Simulatable Digital Twins

A value-added connection between MBSE, Design, and Manufacturing

Agenda

- What is a Digital Twin?
- Static Digital Twins
- Simulation-Based Digital Twins

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- What is a Digital Twin?
- Static Digital Twins
- Simulation-Based Digital Twins

The Many Definitions of Digital Twin

AIAA

Table 1: Digital Twin Definition

A **Digital Twin** is a virtual representation of a connected physical asset.

A Digital Twin is defined as

A set of ***virtual information*** *constructs that mimics the* ***structure, context and behavior*** *of an* ***individual / unique physical asset****, or a group of physical assets, is* ***dynamically updated*** *with data from its physical twin* ***throughout its life cycle*** *and* ***informs decisions*** *that* ***realize value****.*

https://aiaa.org/wp-content/uploads/2024/12/digital-twin-institute-position-paper-december-2020.pdf

DAU

A digital twin is a virtual replica of a physical entity that is synchronized across time.

https://www./digital-product-support-minute-programs-use-digital-twins

DoD Instruction 5000.97
Digital Engineering

Digital Twin

A computerized representation (integrated set of models) that serves as the real-time digital counterpart of a physical object or process.

https://www.esd.whs.mil/Portals/54/Documents/DD/issuances/dodi/500097p.PDF

McKinsey & Company

A digital twin is a digital replica of a physical object, person, system, or process, contextualized in a digital version of its environment. Digital twins can help many kinds of organizations simulate real situations and their outcomes, ultimately allowing them to make better decisions.

https://www.mckinsey.com/featured-insights/mckinsey-explainers/what-is-digital-twin-technology

MathWorks

A digital twin is a digital representation of a product, process, or system either in operation or in development. When in operation, it reflects the asset's current condition and includes relevant historical data; digital twins are used to evaluate an asset's current state and, more importantly, to predict future behavior, refine control systems, or optimize operations. During development, the digital twin acts as a model of a to-be-built product, process, or system that facilitates development, testing, and validation.

https://www.mathworks.com/discovery/digital-twin.html

digital twin CONSORTIUM

/ dig•i•tal twin /

noun

A digital twin is an integrated data-driven virtual representation of real-world entities and processes, with synchronized interaction at a specified frequency and fidelity.

https://www.digitaltwinconsortium.org/initiatives/the-definition-of-a-digital-twin/

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Digital Transformation Strategies being defined by DoD and Services

Air Force Digital Building Code and Scorecard

DEPARTMENT OF THE AIR FORCE
WASHINGTON, DC

OFFICE OF THE ASSISTANT SECRETARY

MEMORANDUM FOR THE ACQUISITION ENTERPRISE

SUBJECT: Digital Building Code for the Transformation of Acquisition and Sustainment

In line with the National Defense Strategy, the Department of Defense's Digital Engineering Strategy, and Chief of Staff of the Air Force's Accelerate Change or Lose Paper, the Department of the Air Force (DAF) is implementing a Digital Transformation across the acquisition and sustainment enterprise. This is truly a cultural, business, and technological transformation. As such, it requires the continued support and engagement of the entire community: across all functional domains; from program trenches to headquarters staffs; from freshly hired graduates to seasoned veterans; and with government and industry collaboration. A Digital Transformation is the disruptive enabler we need to overcome our adversaries' rapidly increasing parity. Through this Digital Transformation, and the relentless spirit of Airmen and Guardians across the Department, we can and will transform our acquisition enterprise into one that securely delivers capability at the speed of relevance.

In response, the DAF laid out a strategic vision to improve its acquisition and sustainment practices through a Digital Transformation that includes Digital Engineering and Management, Agile Software Development, and Open System Architectures. This strategic vision promotes digitally enabled processes and replaces the linear, document-centric approach of today with a dynamic, model-centric approach. This new approach places emphasis on evolving and refining models as opposed to updating paper documents; obtaining appropriate intellectual property (IP) rights to prevent vendor-lock during sustainment; and developing and delivering capabilities in rapid, innovative, and agile ways. Implementing the Department's Digital Transformation involves artful execution of this "Digital Building Code." The Digital Building Code is intended to be a living set of best practices that will be updated and to capture lessons learned along the DAF's Digital Transformation journey.

Digital Acquisition and Sustainment hold the key to unleashing the speed and agility we need to field capability at the tempo required to win in future conflicts with peer competitors. The attached tabs give a point of departure for executing programs aligned with the Digital Transformation concept of operations.

Andrew P. Hunter
Assistant Secretary of the Air Force
(Acquisition, Technology & Logistics)

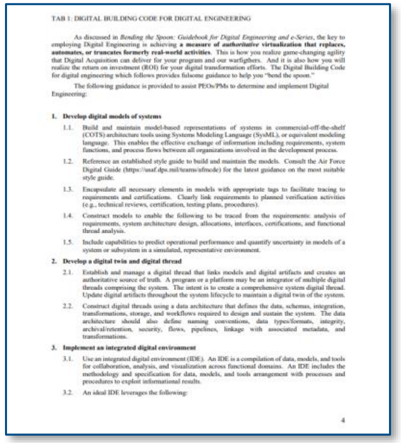
Frank Calvelli
Assistant Secretary of the Air Force
(Space Acquisition & Integration)

Attachments:
1. Digital Building Code for Digital Engineering and Management
2. Digital Building Code for Agile Software
3. Digital Building Code for Open Systems Architecture

* https://guide.dafdto.com/wp-content/uploads/2023/01/Digitial-Building-Code-2022-Memo-Signature-Final.pdf

1. Develop digital models of systems

1.1 Build and maintain appropriate fidelity model-based representations of systems in commercial-off-the-shelf (COTS) architecture tools using Systems Modeling Language (SysML), or equivalent modeling language. This enables the effective exchange of information including requirements, system functions, and process flows between all organizations involved in the development process and through sustainment.



1.2 Determine guidelines/use cases that will scope what needs to be modeled and to what fidelity given acquisition and sustainment strategies. Reference an established style guide to build and maintain the models. Consult the Air Force Digital Guide (https://usaf.dps.mil/teams/afmcde) for the latest guidance on the most suitable style guide.

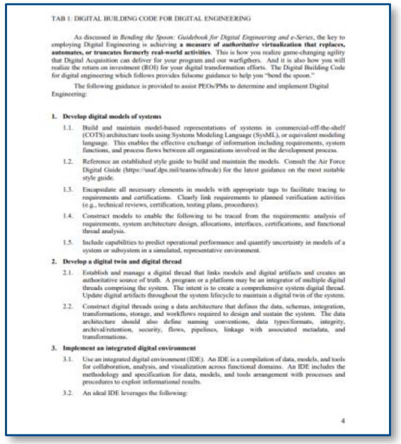
1.3 Encapsulate all necessary elements in models with appropriate tags to facilitate tracing between requirements, technical data, and certifications. Clearly link requirements to planned verification activities (e.g., technical reviews, certifications, testing plans, and procedures).

