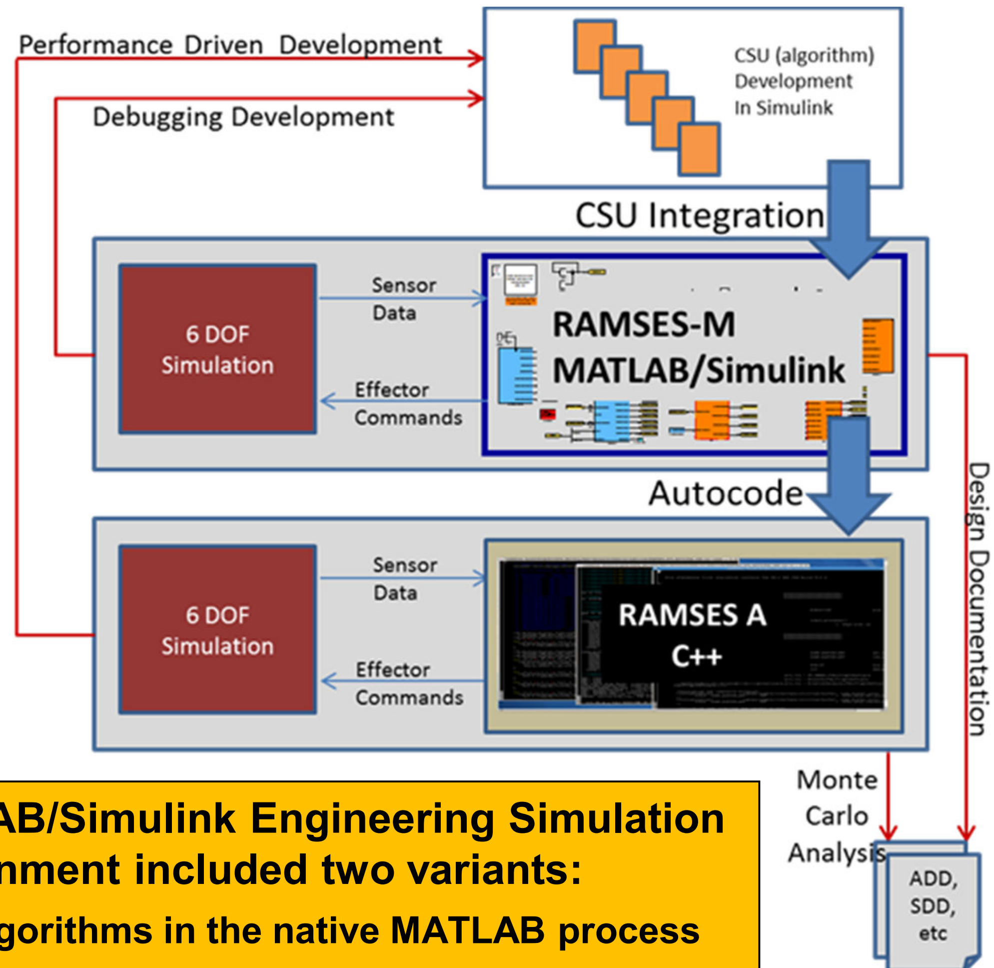


Development Tools: Simulation Tools

Working, well understood legacy simulations, together with the desire/requirement for autocode led to a hybrid tool set

Hybrid Tools

legacy 6 DOF simulations were attached to MATLAB process for Simulink algorithm development, debugging and test.

