Human Exploration and Operations

# NASA Modeling and Simulation

# Verification, Validation, & Accreditation

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# NASA Model And Simulation VV&A

- NASA has recently instituted requirements for establishing agency-level safety thresholds and goals that define long-term targeted and maximum tolerable levels of risk to the crew as guidance to developers in evaluating “how safe is safe enough” for a given type of mission.
- Some of the major benefits of high-fidelity modeling and simulation include training and decision-support systems that increase performance and safety while decreasing cost by using modeling and simulation (M&S) directly in mission systems.
- If models and simulations are to be used in safety-critical decision making, the reliability of their prediction needs to be thoroughly investigated.
- To this end, NASA has developed a process of Verification, Validation, and Accreditation (uncertainty quantification) to rigorously evaluate the credibility of computational model predictions.

# Agenda

- Models & Simulations (M&S)
  - Types and Uses
  - Incorporation in Project Lifecycle
- Verification, Validation, & Accreditation (VV&A)
  - Definition
  - Process Overview
  - Phase 1: Initialization
  - Phase 2: Planning
  - Phase 3: Execution
- Specific Model and Simulation VV&A Example
  - Component Level Modeling and Test-Correlation (V&V)
  - System Level Modeling and Test-Correlation (V&V)
  - Post Test-Correlation M&S Activities (A)

# M&S "Types and Uses" Span Multiple System Levels

Mission System Architecture, Design - Top-Down

Mission
Segments
Elements
Assemblies
Components
Phenomena

Simulation Case 8
Integrated Logistics
Spreadsheet

Simulation Case 5
Distributed
SOS Simulation

Simulation Case 6
Mission Operations
Training Simulator

Simulation Case 1
TableTop
Spreadsheet

Simulation Case 4
Space Environ Model

Simulation
Case 3
Component
Behavior and
Performance

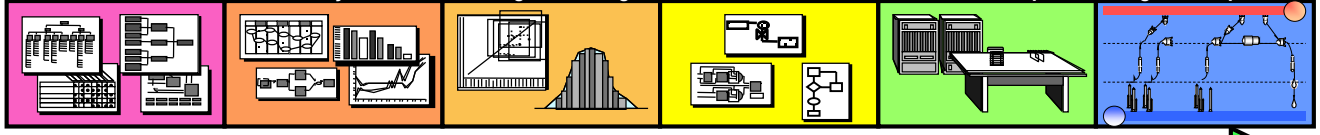
Simulation Case 7
Embedded Flight
Simulator

Simulation Case 2
CFD Code for Aero Flows, Loads, etc.

System Design, Develop, Integrate, Test - Bottom-Up

NOMINAL
PROGRAM
MATURITY

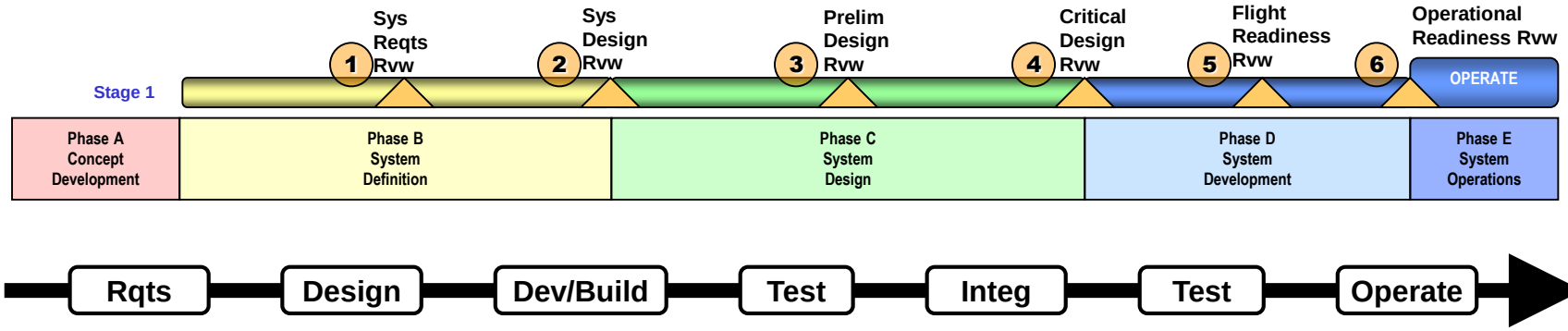
Studies | Analysis | Design-Modeling | Simulation | In-The-Loop | Integration-Operation



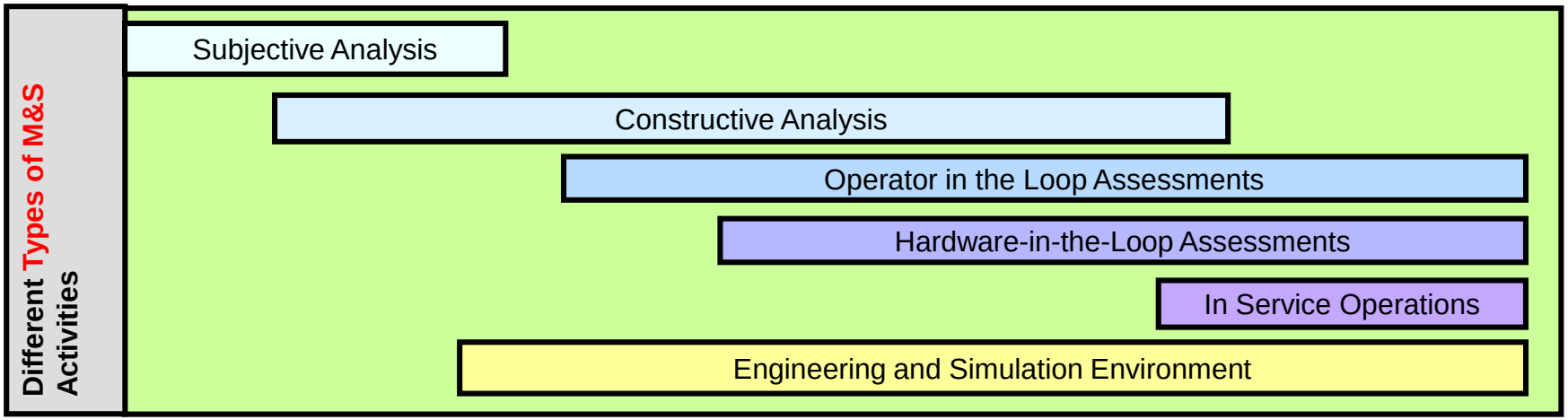
Increasing Completeness, Design, Usability, & Operational Maturity

# How M&S Fits into the Project-Management Lifecycle

## NASA SYSTEM DESIGN LIFECYCLE




## USES of M&S DURING LIFECYCLE



# The Essential "V", "V", and "A" Definitions


Developer
**Verification Agent**

## VERIFICATION

**The process of determining that a model [or simulation] implementation and its associated data accurately represents the developer's conceptual description and specifications…***Did we build the thing right?*


Functional Expert
**Validation Agent**

## VALIDATION

**The process of determining the degree to which a model [or simulation] and its associated data provides an accurate representation the real world from the perspective of the intended uses of the model or simulation…** *Did we build the right thing?*