1.4 Construct models to enable the following to be traced from the requirements: analysis of requirements, system architecture design, allocations, interfaces, certifications, and functional thread analysis.

1.5 Include the capability to **predict operational performance** and quantify uncertainty in models of a system or subsystem in a **simulated, representative environment**.

* https://guide.dafdto.com/wp-content/uploads/2023/01/Digitial-Building-Code-2022-Memo-Signature-Final.pdf

2. Develop a digital twin and digital thread



TAB 1: DIGITAL BUILDING CODE FOR DIGITAL ENGINEERING

As discussed in *Bending the Spoon: Guidebook for Digital Engineering and e-Series*, the key to employing Digital Engineering is achieving **a measure of authoritative virtualization that replaces, automates, or truncates formerly real-world activities**. This is how you realize game-changing agility that Digital Acquisition can deliver for your program and our warfigthers. And it is also how you will realize the return on investment (ROI) for your digital transformation efforts. The Digital Building Code for digital engineering which follows provides fulsome guidance to help you "bend the spoon."

The following guidance is provided to assist PEOs/PMs to determine and implement Digital Engineering:

1. **Develop digital models of systems**
   - 1.1. Build and maintain model-based representations of systems in commercial-off-the-shelf (COTS) architecture tools using Systems Modeling Language (SysML), or equivalent modeling language. This enables the effective exchange of information including requirements, system functions, and process flows between all organizations involved in the development process.
   - 1.2. Reference an established style guide to build and maintain the models. Consult the Air Force Digital Guide (https://usaf.dps.mil/teams/afmcde) for the latest guidance on the most suitable style guide.
   - 1.3. Encapsulate all necessary elements in models with appropriate tags to facilitate tracing to requirements and certifications. Clearly link requirements to planned verification activities (e.g., technical reviews, certification, testing plans, procedures).
   - 1.4. Construct models to enable the following to be traced from the requirements: analysis of requirements, system architecture design, allocations, interfaces, certifications, and functional thread analysis.
   - 1.5. Include capabilities to predict operational performance and quantify uncertainty in models of a system or subsystem in a simulated, representative environment.
2. **Develop a digital twin and digital thread**
   - 2.1. Establish and manage a digital thread that links models and digital artifacts and creates an authoritative source of truth. A program or a platform may be an integrator of multiple digital threads comprising the system. The intent is to create a comprehensive system digital thread. Update digital artifacts throughout the system lifecycle to maintain a digital twin of the system.
   - 2.2. Construct digital threads using a data architecture that defines the data, schemas, integration, transformations, storage, and workflows required to design and sustain the system. The data architecture should also define naming conventions, data types/formats, integrity, archival/retention, security, flows, pipelines, linkage with associated metadata, and transformations.
3. **Implement an integrated digital environment**
   - 3.1. Use an integrated digital environment (IDE). An IDE is a compilation of data, models, and tools for collaboration, analysis, and visualization across functional domains. An IDE includes the methodology and specification for data, models, and tools arrangement with processes and procedures to exploit informational results.
   - 3.2. An ideal IDE leverages the following:

4

2.1 Establish and manage a digital thread that links models and digital artifacts and creates an authoritative source of truth. A program or a platform may be an integrator of multiple digital twins comprising the system. **Update digital artifacts throughout the system lifecycle to maintain a digital twin of the physical system.**

What is a Static Digital Twin?

A Static Digital Twin is a connected hierarchy of Digital Artifacts that are updated throughout the system lifecycle

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What ROI do we get from a Static Digital Twin?