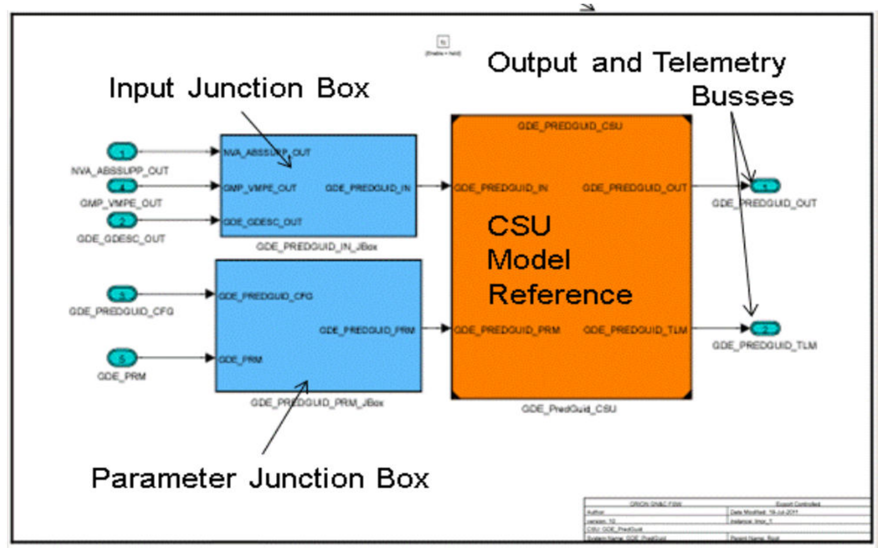


- **Termed The Rapid Algorithm MATLAB/Simulink Engineering Simulation (RAMSES), the hybrid environment included two variants:**
  - **RAMSES-M executed the GN&C algorithms in the native MATLAB process**
  - **RAMSES-A executed the autocoded algorithms in a hand coded wrapper for higher speed execution and Monte Carlo Analysis**

Development Tools: GN&C CSU's and Domains

Project Orion

- **GNC CSU's are expressed as Simulink diagrams housed within model reference blocks (MRBs)**
  - MRBs allow CSU's to be housed in separate files for configuration management – simple subsystems would mean that all changes are made to a single file.



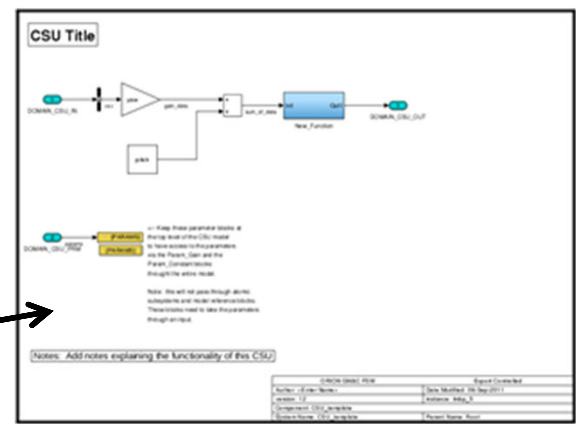
- **Each CSU has 4 interfaces which are expressed as Simulink bus types:**
  - Inputs – time varying signals from upstream CSU's or sensors
  - Parameters – static values that are initialized upon SW load. Some parameters may be changed on events by the automation and sequencing software.
  - Outputs – signals produced for consumption by downstream CSU's or effectors
  - Telemetry – items needed for analysis of internal functioning
- **Junction boxes pick off output signals from upstream CSUs or parameter buses**
- **CSU's are unit tested with drivers that populate inputs and parameters and compare outputs.**

Development Tools: Orion Library and CSU Template

- **Modeling library and template**
  - All Simulink atomic-level blocks were reproduced in an Orion library to provide control over autocode configurations, standards on settings, etc. This is highly recommended for serious MBD projects
  - Orion developed a template for all CSU's to provide uniformity, limit diagram size in a layer, and provide printable artifacts.
  - A standard configuration set was used by all CSUs to ensure compatibility and autocode efficiency