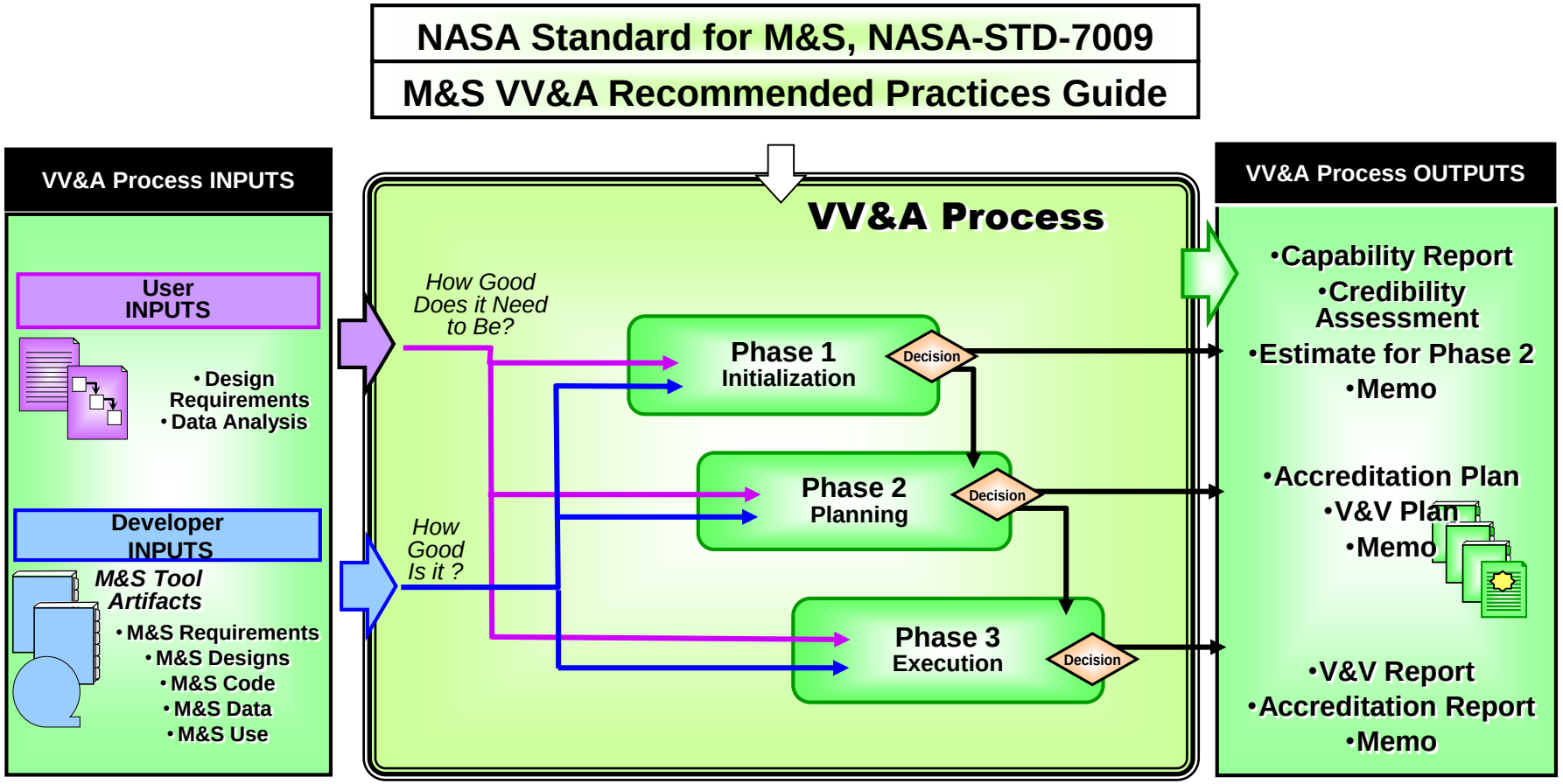

Requester/User
**Accreditation Agent**

## ACCREDITATION

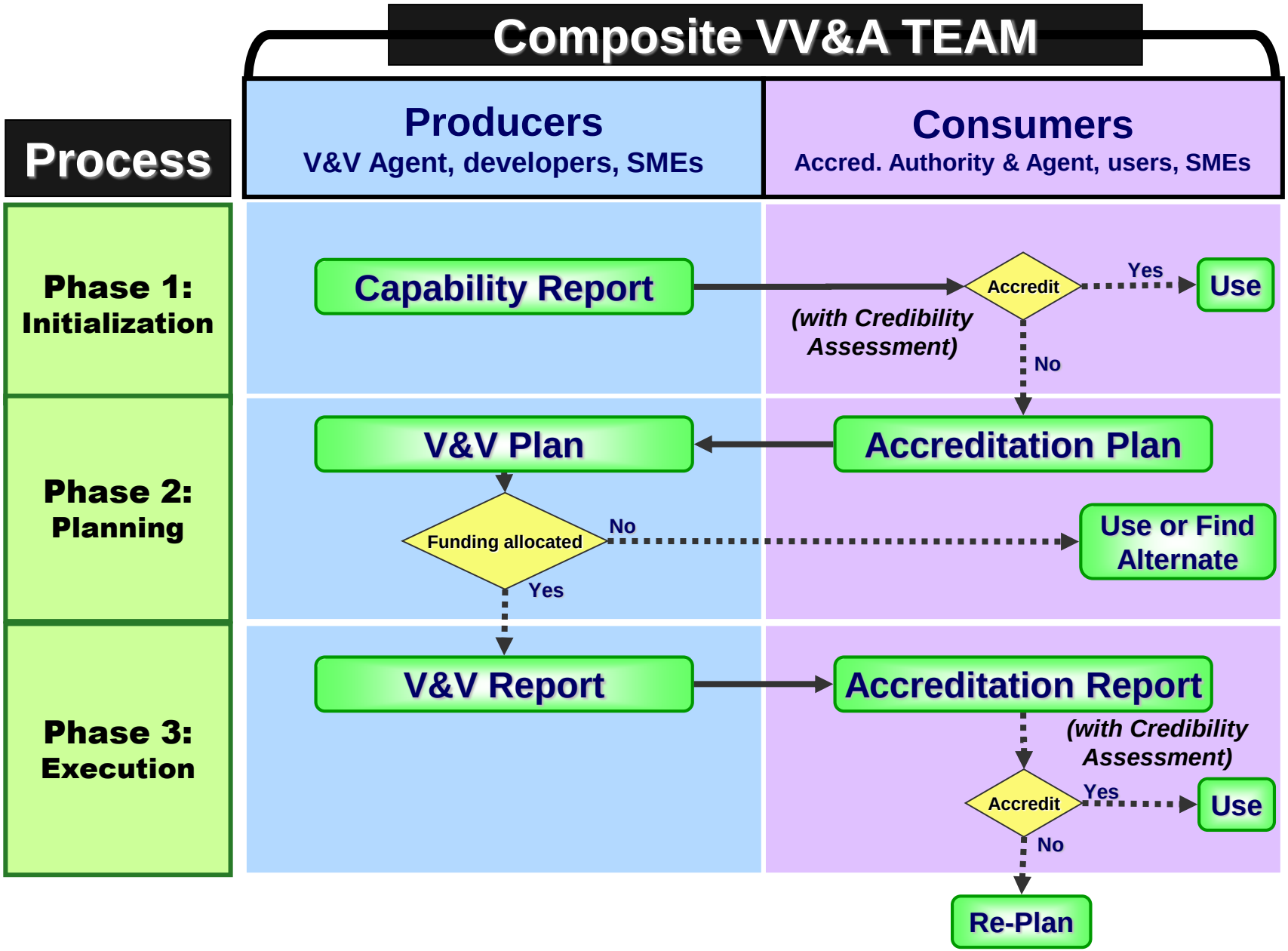
**The official acceptance of a model or simulation or federation of models and simulations and its associated data to use for a specific purpose…** *Should it be used?*

**Verification, Validation, and Accreditation (VV&A):**
**A process for substantiating the credibility of models and simulations.**

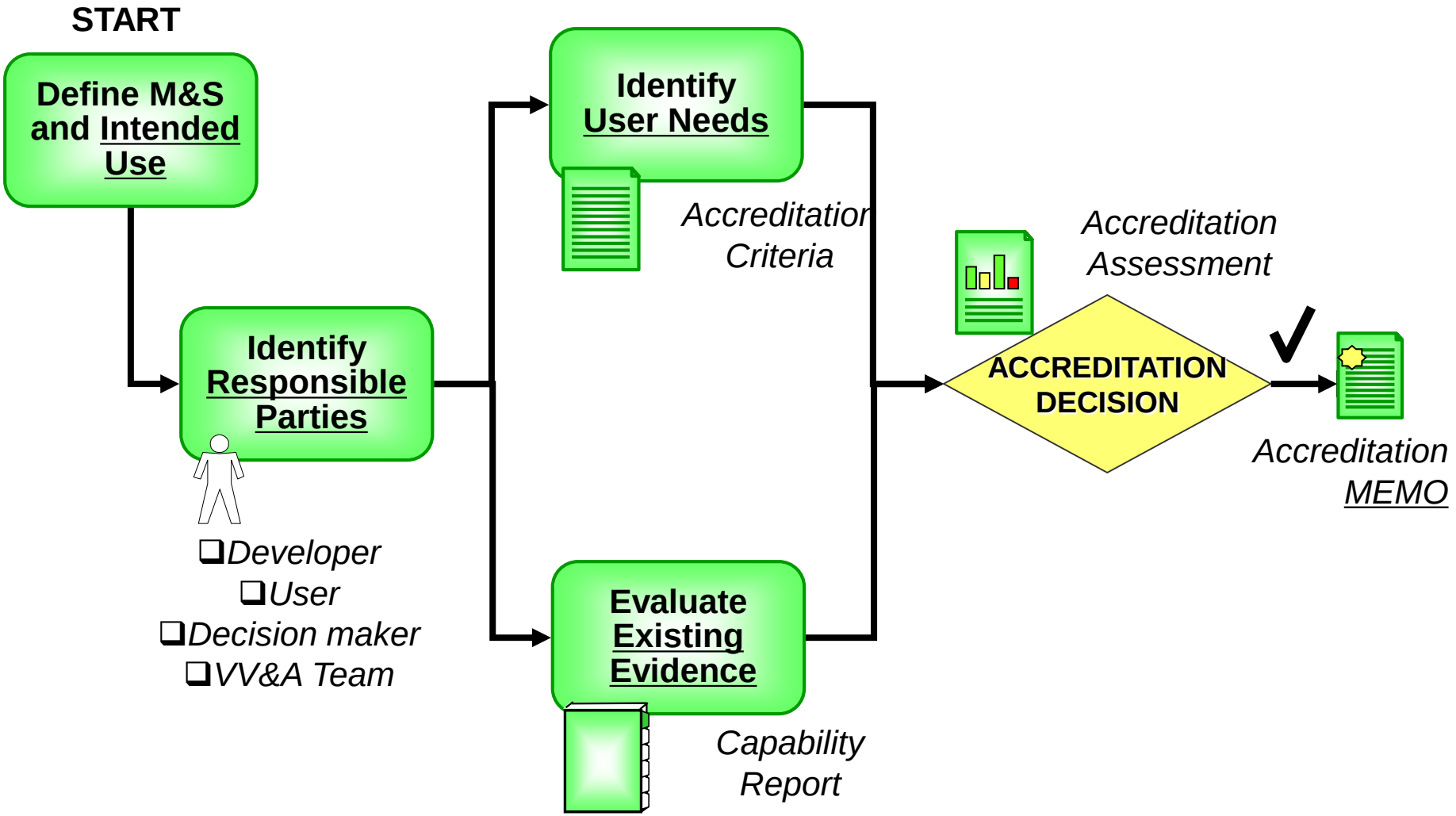
# VV&A Process Overview



# VV&A Process, Responsibilities and Products



# VV&A Phase 1: Initialization Process



# M&S VV&A Accreditation Authority

**Accreditation Authority**

## Organizational Authority

- ❑ Reports to program/project management
- ❑ Must have the authority to prescribe & approve specific M&S use
- ❑ Must have the authority to commit resources for specific M&S VV&A