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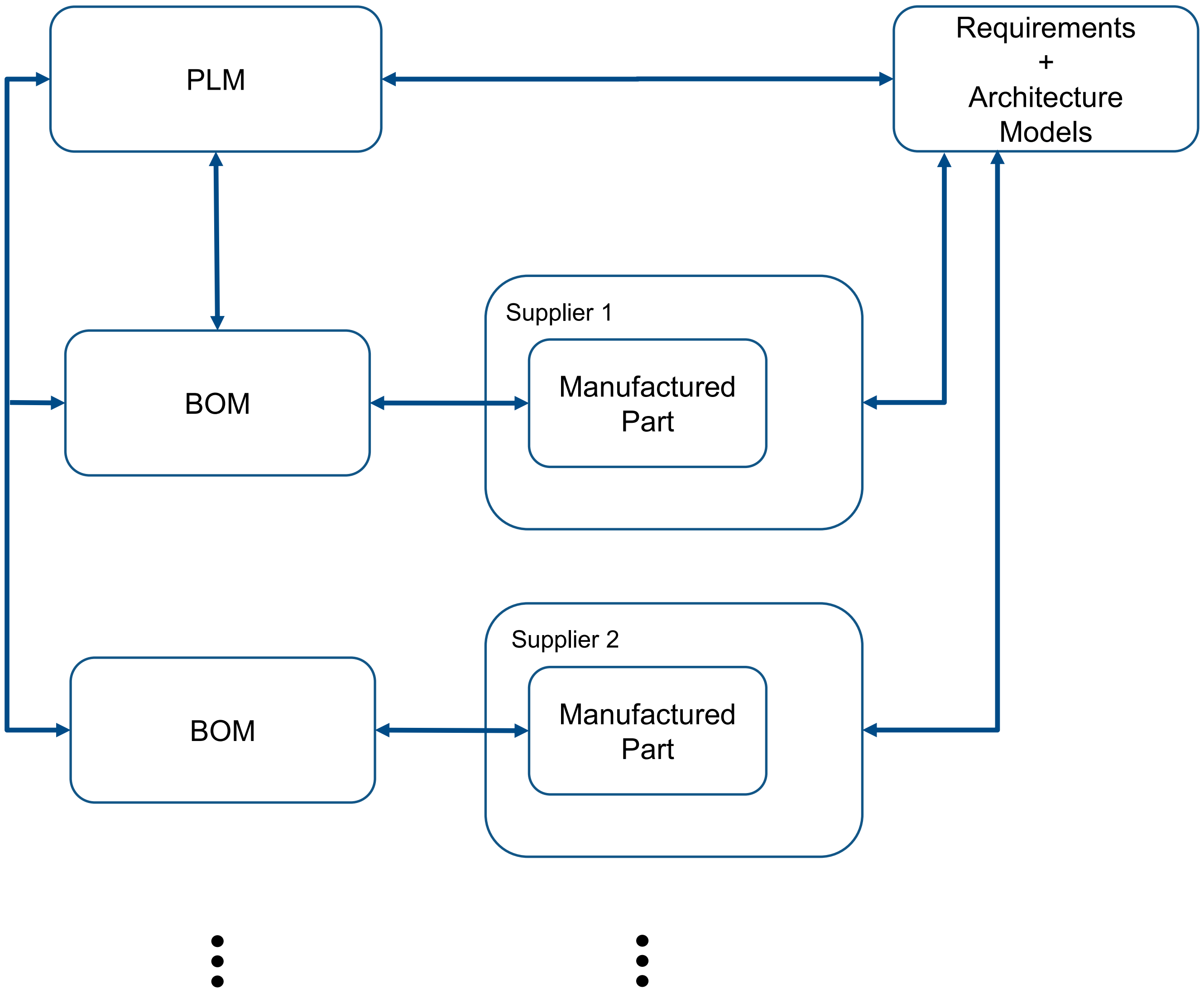
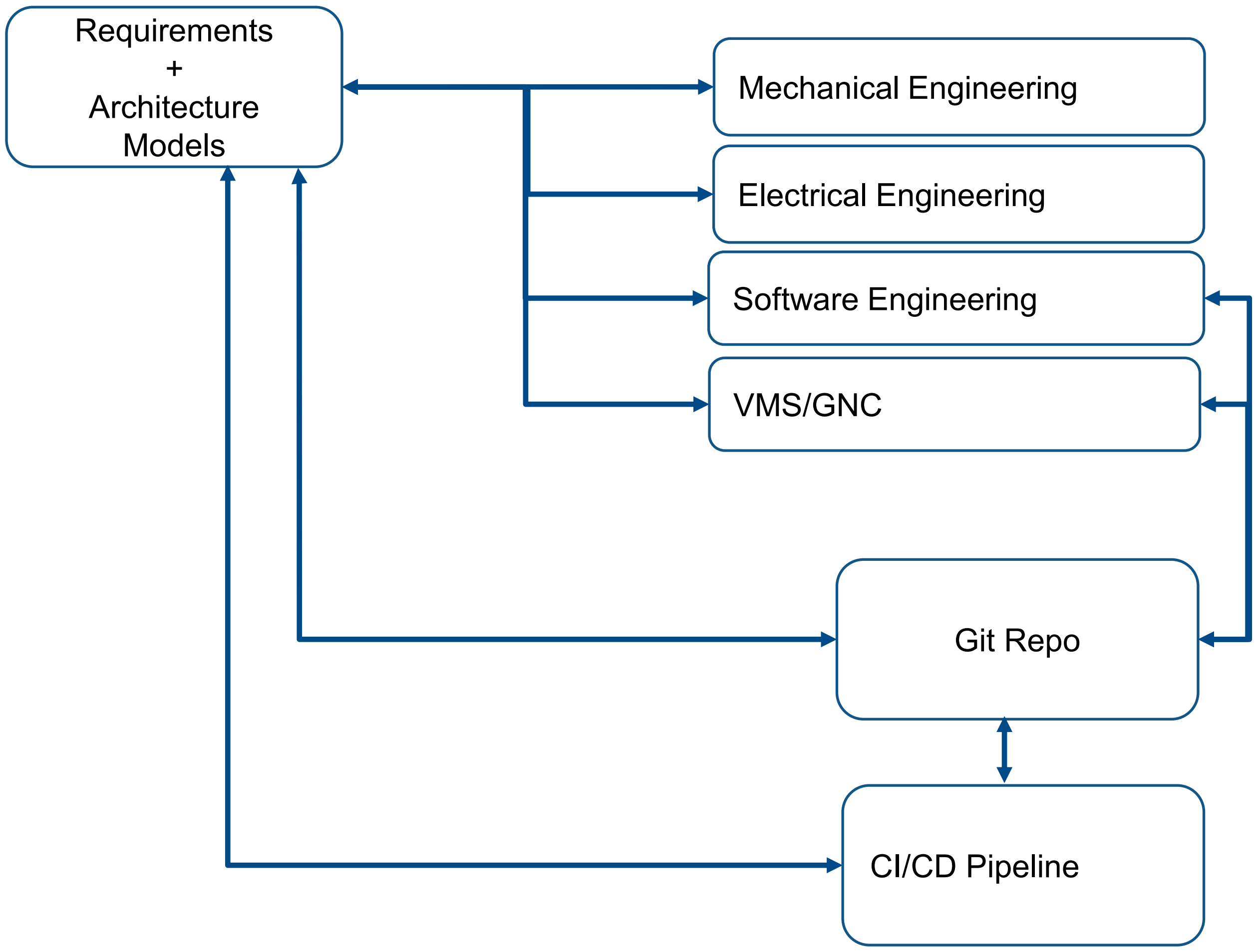
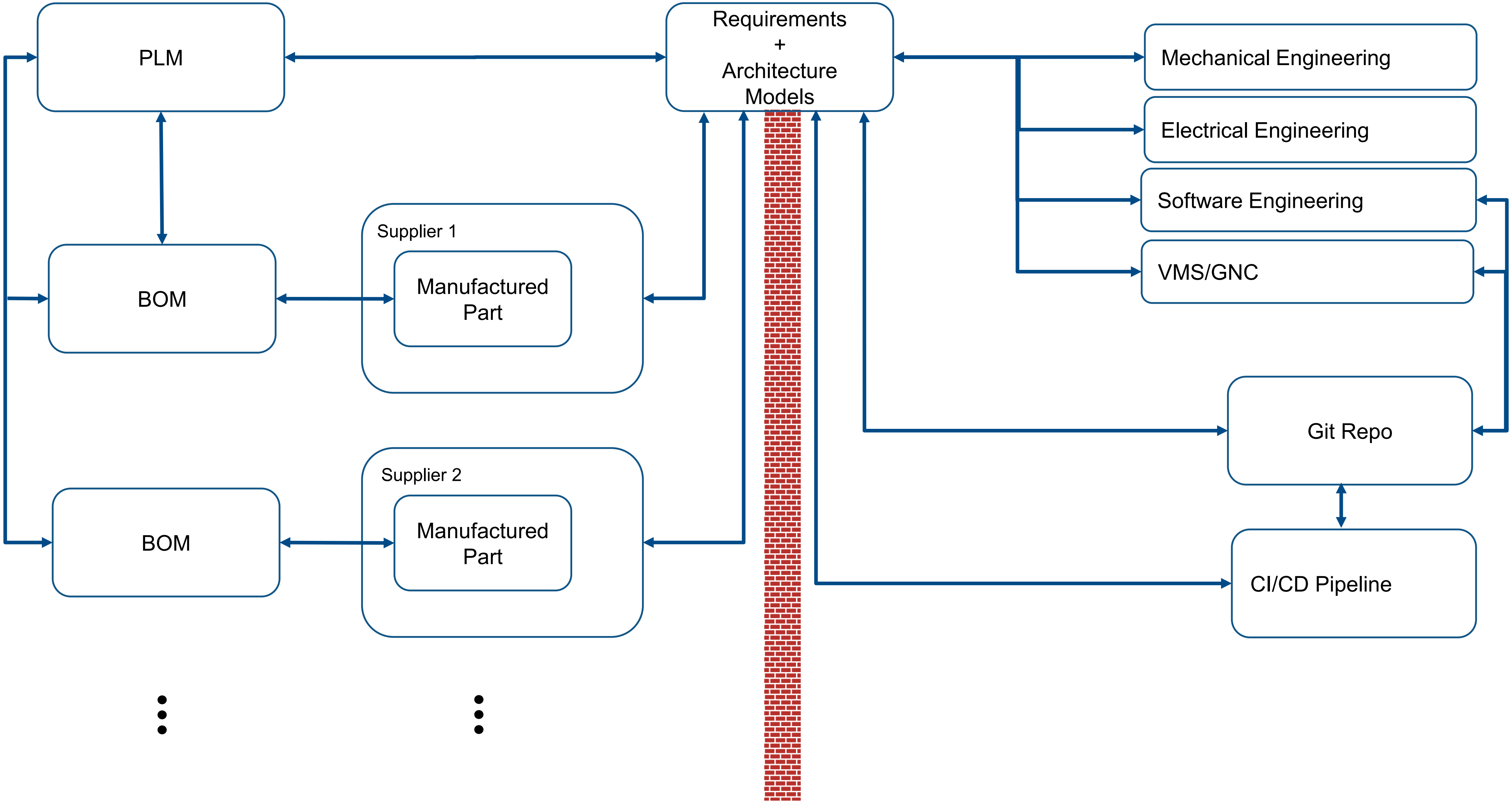
Supplier Management/Manufacturing Digital Twin