Orion Block Library

Orion CSU Template



Development Tools: Modeling Standards and Guidelines

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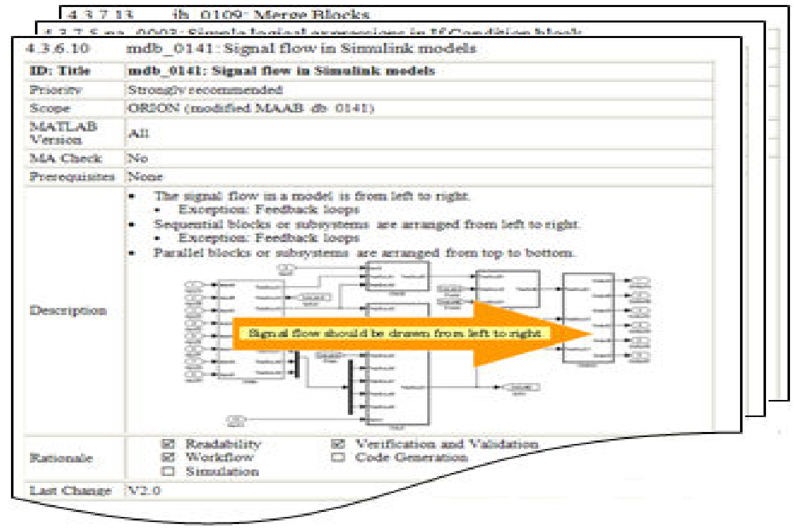
- **When the program started, there were no Aerospace Specific Modeling standards**
  - Needed a Standard for modeling the GN&C algorithms in Simulink, Stateflow, and embedded Matlab (eML).
- **Started with Automotive Industry's published "MAAB" (MathWorks Automotive Advisory Board) Standard**
  - This document was tailored (via GNC & FSW splinter team) based on previous experiences and known architectural drivers for the Orion GN&C FSW.
- **Standards are available from the Mathworks website for the aerospace community.**
- **Three major drivers behind the standards**
  - Compatibility
  - Autocode Quality
  - Readability
  - Efficiency



4.3.6.10 mdb_0141: Signal flow in Simulink models

ID: Title	mdb_0141: Signal flow in Simulink models
Priority	Strongly recommended
Scope	ORION (modified MAAB db_0141)
MATLAB Version	All
MA Check	No
Prerequisites	None
Description	• The signal flow in a model is from left to right. • Exception: Feedback loops • Sequential blocks or subsystems are arranged from left to right. • Exception: Feedback loops • Parallel blocks or subsystems are arranged from top to bottom. Signal flow should be drawn from left to right.
Rationale	☒ Readability ☒ Workflow ☐ Simulation ☒ Verification and Validation ☐ Code Generation
Last Change	V2.0