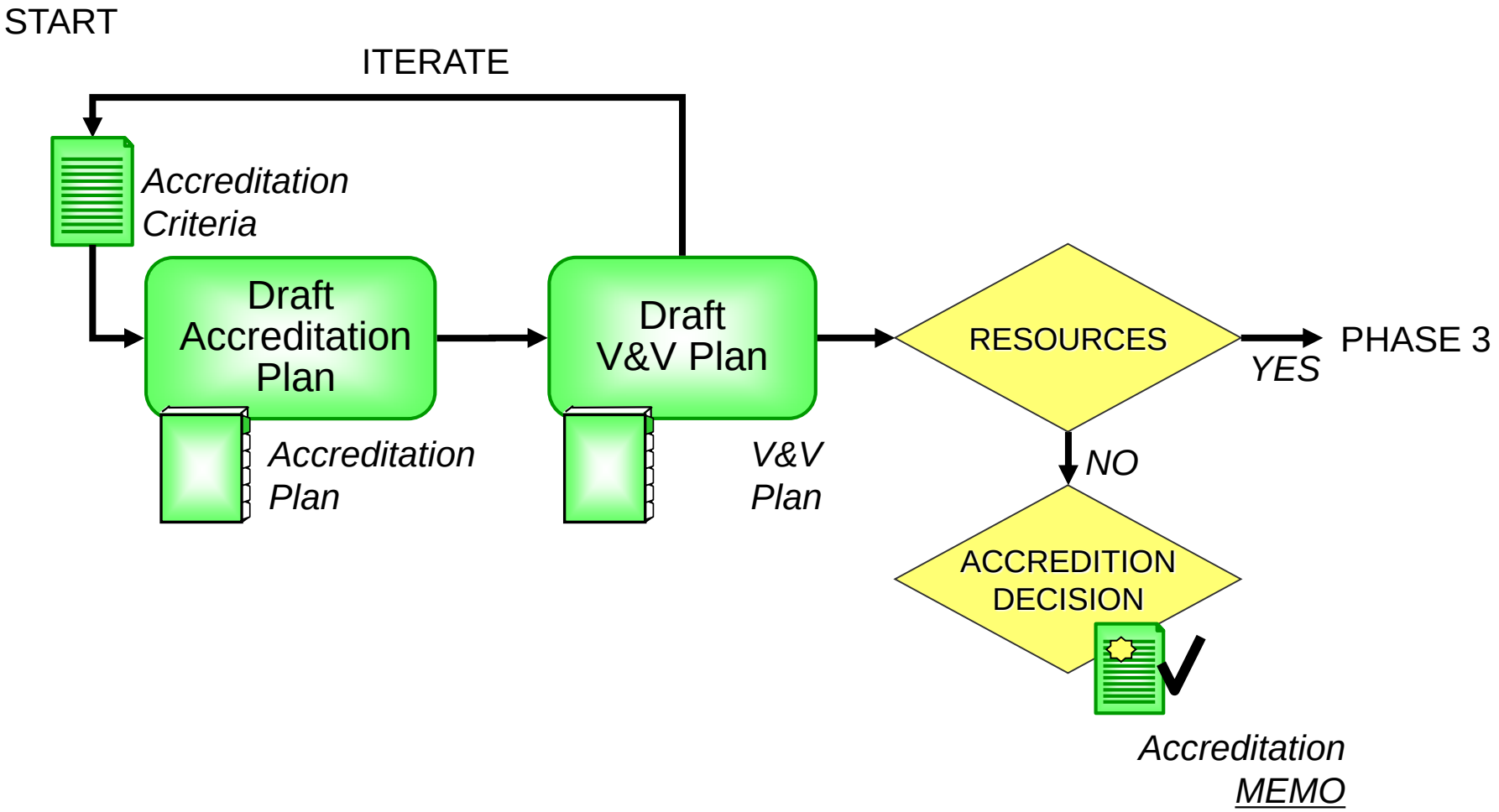
## Qualifications

- ❑ Must have the technical cognizance to assess the proper use of specific M&S applications
- ❑ Must be able to weigh cost, schedule, and risk against alternatives

## M&S VV&A Responsibilities

- ❑ Specifies (and documents) the programmatic priorities for specific M&S use
  - *based upon technical need, schedule, and any associated risk factors*
- ❑ Approves resource expenditures and schedules for specific M&S VV&A
- ❑ Specifies (and documents) the technical requirements for specific M&S use
  - *specifies the specific minimum levels reqd for each VV&A accreditation criterion*
- ❑ Reviews and Approves Accreditation Plans for specific M&S use
- ❑ Makes Go/No-Go decisions for each of Three VV&A Phases
- ❑ Makes accreditation decision based upon results of VV&A assessment results, and other inputs
  - *Approves and signs accreditation memos and memorandum of records for M&S*
- ❑ Reports to project management on any special conditions of specific M&S use
  - *caveats, limitations, assumptions, constraints of specific M&S*

# VV&A Phase 2: Planning Process



# A V&V Taxonomy based on Execution Method & Formalism

(DMSO)

## VERIFICATION AND VALIDATION TECHNIQUES

### INFORMAL

Audit
Desk Checking
Face Validation
Inspections
Reviews
Turing Test
Walkthroughs

### STATIC

Cause-Effect Graphing
*Control Analysis*
  Calling Structure Analysis
  Concurrent Process Analysis
  Control Flow Analysis
  State Transition Analysis
*Data Analysis*
  Data Dependency Analysis
  Data Flow Analysis
Fault/Failure Analysis
*Interface Analysis*
  Model Interface Analysis
  User Interface Analysis
Semantic Analysis
Structural Analysis
Symbolic Evaluation
Syntax Analysis
Traceability Assessment

### DYNAMIC

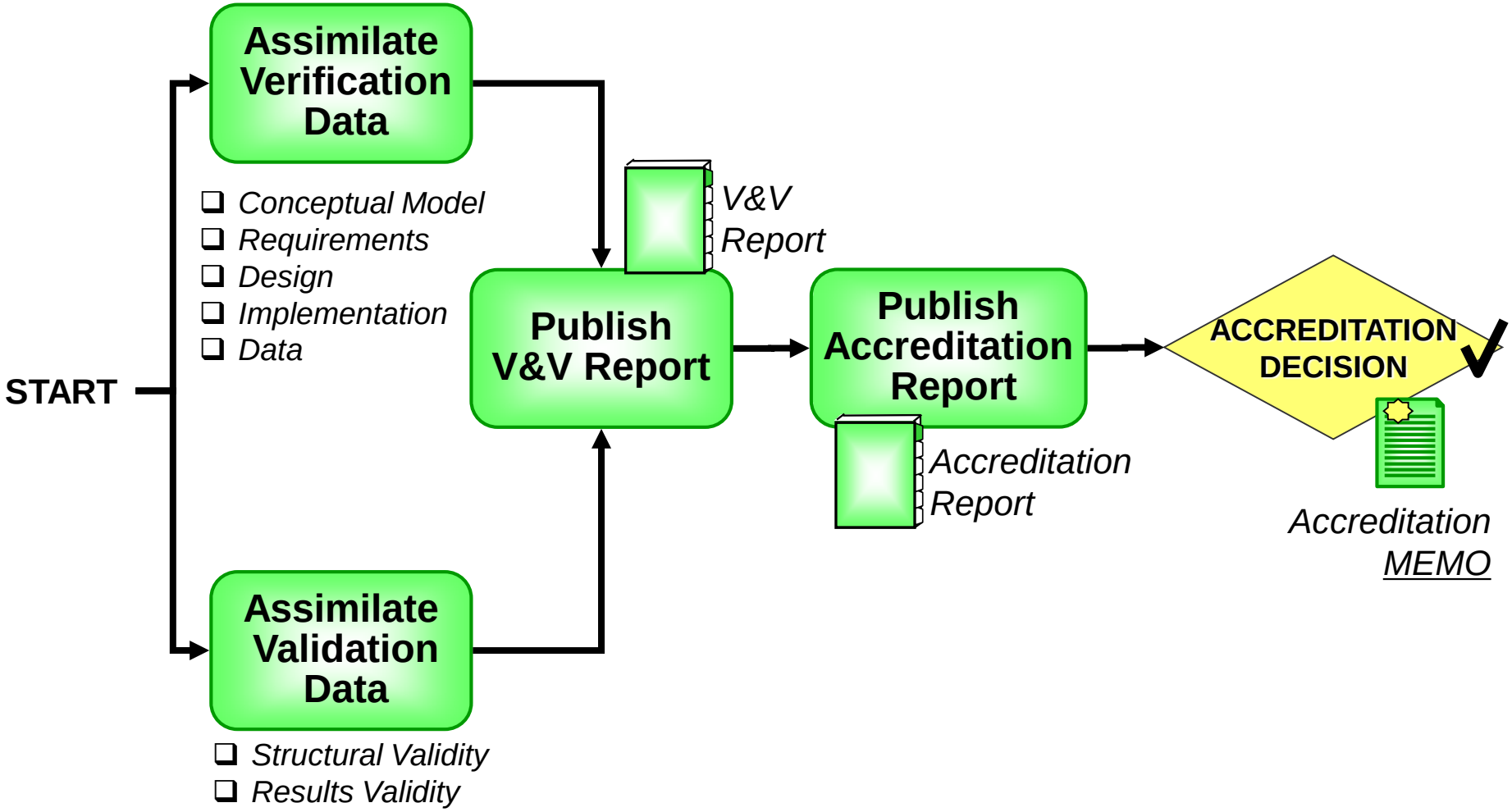
Acceptance Testing
Alpha Testing
Assertion Checking
Beta Testing
Bottom-up Testing
*Comparison Testing*
  Authorization Testing
  Performance Testing
  Security Testing
  Standards Testing
Debugging
*Execution Testing*
  Execution Monitoring
  Execution Profiling
  Execution Tracing
Fault/Failure Insertion Testing
Field Test
Functional (Black-Box) Testing
Graphical Comparisons
*Interface Testing*
Data Interface Testing
Model Interface Testing
User Interface Testing
Object-Flow Testing
Partition Testing
Predictive Validation
Product Testing
Regression Testing
Sensitivity Analysis
*Special Input Testing*
  Boundary Value Testing
  Equivalent Partitioning Testing
  Extreme Input Testing
  Invalid Input Testing
  Real-Time Input Testing
  Self-Driven Input Testing
  Stress Testing
  Trace-Driven Input Testing
*Statistical Techniques*
*Structural (White-Box) Testing*
  Branch Testing
  Condition Testing
  Data Flow Testing
  Loop Testing
  Path Testing
  Statement Testing
Submodel/Module Testing
Symbolic Debugging
Top-Down Testing
Visualization / Animation

### FORMAL

Induction
Inductive Assertions
Inference
Lamda Calculus
Logical Deduction
Predicate Calculus
Predicate Transformation
Proof of Correctness

*Note: Extracted from the "DoD VV&A Recommended Practices Guide" developed by DMSO.*