Engineering and Design Digital Twin



Static Digital Twins limit collaboration between Design and Manufacturing



Thought Exercise: Digital Twins and Manufacturing

A company that designs and manufactures quadcopters requires 1 or more Inertial Measurement Units (IMUs) for each airframe. This company will source the IMU from a supplier.

Due to the low-cost nature of the quadcopter, the manufacturer opts for a COTS part. The manufacturer can obtain the specification for the COTS part based on the datasheet provided by the supplier. The datasheet serves as the requirements for the performance of the IMU part.

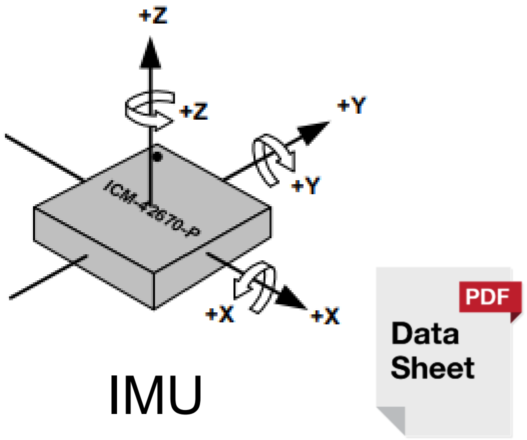
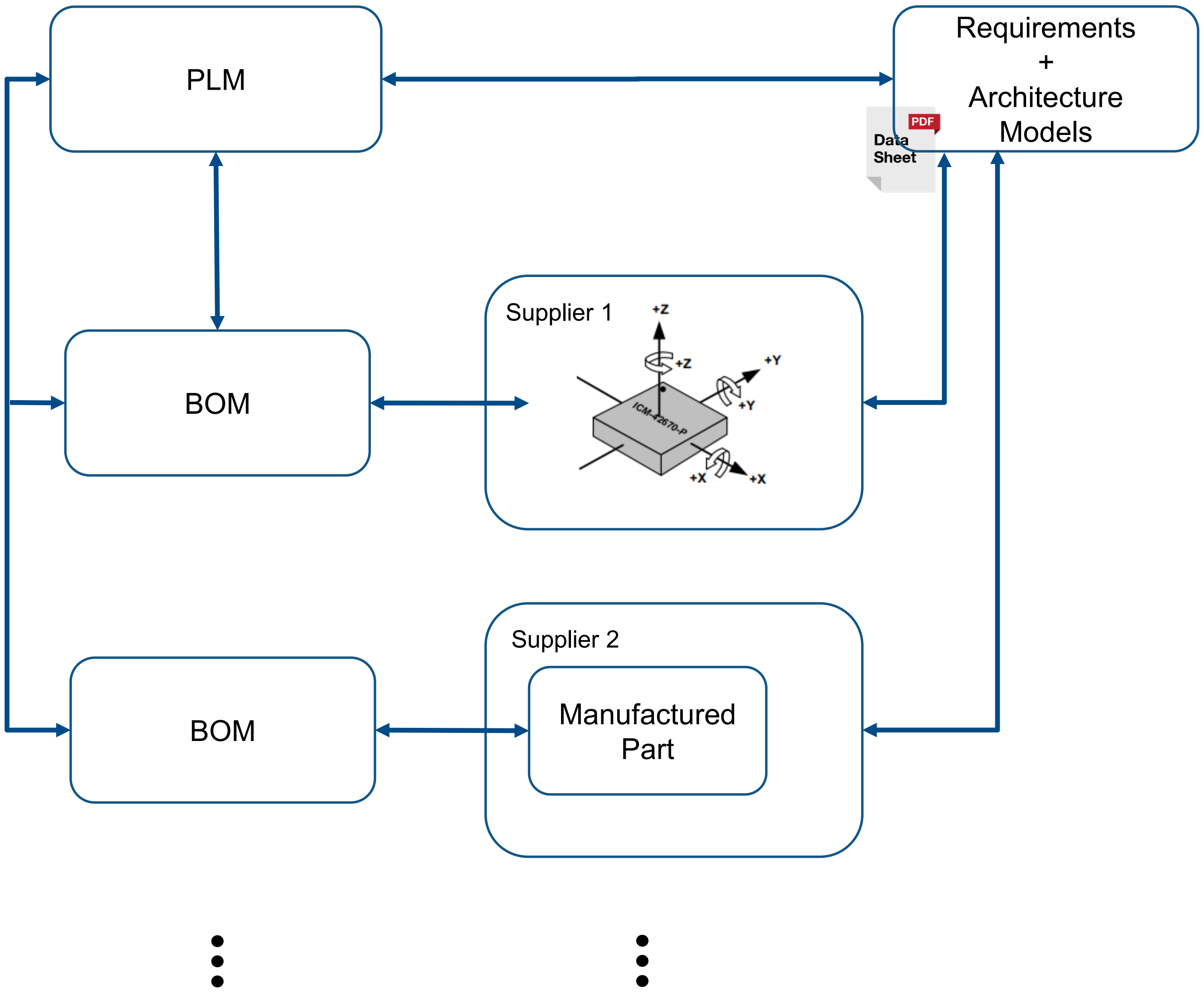


