From Documents to Models: The Vision for Model Based Systems Engineering (MBSE)

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Systems Engineering

Vision for Systems Engineering: Model-based

- Benefits:
  - Faster Development
    - Develop initial concept models quickly
    - HIL/SIL/Code Generation
  - Higher Performance
    - Multiple concepts can be studied
  - Lower Risk
    - Focus on requirements
    - Collaboration
    - Highly graphical output
  - Lower Development Costs

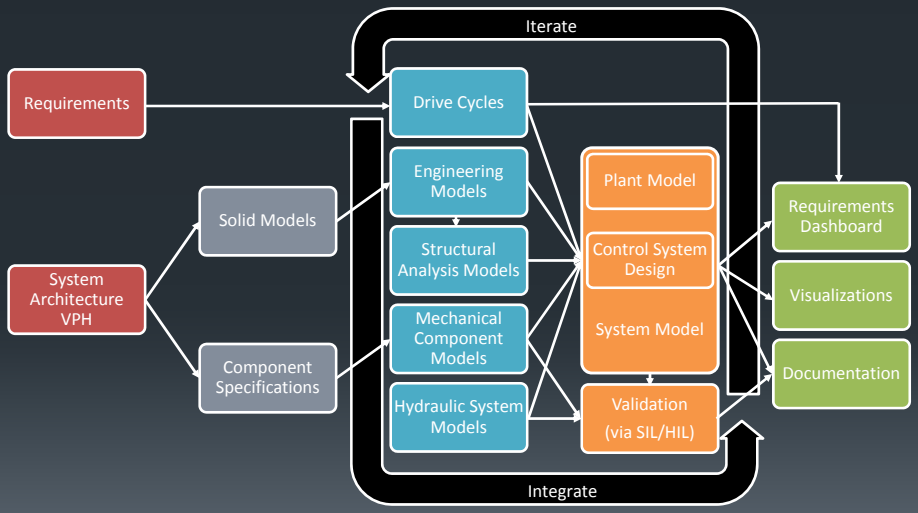
True Story - Drill Rig Development

- Getting from Idea to “Will it work?”
- Show me!
- Machine Concept (Function) Defined
  - Structures
  - Mechanisms
  - Operating Modes and Performance
- Getting it to do that
  - Development of Hydraulics & Controls
  - Understood that a Model-Based approach was critical
  - Did not know how to execute

Documents, yes, but no Systems

- Cross-functional team
  - Individual contributors, contributing individually
    - Hydraulics Engineer - Hydraulic Circuit (function) and Component Selection
    - Electrical Engineer - Control System (components) selection
    - University Consultants (Professors) Mechanism dynamic performance was to be assessed by developing closed-form equations of motion

M&S Approach

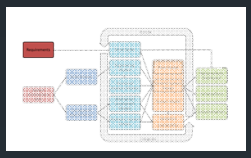


M&S Approach

Definitions:

- **Model-Based System Engineering (MBSE):** The application of systems engineering tools and techniques using engineering models and simulations
- **Model:** Modeling is the art of capturing the essential details required to analyze the necessary attributes of the system
- **Simulation:** For a model to be truly useful, it must be capable of being in an executable form in order to extract results from the model performing a virtual task or event
- **Drive Cycles:** The driving motion sequences and environment are derived from the customer supplied requirements documentation and put into a form that can be utilized by the M&S tool(s) to simulate the system's behaviors

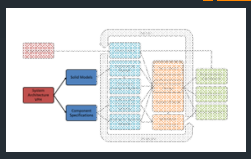
Requirements Analysis



Requirements:

- Customer Input Data
  - Major requirements (descriptions/depictions of motion sequences, cycle time requirements, specifications, etc.) have been communicated
- Industrial Standards and Regulations
  - Relevant standards and regulations will be reviewed and incorporated as appropriate. These may include API, ABS, DNV, etc.

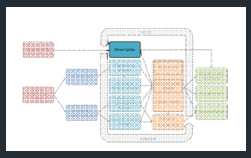
Requirements Analysis



System Architecture

- Customer Input Data
  - The VPH system architecture is largely prescribed (major exceptions being control system and hydraulic system) by client.
  - Our development team received information describing the system architecture via the following documents:
    - Animations
    - CAD Solid Models in SolidWorks format
    - Component specification spreadsheets

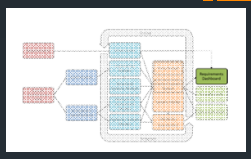
Requirements Analysis



Drive Cycle

- The machine Drive Cycles will be developed in a form that can be used with the models to either drive individual motions or drive the system to a path in a way that conforms to the functions that must be performed
- The Drive Cycles are largely derived from the motion sequences requested

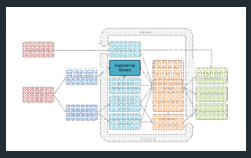
Requirements Analysis



Requirements Dashboard

- A document called the Requirements Dashboard in an Excel Spreadsheet format was created to internally and externally communicate the machine's requirements.
- The document is updated with performance results for every simulation run per iteration (as quickly and as often as possible; the goals are to obtain fast and automatic parameter population).
- By consolidating results into one document and providing a comparison to the requirements, rapid design decisions can be made. This method of documenting performance against the requirements provides a wealth of information at the product level and project level.