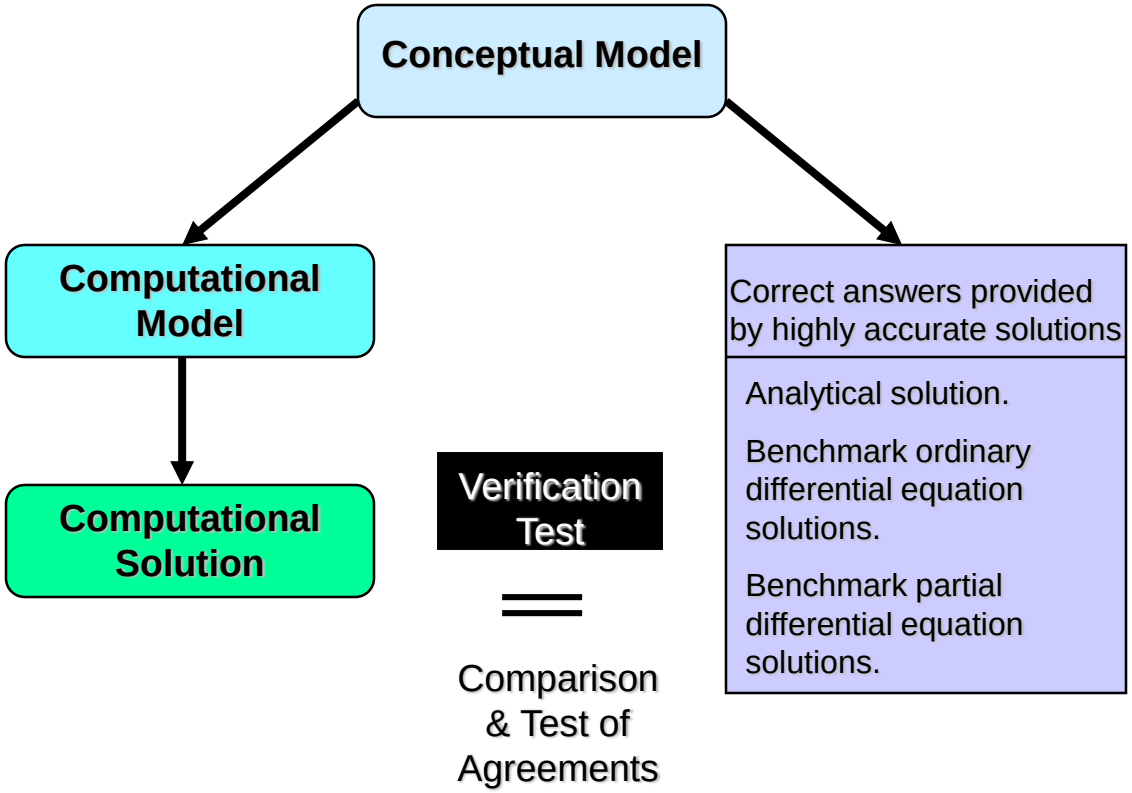
# VV&A Phase 3: Execution Process



# Evaluation Criteria

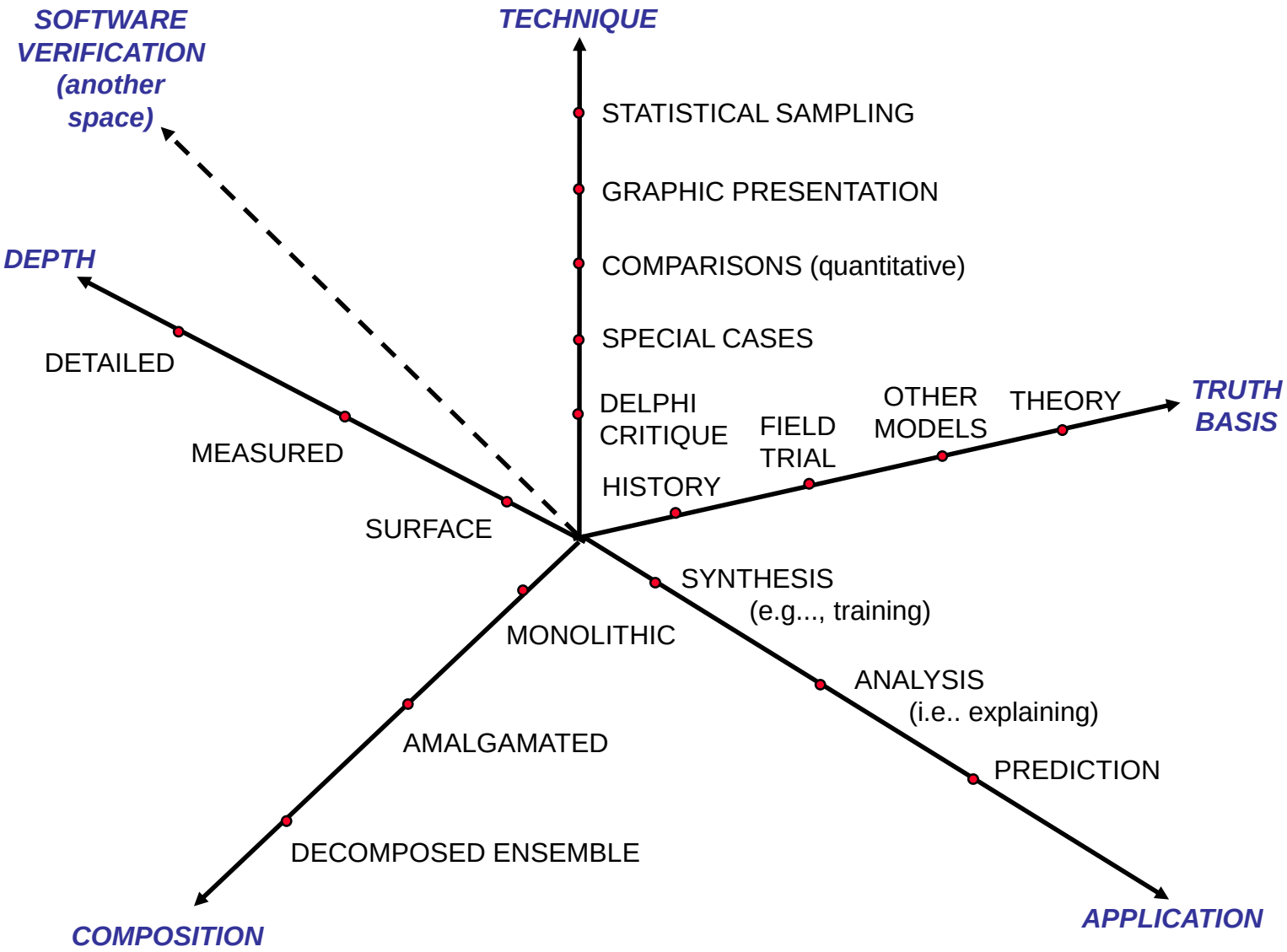
- Completeness
  - The simulation conceptual model identifies all representational entities and processes of the problem domain, the mission space, and all control and operating characteristics of the simulation, simulation space, needed to ensure that specifications for the simulation fully satisfy simulation requirements.
- Consistency
  - Representational entities and processes within the conceptual model are addressed from compatible perspectives in regard to such features as coordinate systems and units, levels of aggregation/de-aggregation, precision, accuracy, and descriptive paradigms.
- Coherence
  - The conceptual model is organized so that all elements of both mission space and simulation space have function (i.e., there are not extraneous items) and potential (i.e., there are no parts of the conceptual model which are impossible to activate).
- Correctness
  - The simulation conceptual model is appropriate for the intended application and has potential to perform in such a way as to fully satisfy simulation requirements.

# Verification Deals with Mathematics



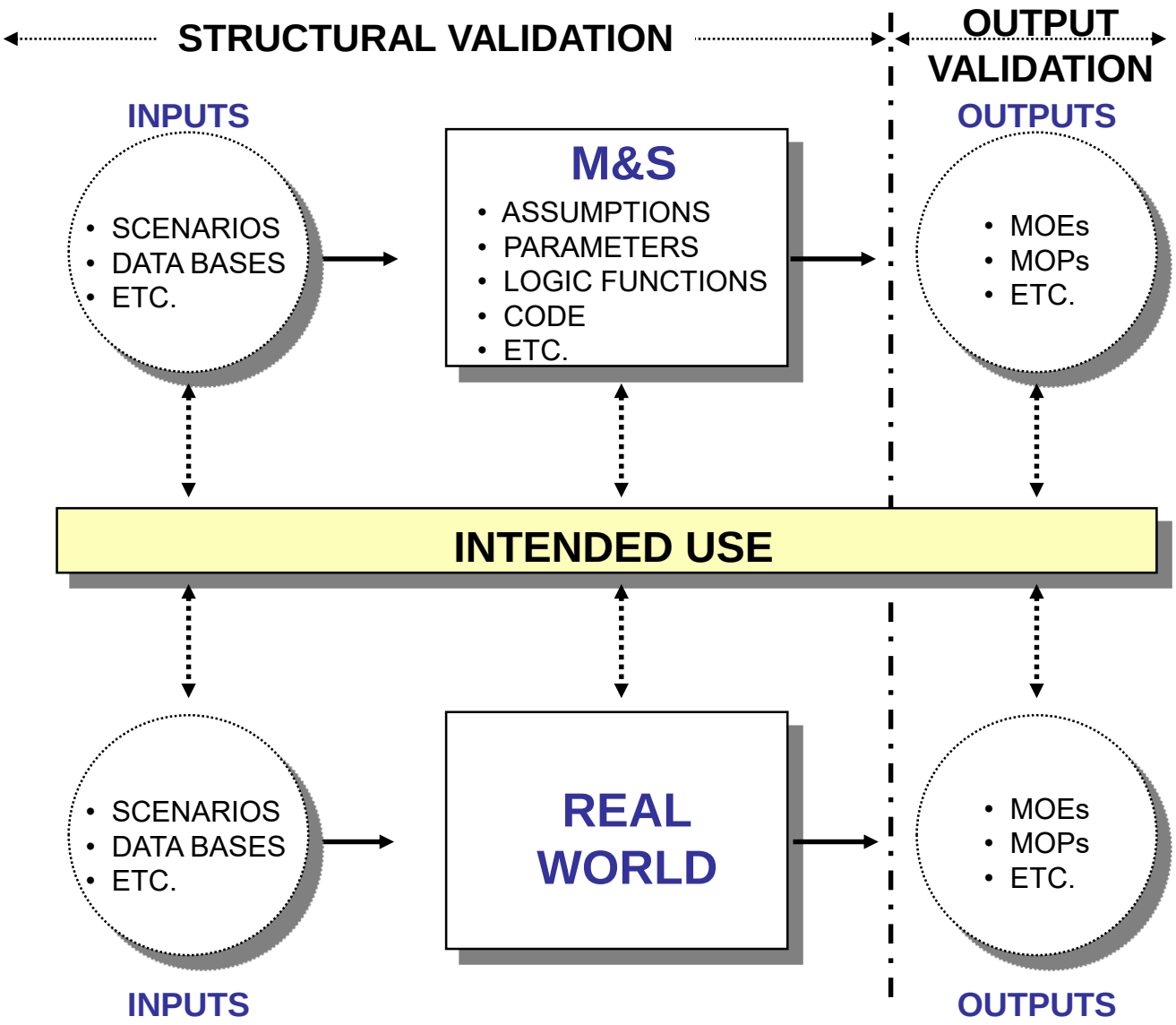

Source: Sandia National Laboratories *Verification & Validation in Computational Simulation*