Image Source: https://invensense.tdk.com/wp-content/uploads/2021/07/ds-000451_icm-42670-p-datasheet.pdf

Supplier Management and Manufacturing



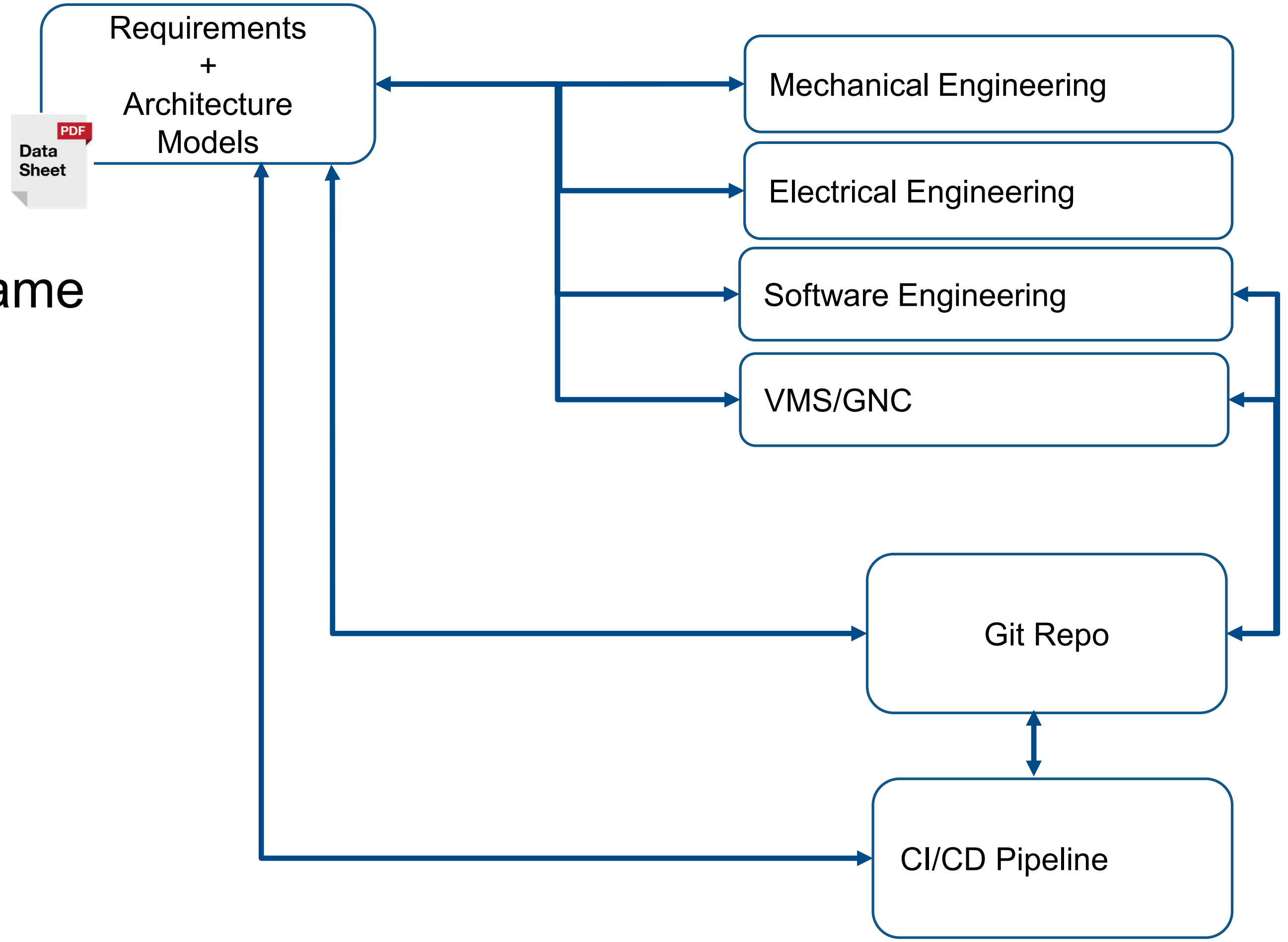
These teams care about:

- Unit Cost of the IMU
- Delivery schedule
- Acceptance Tests of the IMUs
- Hardware Compatibility between the IMU and the Airframe
- Installation of the IMU during manufacturing

Engineering and Design

These teams care about:

- Mechanical
  - Mass of the IMU
  - Location of the IMU on the airframe
- Electrical
  - Power requirements of the IMU
  - Pinout of the IMU
- Software
  - IMU Pinout
  - IMU Data Interface
- GNC
  - Sensor Noise
  - Location of the IMU on the airframe



Leveraging the Static Digital Twins

Assume we have a complete static digital twin.

Scenario 1

- During HW acceptance testing, it is observed that a batch of the delivered IMUs all have more noise in their gyro readings than the data sheet specified

What is the resolution?

Leveraging the Static Digital Twins

Assume we have a complete static digital twin.

Scenario 1

- During HW acceptance testing, it is observed that a batch of the delivered IMUs all have slightly more noise in their gyro readings than the data sheet specified

What is the resolution?

We can reject the batch of IMUs for being out-of-spec, but this will likely delay delivery of quadcopters and potentially impact profit.

Leveraging the Static Digital Twins

Assume we have a complete static digital twin.

Scenario 2

- All IMUs are tested and meet specifications, however flight test data on some aircraft shows degraded performance that is failing system verification

How do we find the problem and resolution?