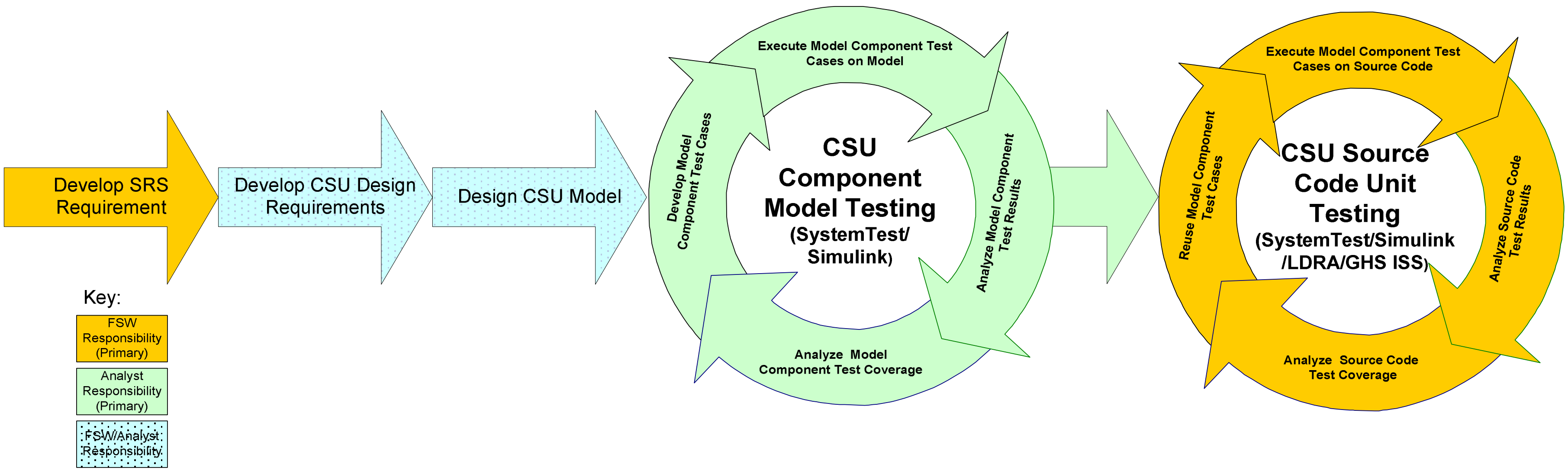
Algorithm Type	Simulink	Stateflow	eML	Notes/examples
Simple Logic •if/then •switch/case •for/while loops	X preferred	X	X	Ex: If/then with <5 paths and no nesting
Complex Logic •nested if/then •nested switch/case •nested for/while loops		X preferred	X	Ex: If/then with numerous paths and multiple levels of nesting
Simple/Short Numerical Expressions	X			Ex: <6 consecutive operations, <6 variables/signals
Complex/Lengthy Numerical Expressions	X either		X either	Ex: >6 consecutive operations, >6 variables/signals
Numerical Expressions containing continuously valued states	X*			Ex: Difference equations, integrals, derivatives, filters *The actual integrator function can be written in eML
Combination of: •Complex Logic •Simple Numerical Expressions		X		iterating a counter is considered a simple numeric calculation
Combination of: •Simple Logic •Complex Numerical Expressions	X either		X either	•Can use only Simulink, only eML or use Simulink for the logic and eML for the math
Combination of •Complex logic •Complex Numerical Expressions	X either for Math	X for Logic	X either for Math	•Use Simulink or eML for the numerical calculations •Stateflow should invoke the execution of this subsystem using a function-call
Modal Logic		X		Where the control function to be performed at the current time depends on a combination of past and present logical conditions

Inspections and CSU Memo

- Detailed inspections were performed on the models, not autocode – CSU Development Checklist were used to aid CSU preparation for reviews

- CSU memo's where generated to further document and clarify design, derived requirements, and testing