# Dimensions of Validation




*Note: Extracted from the "MORS Simulation Validation Workshop Proceedings (SIMVAL II)."*

# Potential Comparison for Validation




*Note: Extracted from the "MORS Simulation Validation Workshop Proceedings (SIMVAL II)."*

# Output/Results Validation Technique Overview

- Output/Results Validation focuses on how well the model results compare with the perceived real world.
- Approaches:
  - Sensitivity Analysis
  - Test/Field Comparison
- Objectives:
  - To establish the fidelity of model predictions under certain conditions.
  - To determine if model fidelity is acceptable for a particular application.
  - To determine if the M&S produces results that are feasible.
  - To determine if the model outputs are reasonable relative to the inputs.
  - To determine if a difference in the input produces an expected proportional change in the output.

# Sensitivity Analysis

- Evaluates simulation sensitivity to the proper input data items; i.e., that the difference between two sets of simulation results reflect a possible/ believable result.

- Evaluates simulation sensitivity of model-to-model interactions within the simulation; i.e., that the interactions between multiple models within the testbed reflect possible/believable results.

- Evaluates simulation sensitivity to scenario changes within the simulation; i.e., that the interactions between scenario elements, the geophysical and environmental data within the testbed reflect possible/believable results.

# Test/Field Comparison

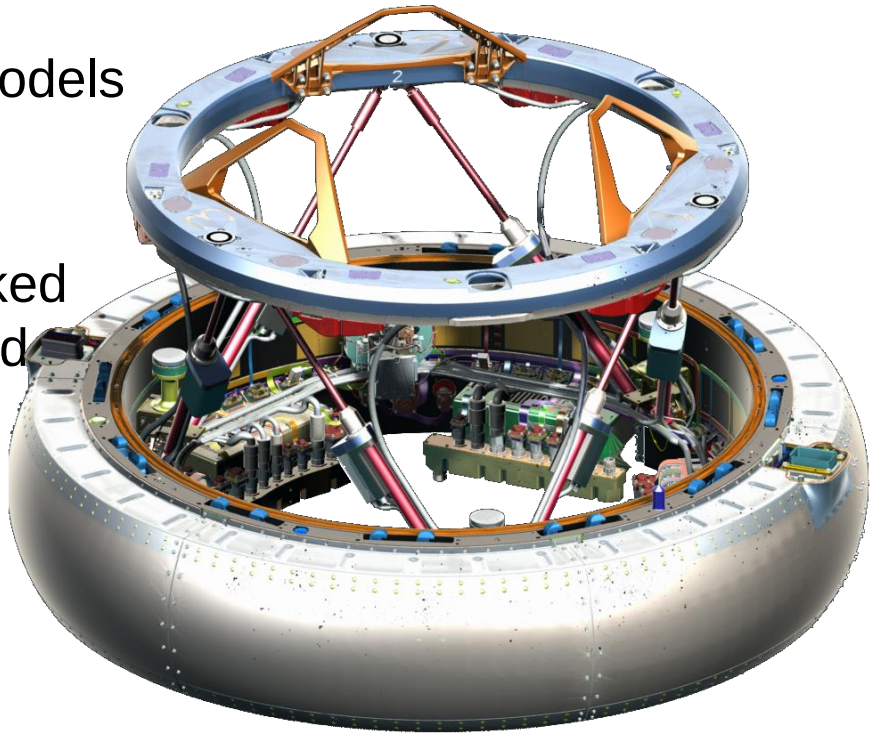
- Comparison of simulation results to documented or instrument data from exercises to evaluate exercise interactions in comparison to interactions exhibited in the simulation.
- Typical activities applicable to this type of comparison are:
  - Pre-test and post-test exercises
  - Identification of significant dependent variables
  - Identification of correlative variables between M&S and test results
  - Qualify allowable variance between M&S and test result variables
  - Net assessment of variance between M&S and test result variables
  - Identify any failures of comparison, anomalies and annotate implications

# NDS Dynamics Simulation Software

The NDS Dynamics Simulation Software is an end-to-end simulation of an on-orbit docking scenario between two space vehicles via the proposed androgynous peripheral NASA Docking System (NDS), using test correlated hardware component models. The Simulation can be described in terms of 4 major modules:

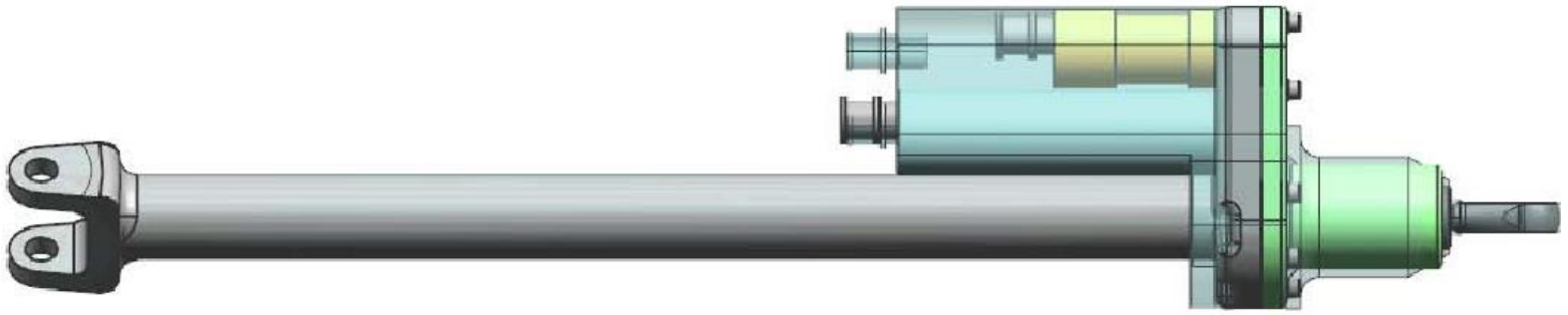
- NDS Mechanism Hardware Models
- NDS Control Systems Models
- Specific and Generic Vehicle Models
- Testbed Facility Models

The NDS Dynamics team was tasked with developing HWIL test validated models and simulations for the purposes of performance analysis, flight operations risk mitigation, and fault tolerance assessment.

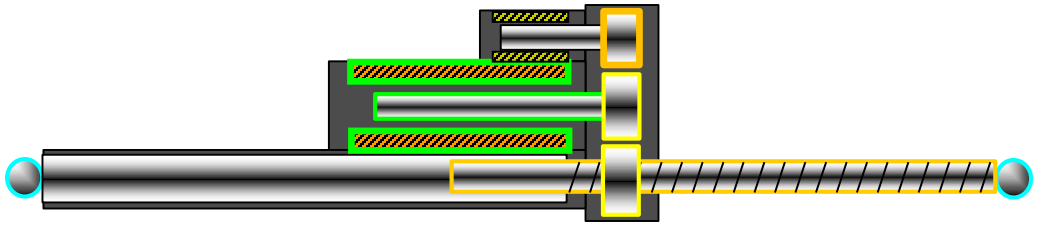


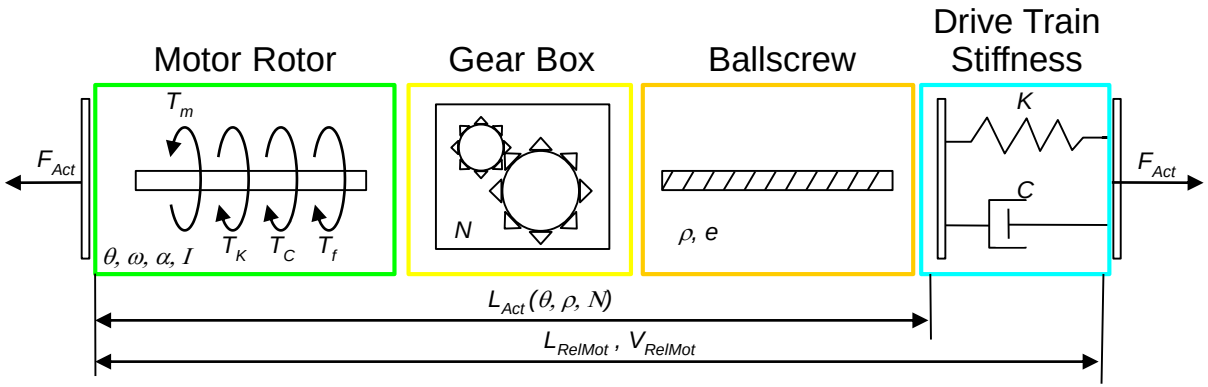
# NDS Component M&S V&V

- The NASA Docking System (NDS) Project released a set of design requirements for the NDS Linear Electromechanical Actuator (EMA) as a Vendor Support Item
- During the bidding process, the vendors supplied NASA high level motor/drive train parameters per requests and as agreed to by NDS designers
- The NDS Dynamics Group was tasked with modeling the Linear EMA component as part of the NDS Dynamics simulation to be closer to the proposed flight-like design using the vendor supplied parameters in combination with test-correlated parameters in support of several on-going analyses.