Agenda

- What is a Digital Twin?
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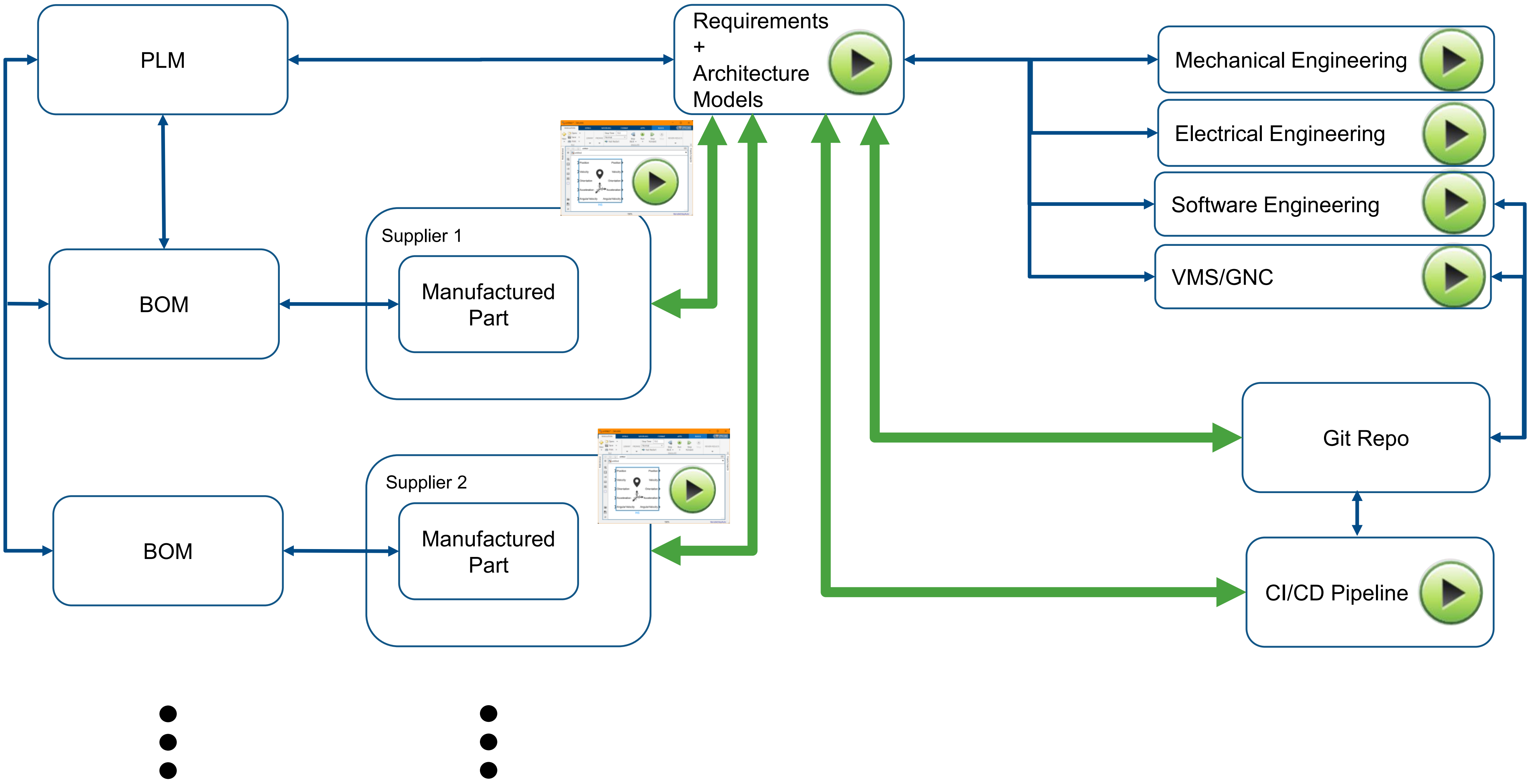
What is a Simulatable Digital Twin?

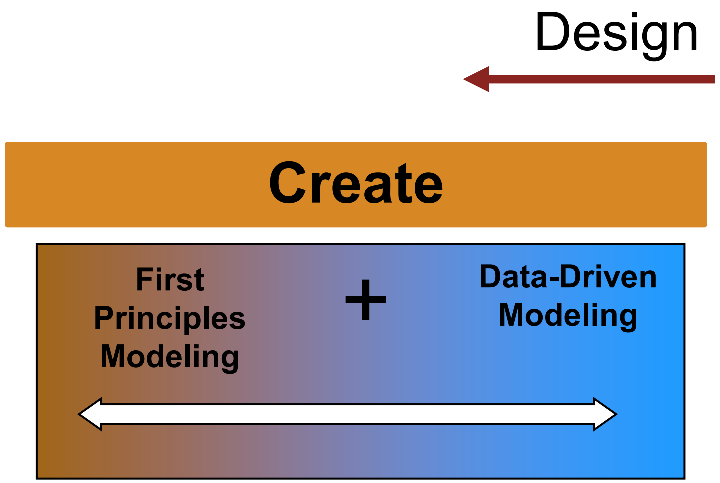
A simulatable digital twin is an evolving, data-connected hierarchy (SoS→system→component) of simulatable models kept at task-appropriate fidelity to predict behavior to inform design, test, and operations decisions across the lifecycle.