Unit Testing:
FSW CSU Simulink Model Design & Test Workflow

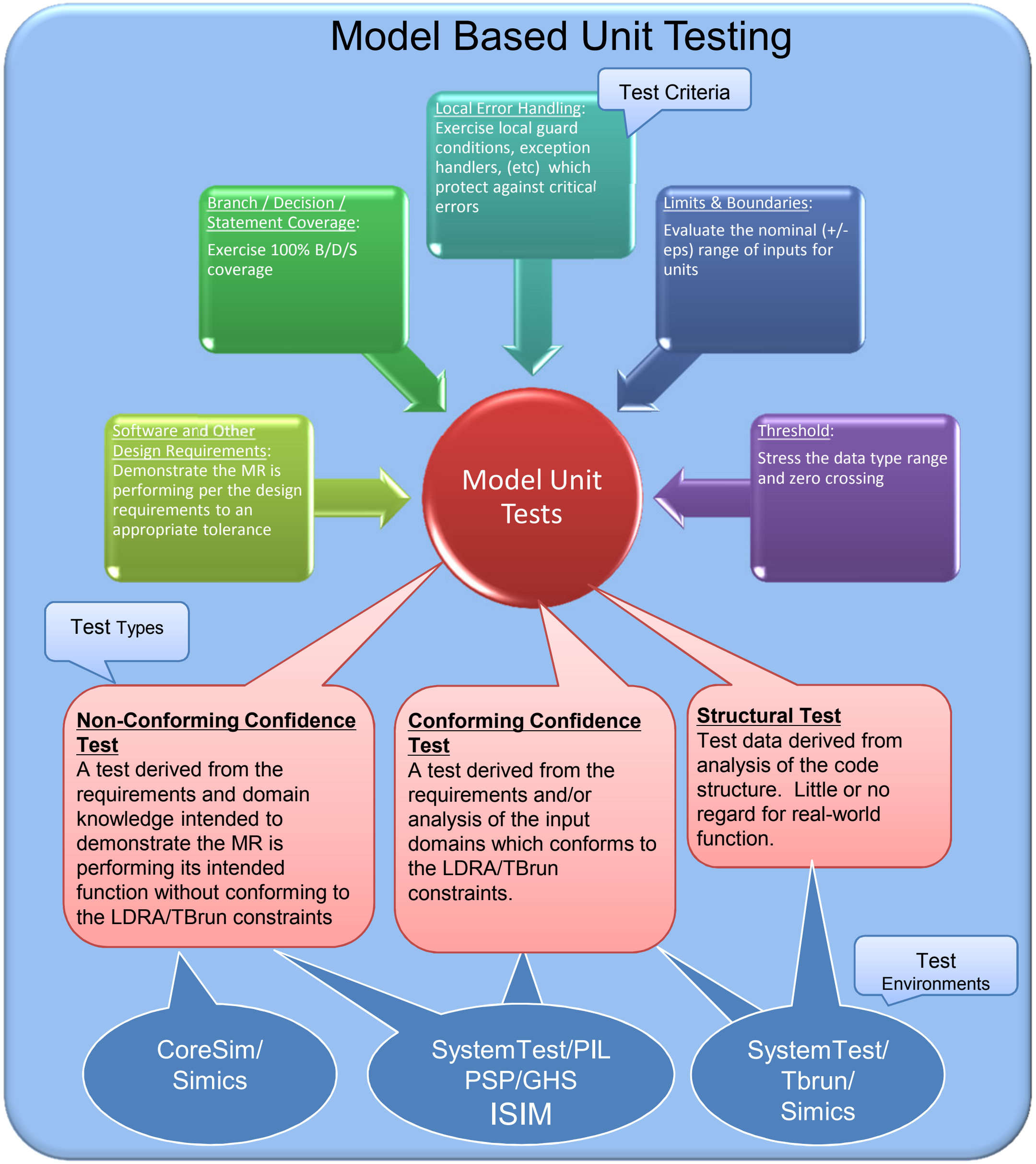


- CSU design requirements and model development is iterative
- Re-use of model component test suite by FSW is a significant cost/schedule reduction opportunity