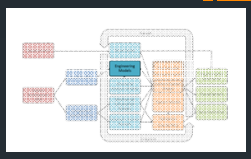
Initial Model Development



Engineering Model (Introduction)

- Engineering Models are low-fidelity, geometric/kinematic representations of components in systems. They are created for the explicit purpose of supporting the engineering activities required for development
- The Physical Architecture of the systems is modeled in a CAD system using an Engineering Modeling methodology.

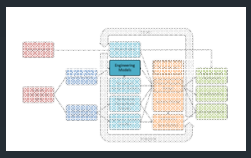
Initial Model Development



Engineering Model (Details)

- Engineering Models should only have enough detail to capture the following:
  - Functional geometry, interfaces, mass & inertia, volume, etc.
  - Non-product geometry like keep-out zones (or the inverse: package space allocations), tooling clearances, service points, sight-lines and blind spots, or other geometric requirements or design aids are incorporated.
- Product structure (BOM-structure) is not typically consistent with the model structure of an Engineering Model.

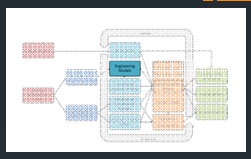
Initial Model Development



Engineering Model (Mechanisms)

- Mechanisms are represented in the CAD system with this methodology typically by using assembly constraints (mates) between Engineering Model components or sub-assemblies
- Mechanism constraints (utilizing mechanism or motion capabilities) may also be utilized. Basic kinematic studies, interferences, motion paths, etc. can often be developed this way
- Mass properties, joint definitions, and component geometry are exported for use in functional performance M&S tools

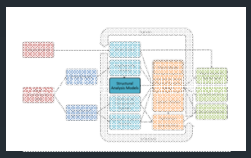
Initial Model Development



Engineering Model (Structures)

- Structures are modeled with sufficient detail to accurately capture mass properties and interfaces in the CAD tool but more importantly to allow for accurate meshes to be rapidly generated by the Finite Element Method (FEA) tool being utilized.
- The goal is to model the geometry to obtain a structural representation that will ultimately have accurate stiffness (local and global), modes (frequencies and shapes), and (if needed) stresses.

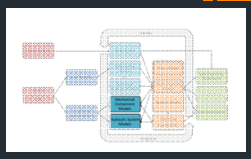
Initial Model Development



Structural Analysis

- The SolidWorks Engineering Models of the appropriate structural components will be analyzed with Finite Element Analysis
- Load-cases, boundary conditions, etc. were defined to conduct Static and dynamic structural simulations as appropriate (at component and/or system level)

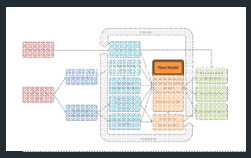
Initial Model Development



Component Models

- Machine components are modeled in the system engineering tool the either by utilizing the library components typically available in the system engineering tool or by creating the models from equations that properly model their behaviors.
  - Mechanical (transmissions, cables, bearings, etc.)
  - Electrical (motors, generators, inverters, grid resistors, etc.)
  - Hydraulic (pumps, motors, cylinders, heat exchangers, fluid conveyance lines, etc.)

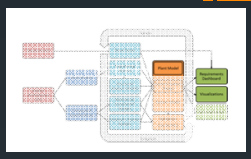
Model-Based System Engineering



Plant Model

- A plant model of the VPH was built with the major Engineering Model representations imported from SolidWorks.
- Additional (non-geometric) machine component models that were created are incorporated as well
- This model represents the majority of the system's physical architecture with rigid bodies.
- Model interrogation and reviews to ensure adherence to the prescribed concept will be performed establishing engineering rigor early.

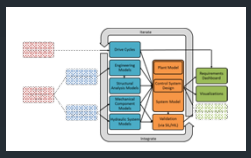
Model-Based System Engineering



Simulation

- Initially a limited set of critical Drive Cycles was used to assess the system's simulated performance
- All information that addresses the requirements was posted back to the Requirements Dashboard
- Animations of motions and plots of relevant parametric data were easily generated and easy to review

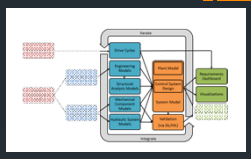
Model-Based System Engineering



Development

- Each development cycle (typically 2 week sprints) will be focused continually on quantifying and validating the high-risk assumptions.
- Development activity is centered on reducing the design risk and maximizing the overall performance of the system within the design constraints.
- Each cycle must conclude with the models being fully consistent and integrated. The results for all requirements being capable of being simulated must be posted to the Requirements Dashboard.

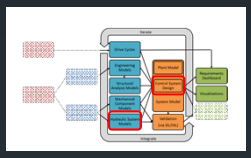
Model-Based System Engineering



Development (Cont.)