Simulatable Digital Twins

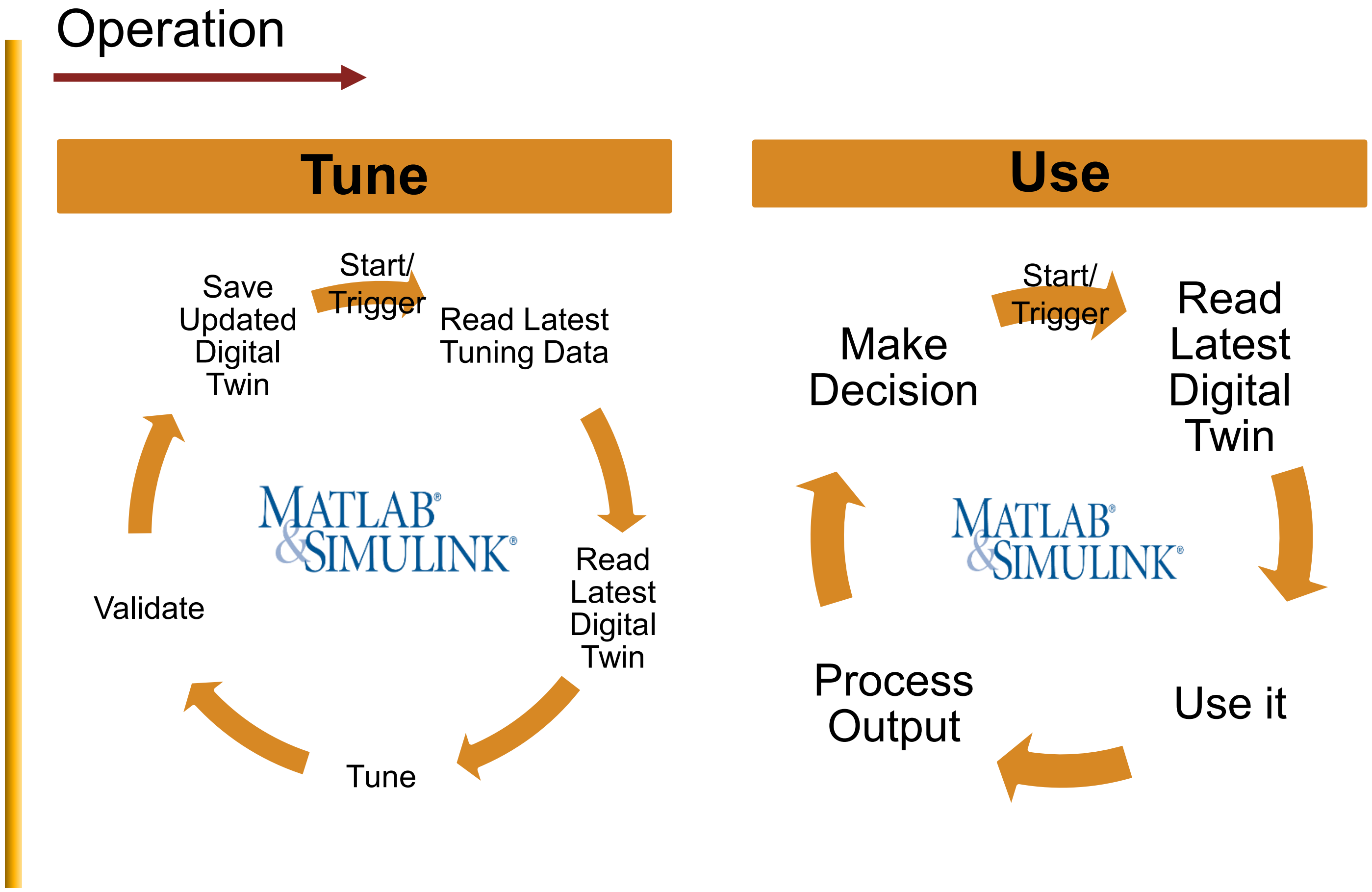
Paul's version



Simulatable Digital Twins Evolve throughout the System Lifecycle



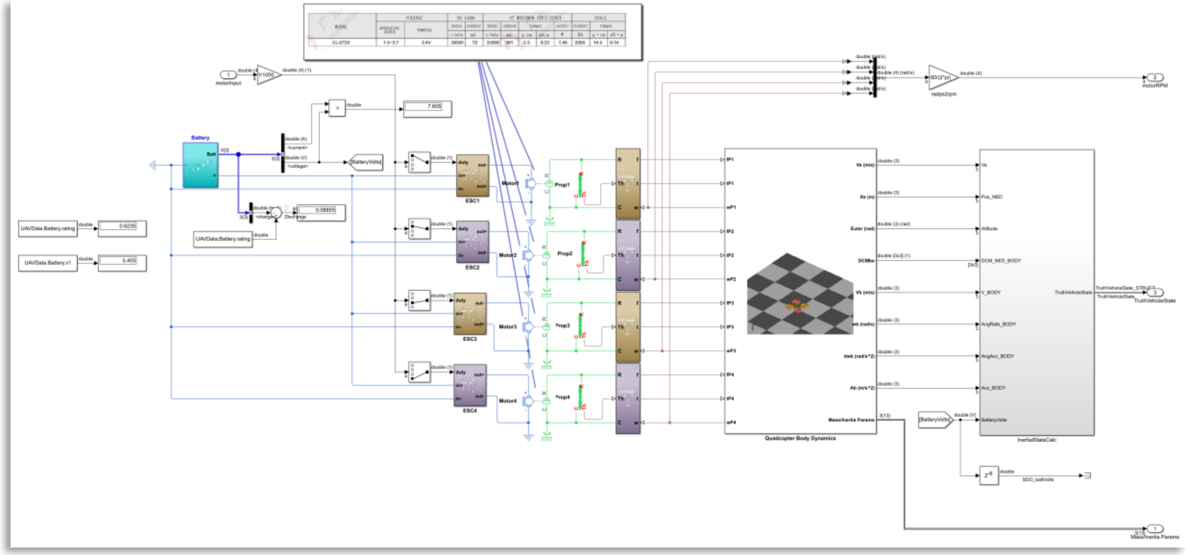
- What is modeled
- How it is modeled
- Needed Level of Fidelity



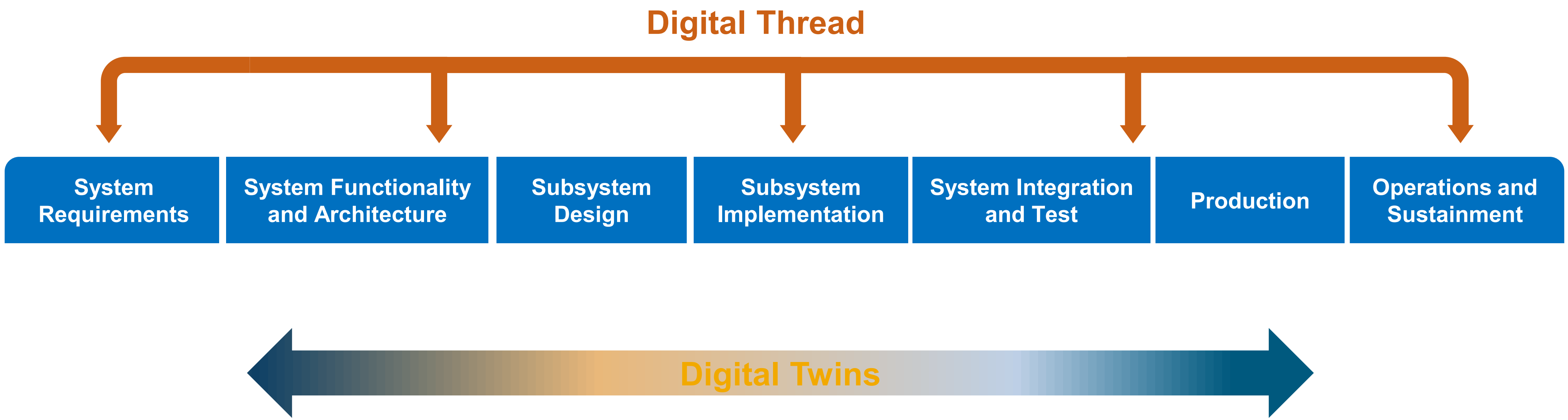
A Simulatable digital twin is connected to Data

A simulatable digital twin uses design, test, and operational data to update the virtual representation of a real asset across the lifecycle