Unit Testing

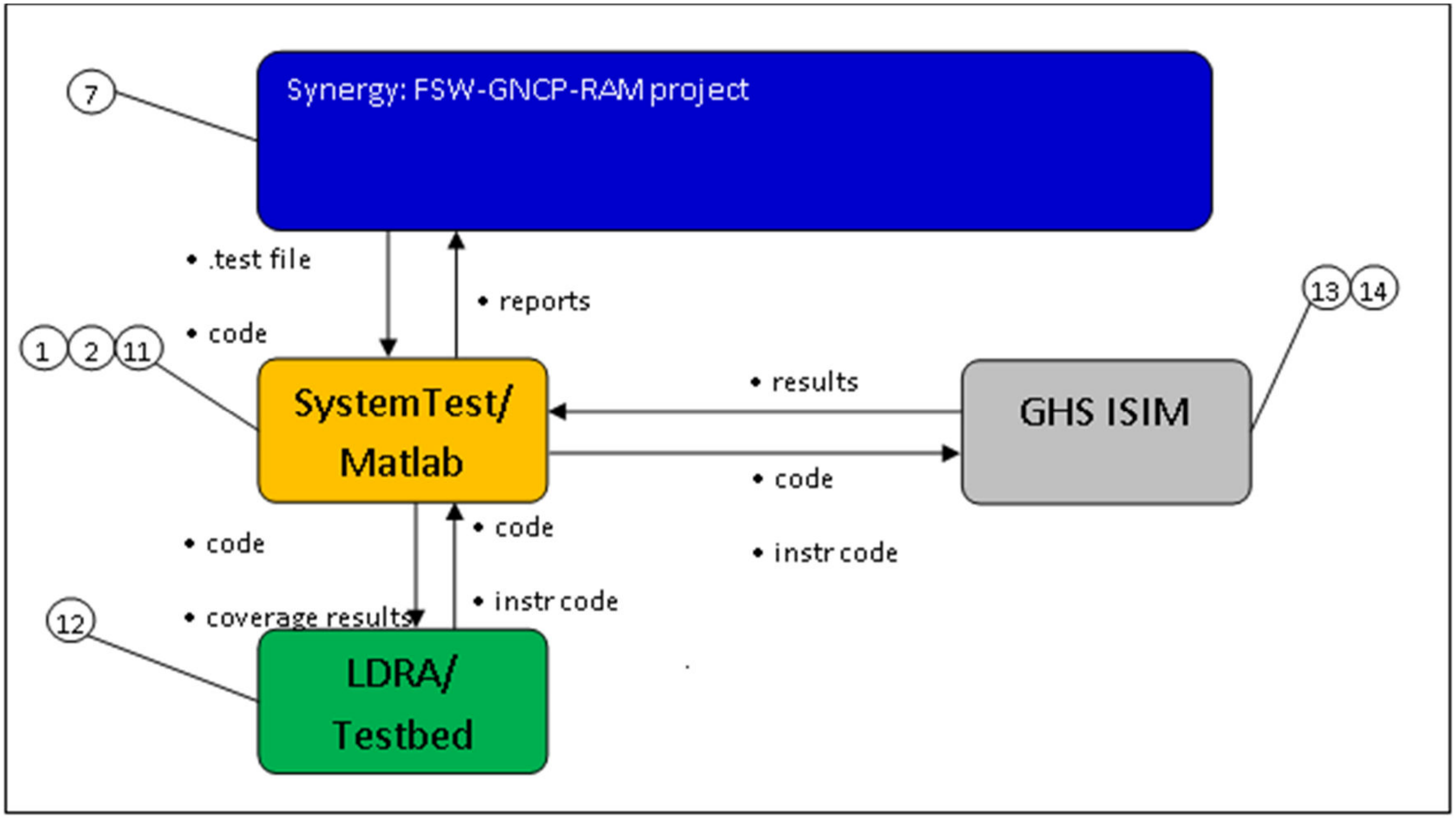
Project Orion

- **Three types of Model tests were developed:**
  - Non-Conforming Confidence tests
  - Conforming Confidence tests
  - Structural Tests
- **5 Types of Test Criteria**
  - Design requirements
  - MCDC
  - Error Handling
  - Limits/Boundaries
  - Threshold



Unit Testing: Processor-in-the-loop Testing

- **Tests can be developed in the Matlab environment and run on the emulated target environment for increased confidence early in the development process**



Process Benefits

1. **GN&C Design & Analysis environment is merged with the FSW Development & Test environment**
   - GN&C designers are directly involved in the flight implementation of the algorithms.
   - Eliminates traditional “translation” phase of having FSW interpret GN&C’s written-word FSSRs, thus eliminating potential source of error.

2. **Orders of magnitude MORE run-time testing on the FSW source (compared to Traditional process)**
   - FSW autocode is being used in all the analysis runs (not proto-code)

3. **Reduces schedule risk.**
   - FSW implementation is largely complete and tested by CDR (vs. just starting)

4. **Single, common algorithmic development environment with Matlab/Simulink.**
   - No mix of prototyping languages (like C, Fortran, Ada, and other analysis tools)
   - Commonality fosters sharing, algorithm/utility reuse (i.e., Orion Std Lib) and consistency.