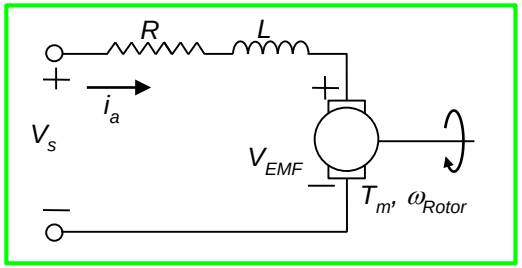


# Linear EMA Model Breakdown






Brushed DC Motor




$$V_{EMF} = K_v \omega_{Rotor}$$

$$V_s = R i_a + V_{EMF} + L \frac{di_a}{dt}$$

$$T_m = K_m i_a$$

$$\alpha = \frac{\left(T_m - T_K - T_C - T_f\right)}{I}$$

$$T_K = \frac{F_K \rho}{2\pi e N}$$

$$F_K = K\left(\frac{\theta\rho}{2\pi N} + L_0 - L_{Relmot}\right)$$

$$\omega = \int \alpha$$

$$T_C = \frac{F_C \rho}{2\pi e N}$$

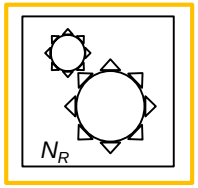
$$F_C = C\left(\frac{\omega\rho}{2\pi N} - V_{Relmot}\right)$$

$$\theta = \int \omega$$

$$T_f = C_{Motor}\omega + T_{Stiction/Friction}$$

$$F_{Act} = F_K + F_C$$

Resolver Gear Box

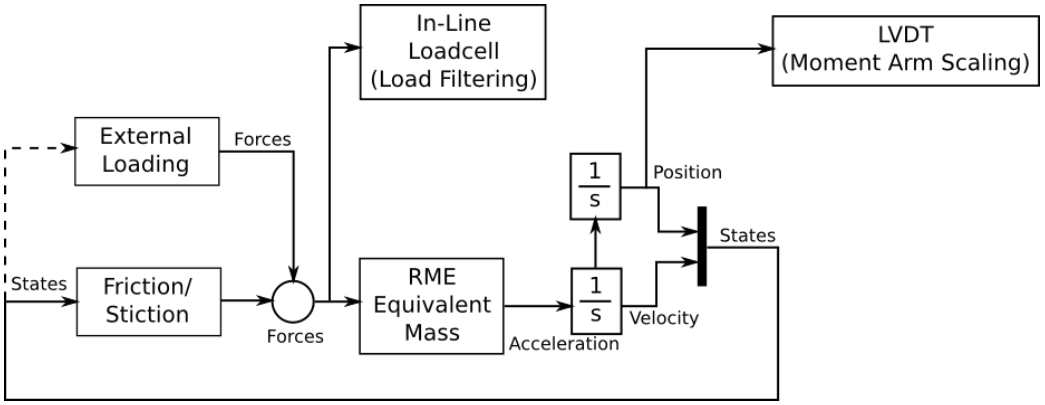



$$\theta_{Res} = \frac{\theta_{Shaft}}{N_R} + \theta_{Res0}$$

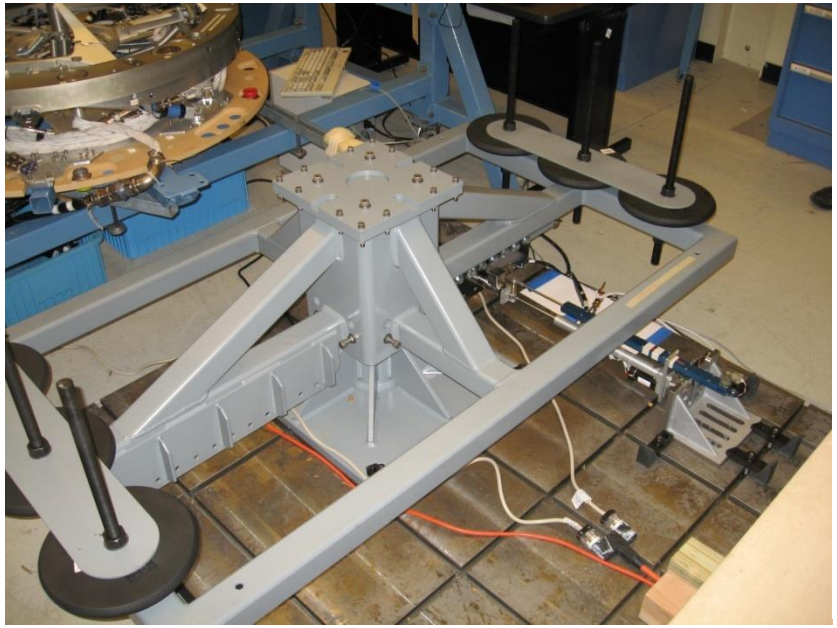
# Linear EMA Characterization Testing

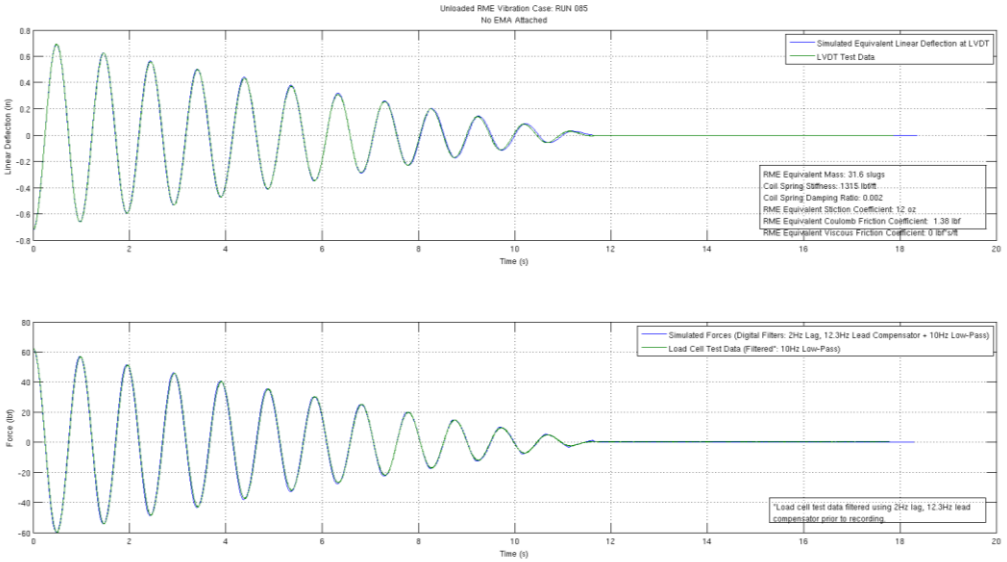
Characterization Testing Requirements

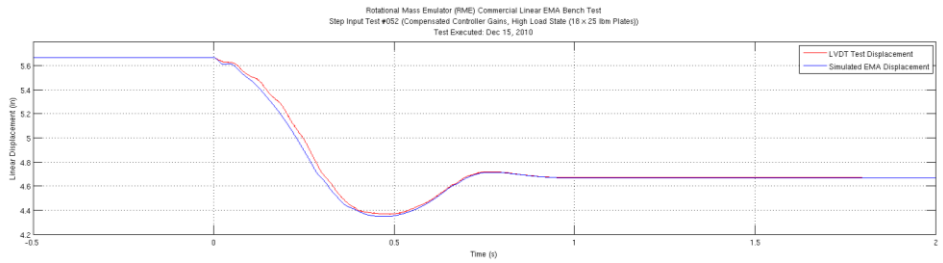
- Linear EMA model to be validated via HWIL test correlation.
- Develop list of critical parameters to be tested.
- Design and build test stand capable of testing all necessary parameters.
- Develop test stand model.
- Characterize test stand via stand-alone tests and correlate model.
- Incorporate test article into test stand and execute test matrix.
- Verify all test data logs.
- Correlate the integrated test stand and test article models to the test data.
- Document model (Verification Report) and test correlation activities (Validation Report)

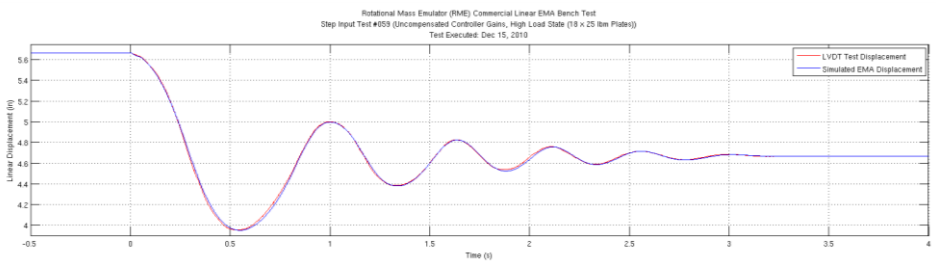


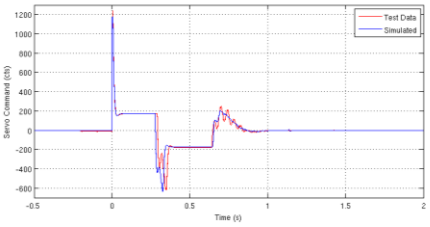
# HWIL Testing and Simulation Correlation