- The types of activities that were conducted:
  - Component model validation
  - Additional Drive Cycle simulations incorporated
    - More requirements addressed with simulations
  - Model fidelity improvements
    - Incorporation of flexible-bodies
    - Component models with greater detail
  - Design modifications (parametric or topological) to components, sub-systems, and/or control systems

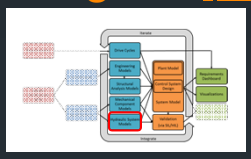
Model-Based System Engineering



Development (Cont.)

- It was within hydraulic system and the controls system where we were able to exercise design control
- The other systems and many components are largely prescribed by the customer

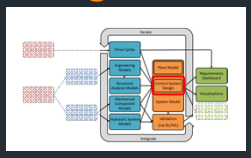
Model-Based System Engineering



Development (Cont.)

- Hydraulic System
  - The Hydraulic System was developed in the context of the system model to best meet the overall system requirements
  - Components specifications will be developed from system requirements and modeled in detail as appropriate

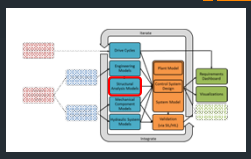
Model-Based System Engineering



Development (Cont.)

- Control System Design
  - The Control System's design will be developed in the context of the system model to best meet the overall system requirements.
  - Requirements for control authority, IO, sensors, etc. will be cascaded as appropriate.
  - Control System Hardware may be utilized to run model in a HIL mode.

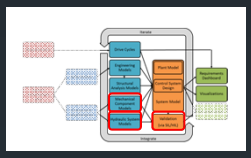
Model-Based System Engineering



Development (Cont.)

- Flexible-Body Implementation
  - Flexible-bodies will be incorporated into the system model as appropriate
  - Structural components that are determined to be modeled as flexible-bodies will have surrogate representations developed in FEA to match the specific flexible-body model definitions in the system model

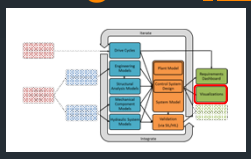
Model-Based System Engineering



Development (Cont.)

- Validation
  - Mechanical and hydraulic component models of critical and/or major components are expected to be validated against their real-world performance giving confidence in the simulated performance of the system
  - System-level performance validation was not possible in this phase, but the models developed will be capable of supporting eventual validation

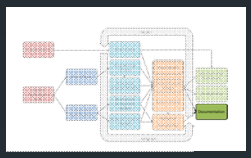
Model-Based System Engineering



Visualization

- With the use modern systems engineering tools the creation of realistic 3-D animations of the physical system's motions **driven by the simulation** are available to use for model interrogation and presentation purposes.
- The geometry from the CAD Engineering Models are the source of the graphics used in the animations.
- Plots of relevant parametric data are also easily generated and incorporated into final documentation.

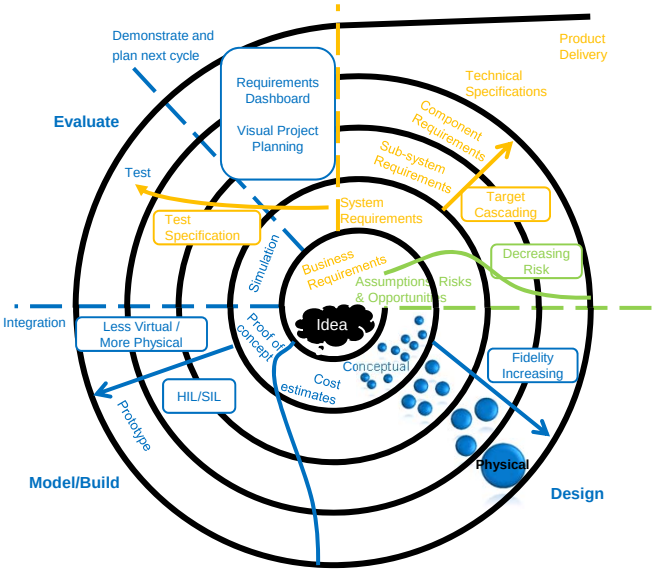
Documentation & Reporting



Documentation

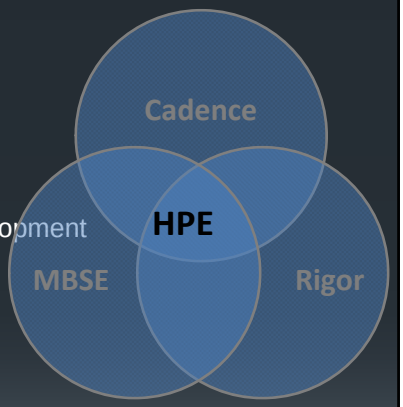
- Were able to generate documentation in these and other topics as required:
  - Model Descriptions
  - Reportable Modeling Techniques
  - Test Cases & Validation
  - Load-case Definition

Spiral Development Process



Putting it All Together

- High Performance Engineering for NPD
  - Rigor
    - Design Thinking Methods
      - True Requirements Capture
    - Small, Highly Capable Teams
    - Set-based Approach to Concept Development
  - Model-Based System Engineering
    - Systems Engineering and Architecture
    - Controls and Software Engineering
  - Cadence
    - Agile Process for Product Development
    - Focus on Deliverables and Integration
    - Demonstration and Transparency



M&S Approach