5. **Use of RTW/Code-Gen by GN&C Team gives them “eyes-on” the flight code**
   - GN&C developers will gain working familiarity with autocode through the practice of generating it themselves for closed-loop testing with the external simulations for analysis and debugging.
   - Is value-added when needing to understand real-time performance or in-flight issues.

Process Benefits (cont)

6. **"Code Inspections" supplemented, if not supplanted, by Model Inspections**
   - Can walk-through the source design graphically (don't need PowerPoint facsimiles)

7. **During Sustaining Engineering, modifications to the "Design Spec" (i.e., the MW Models) can be directly autocoded.**
   - Continuous sync between design, documentation and FSW.

8. **MathWorks tools are fast-becoming the "industry standard"**
   - Modern, prevalent toolset.
   - Matlab programming has become the latest "language" being instituted in many university aerospace curricula today (vs. C or Fortran).

Process Lessons Learned

Project Orion

1. **Mandate Team-wide Use of a Common Matlab/Simulink version baseline**
   - Coordinating & baselining upgrades at mgmt level is needed for large teams w/ multiple companies
2. **Prohibit Dependencies on MW Toolboxes** *(aside from RTW, V&V)*
   - Alleviates cost impacts across a large team.
3. **Use centralized, customized libraries for "one-stop shopping" (in lieu of MW toolboxes)**
   - Ensures the entire team is "on the same page" using only the corralled, approved blocks, which adhere to the standards and are "autocodable".
   - Customization and masks ensures library blocks are used in the intended fashion.
4. **Use a single, secure, collaborative, web-based sharing repository**
   - Minimum requirement for sharing models and releasing baselines across company lines, firewalls.
5. **Every Domain and CSU should have a designated owner/Point of Contact (POC)**
   - The CSU POC is the single, acknowledged "hands-on owner" of the model (aids serial development)
6. **Each CSU should be a Model Reference**
   - Allows CSU to be developed, maintained & config-managed as its own .mdl file (owned by 1 POC).
7. **Each Domain sub-team should have a Code Gen POC**
   - Since RTW access and skill-base may be limited, 1 POC should be identified to help the others.
   - Important for each Domain sub-team to ensure their CSUs integrate and gen-code (as quality check, at a minimum) before submitting updates to the FSW team for the next baseline.
8. **Modeling and algorithm nomenclature standards must be clearly documented, trained, and maintained.**

Process Lessons Learned (cont.)

- **Scalability**
  - Time required to update and process ("Mex") the Simulink diagram, generate autocode and execute time domain simulation grew disproportionately with project size with existing MBD tools
  - Recommendation: See paper for multiple technical solutions to reduce build and execute time, and consider splitting development environment into mission phases – especially during early development
- **Configuration Management**
  - Use model reference blocks to break MBD application into separate CM artifacts, each with an assigned "owner"
  - Avoid parallel development when possible
  - Familiarize team with graphical merge tools and cost the training and licenses
- **Mixed Tool Development Environment**
  - Mixed C simulation and Simulink FSW was workable, but required a broad range of skills for developers. Should probably be avoided for projects that do not have the particular legacy of Orion

Conclusion

- **Orion paid some upfront costs for transitioning to an MBD process:**
  - A steep learning curve for engineers not familiar with MBD tools
  - Initially slow and complex development tools and processes
  - Configuration management issues
- **These issues were mitigated by many of the lessons learned, improved Mathworks products and custom tools that are described in the paper**
- **Some of the benefits that GN&C is now observing include:**
  - Detailed requirements review was replaced by review of MBD artifacts which had proven functionality
  - Automated test framework and report generation has simplified testing and production of test artifacts
  - Automated standards checking tools (e.g. Model Advisor) and graphical artifacts have facilitated the inspection process
  - No schedule time was needed for hand coding GN&C algorithms (40,000+ SLOC were autocoded by CDR)