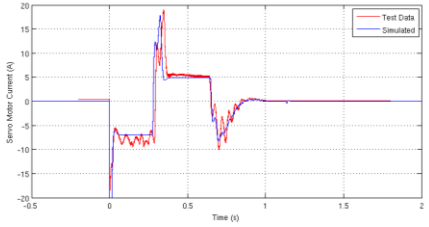


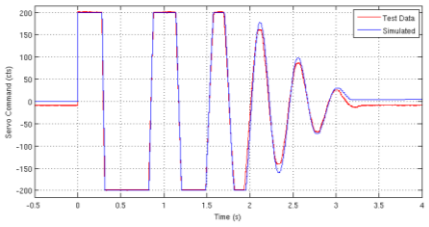


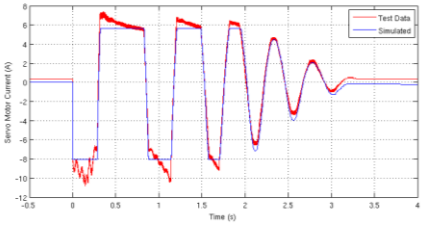



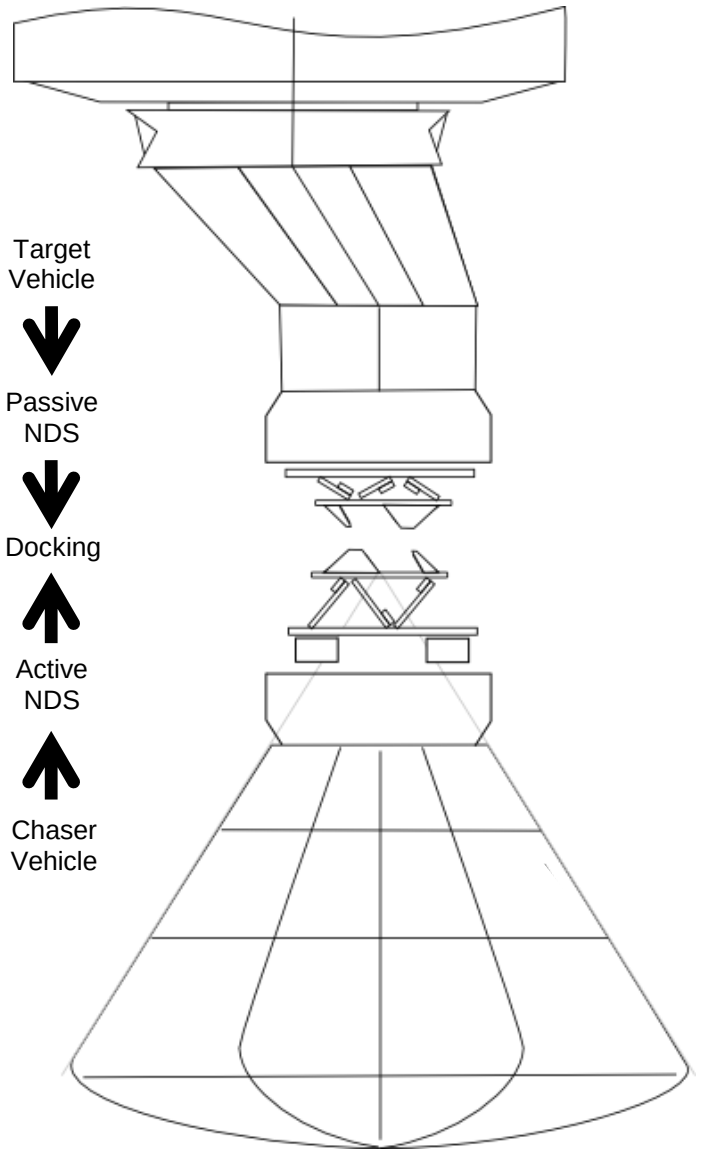



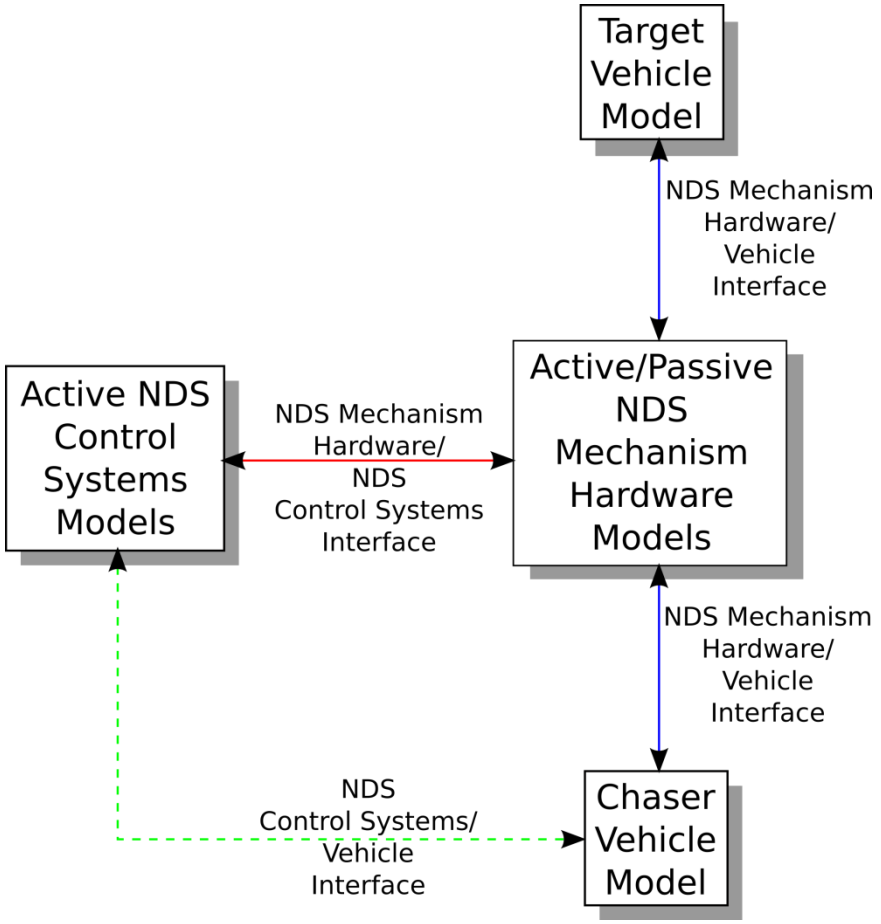



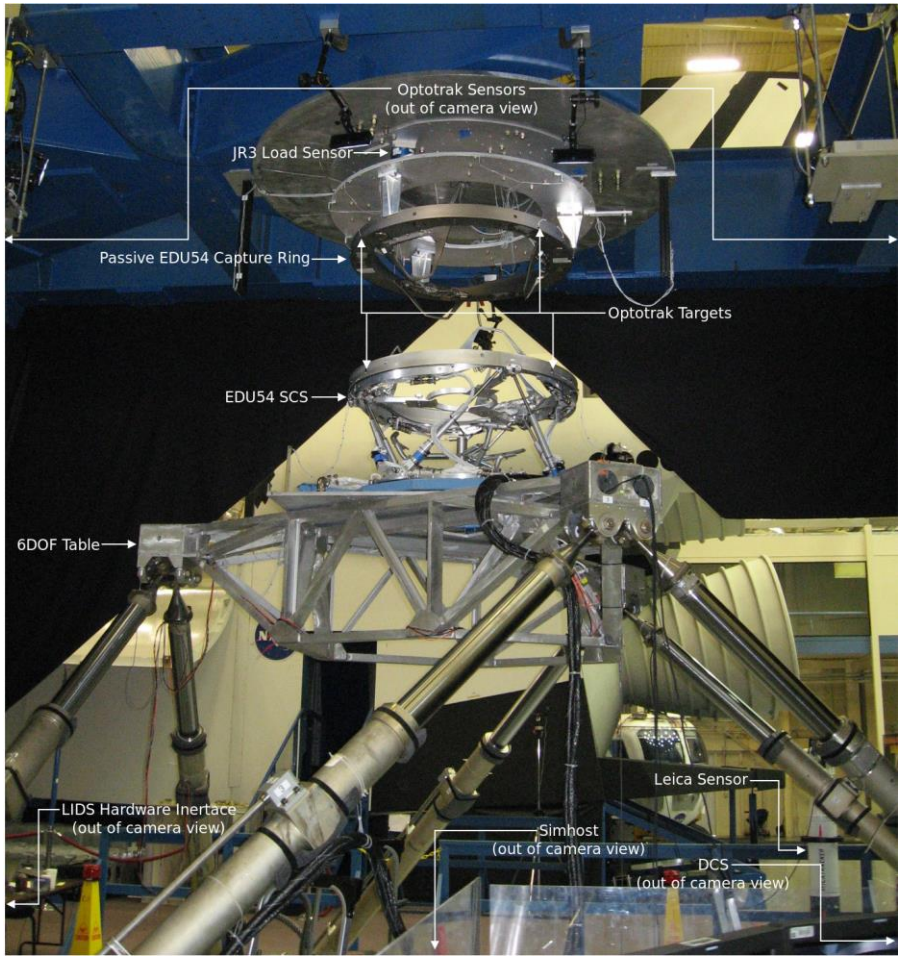



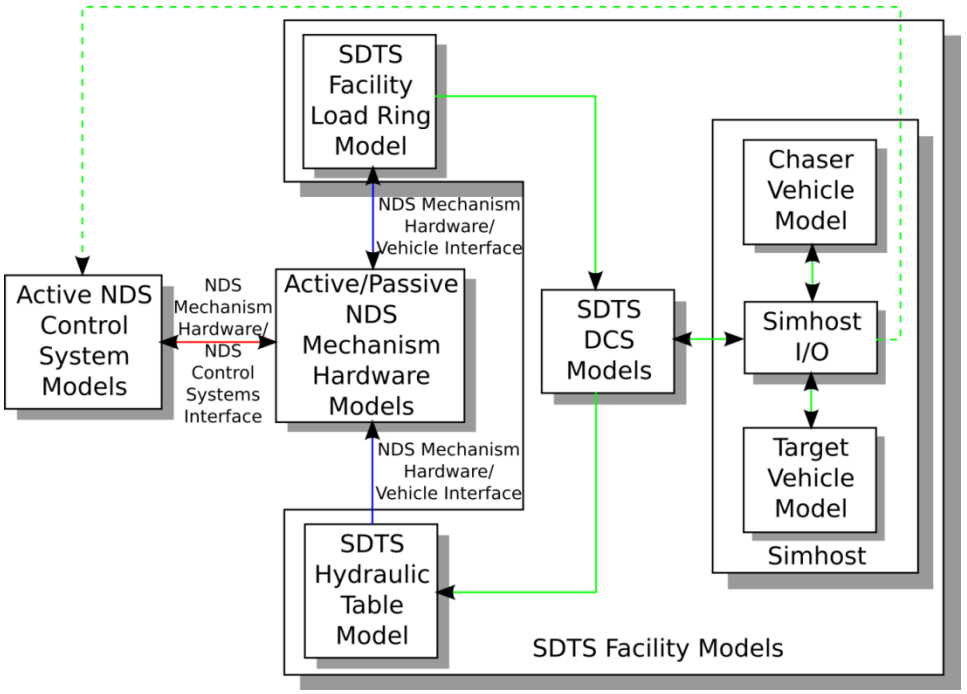
# NDS On-Orbit Dynamics Simulation



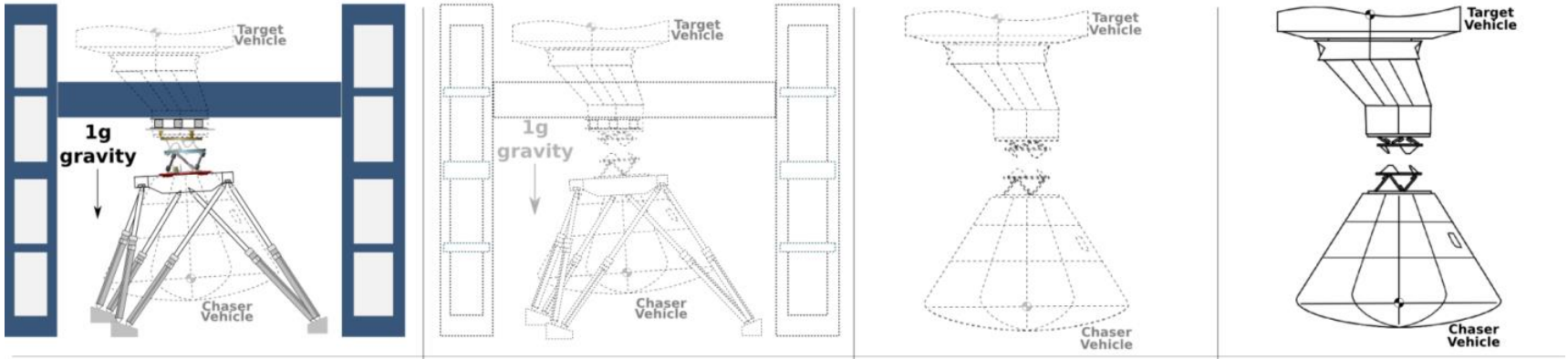
# NDS/SDTS Integrated Dynamics Simulation



# NDS Integrated Simulation V&V Flow

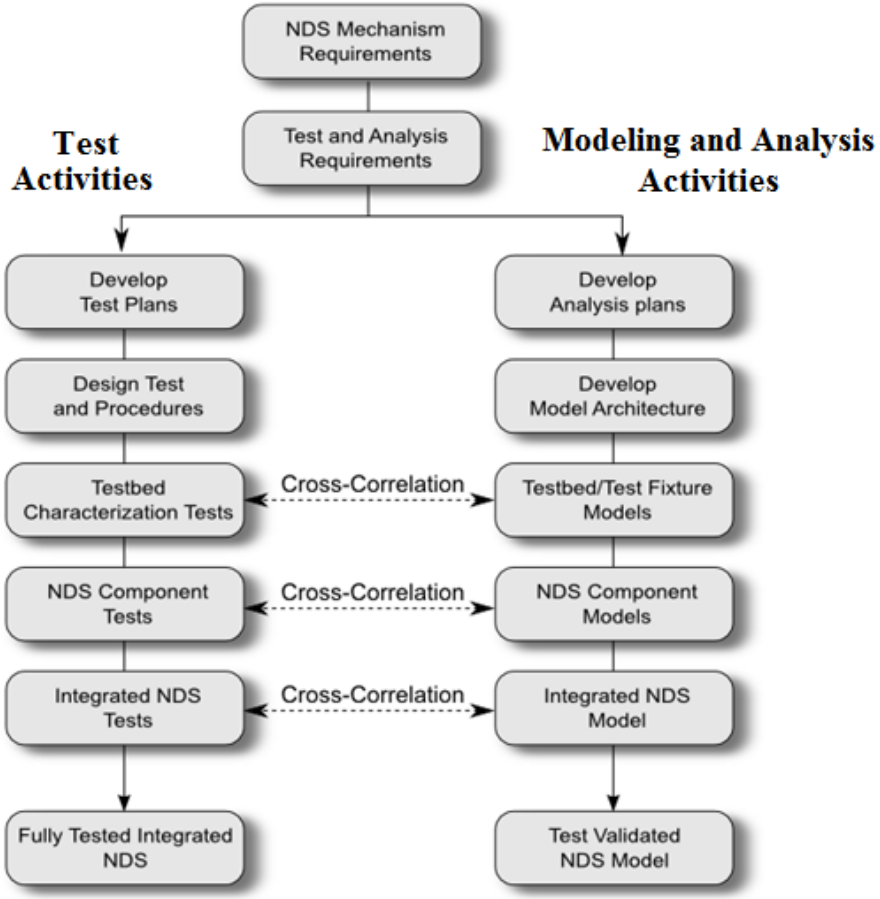
NDS Integrated Simulation Testing,
Validation, and Verification Flow



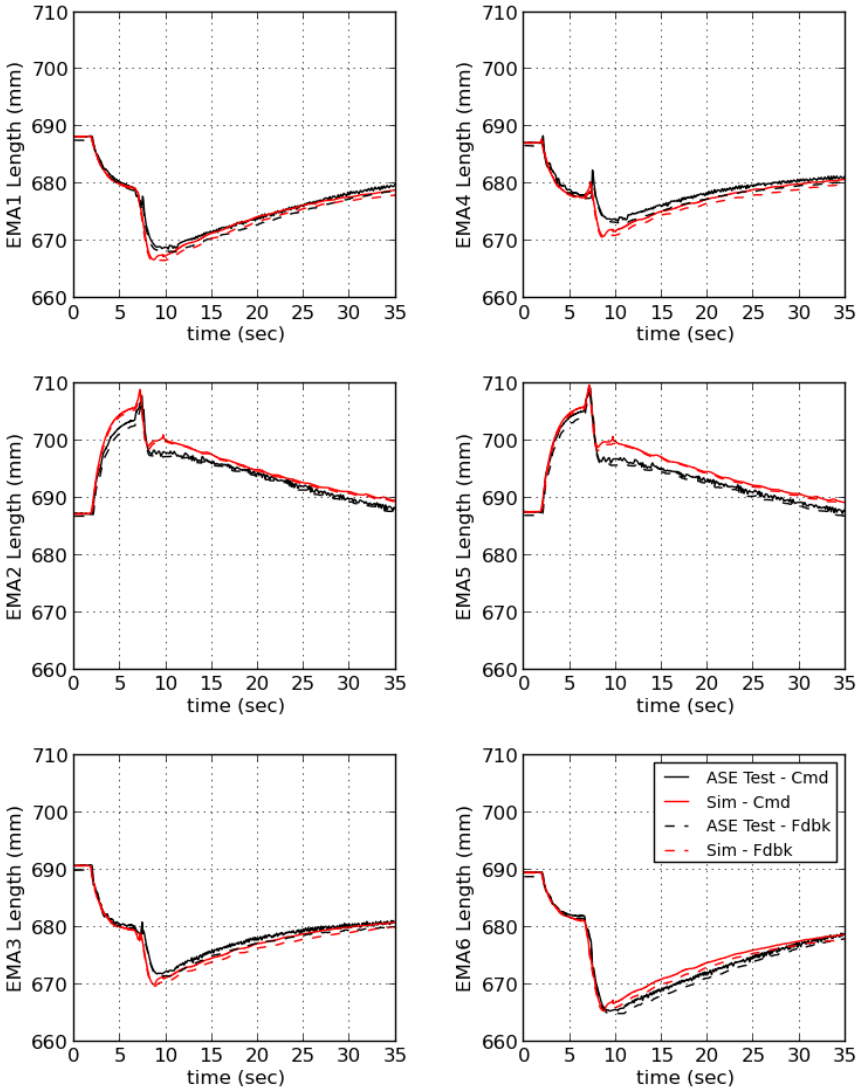

| NDS 6DOF Test | NDS 6DOF Facility Integrated Sim | NDS On-orbit Integrated Sim | NDS On-orbit Docking |
|---|---|---|---|
| NDS Controller Software | NDS Controller Software | NDS Controller Software | NDS Controller Software |
| + | + | + | + |
| NDS Mechanism Hardware | NDS Dynamics Simulation | NDS Dynamics Simulation | NDS Mechanism Hardware |
| + | + | + | + |
| SDTS Testbed | 6DOF Facilty Simulation | | |
| + | + | | |
| On-orbit Dynamics Sim (2-body SimHost Software) | On-orbit Dynamics Sim (2-body SimHost Software) | On-orbit Dynamics Sim (2-body Simulation) | On-Orbit Micro-gravity Environment |

Notes:
1. Dashed lines signify simulated elements
2. Blue boxes are real elements
3. Tan boxes are simulations

# NDS HWIL Test, Analysis, & Correlation




NDS 6DOF Case Study: Maximum Lateral Misalignment



# NDS Post-Test Correlation M&S Activities

- Parameter Sensitivity Study
  - Highlights hardware and/or mission sensitivities.
- Uncertainty Factor Study
  - Provides a quantifiable quality of correlation for certain parameters.
  - Provides a scale/safety factor to apply when checking against system requirements.
- System Requirements Studies
  - NDS related studies include range-of-motion, loads, docking success, etc.
  - Checks that the system performs within specified requirements.
- Documentation of M&S Study Results
- Documentation Review
  - Reviewers include project management, subject matter experts, etc.
  - The review determines:
    - Acceptance of M&S as valid representation of the NDS
    - Acceptance that NDS fulfills system requirements
  - Final acceptance may require multiple iterations of model and/or hardware improvements, re-correlation to test results, post-correlation studies, documentation, and review.

# Summary

- NASA has developed a process of Verification, Validation, and Accreditation to rigorously evaluate the credibility of computational model predictions.
- From the earliest phases of the NDS program as well as many other NASA projects, the accepted approach to evaluate the dynamic hardware performance per project requirements has been verification by analysis using test-validated simulation models.
- This method interleaves hardware verification with model and simulation VV&A allowing for increased performance and safety while decreasing cost for the project overall.
- Model and simulation VV&A is a critical step in continuing NASA's mission of exploration and safety.

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Questions