Sensor data
Operating conditions



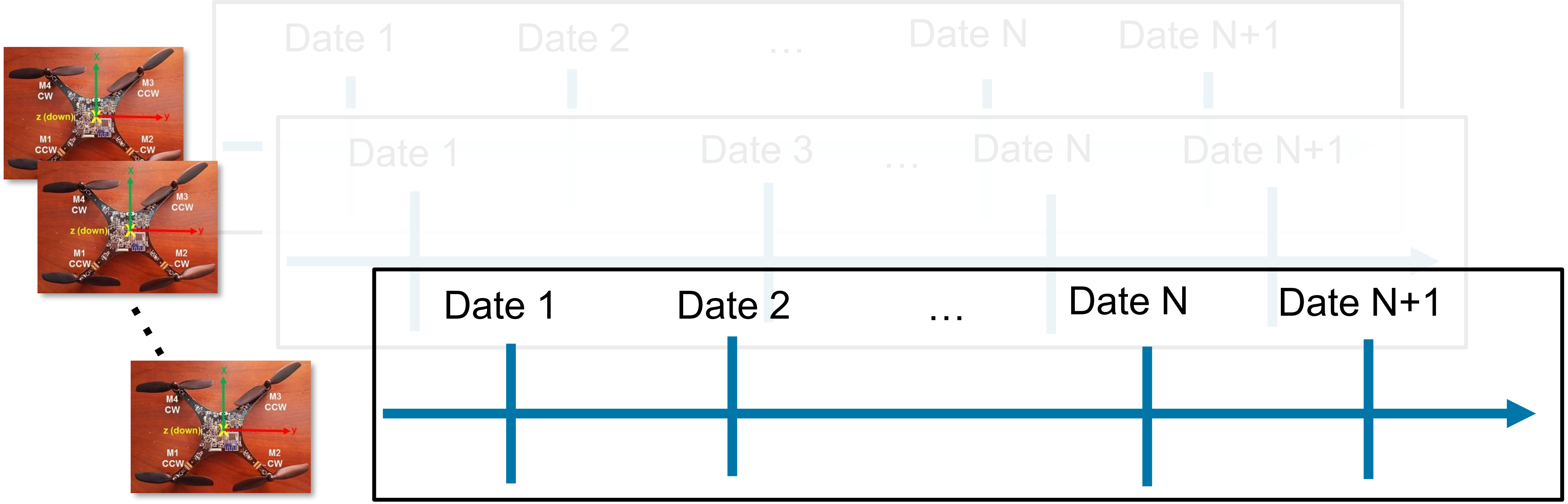
Digital Twins are a direct culmination of the Systematic Use of Data and Models throughout System Lifecycle allowing transparency and reuse across stages



Summary

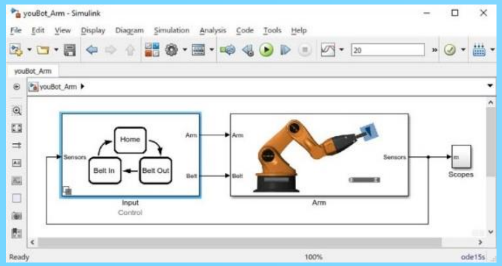
- **Digital Twins** can start anywhere in **System Lifecycle**
- Digital Twin models **progress** as the systems progress
- Value comes from **using models** across lifecycle.
- **Smart connected systems** provide a significant opportunity to use **data and digital twins** in operation

Each Asset has a Digital Twin that is updated throughout the System Lifecycle



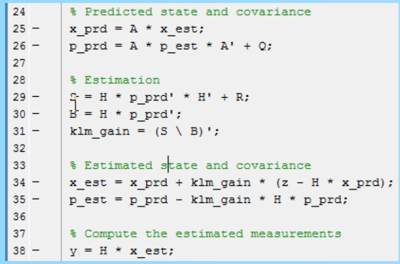
Range of modeling methods for Digital Twins

Physics-Based



- Dynamical models of systems/components
- Electrical, mechanical, algorithms, etc.
- Include third-party models, e.g., FE models via FMI

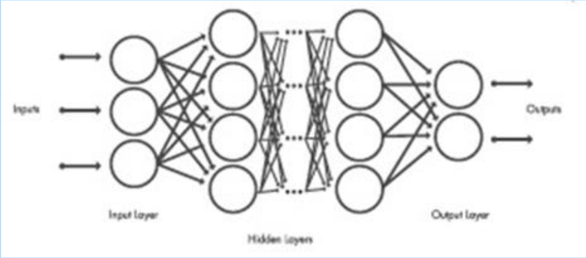
Data-Driven



```
% Predicted state and covariance
x_prd = A * x_est;
p_prd = A * p_est * A' + Q;

% Estimation
S = H * p_prd' * H' + R;
B = H * p_prd';
klm_gain = (S \ B)';

% Estimated state and covariance
x_est = x_prd + klm_gain * (z - H * x_prd);
p_est = p_prd - klm_gain * H * p_prd;

% Compute the estimated measurements
y = H * x_est;
```

- Kalman estimator
- System identification
- etc.

AI-Based



- Machine Learning
- Deep Learning
- etc.

Factors in choosing:

- Do you have knowledge of system's physics or only operational data?
- What does your application need?
- Who has the expertise needed to create it?

Our Approach for Digital Twins

- Enable you to create, modify, and operationalize your own physics-based, data-driven, and AI-based models, using MATLAB and Simulink
  - Foundation skills already exist in most organizations
  - Tools designed, documented, and supported so engineers can use on their own
  - Supports inclusion of models from other tools and languages
- Enable model reuse from your Model-Based Design workflows
  - Physics-based and data-driven models already created by your subject matter experts
  - Support a Digital Thread from development to deployment to operationalization
- Enable your equipment provider to share their models with you
  - Especially powerful when they use Model-Based Design themselves
  - Proven capabilities for sharing models (e.g., used between automotive OEMs and suppliers), including protection of IP in models

Leveraging the Simulatable Digital Twins

Assume we have a simulatable digital twin.

Scenario 1

- During HW acceptance testing, it is observed that the delivered IMUs all have slightly more noise in their gyro readings than the data sheet specified

What is the resolution?

We can use simulation to determine if the existing GNC SW, which includes sensor noise filtering, can handle the excess noise as is, or if a SW update could compensate for the excess noise avoiding the need for any EXPENSIVE HW CHANGES!

Leveraging the Simulatable Digital Twins

Assume we have a simulatable digital twin.

Scenario 2

- All IMUs are tested and meet specifications, however flight test data on some aircraft shows degraded performance that is failing system verification

How do we find the problem and resolution?

We can use simulations of the individual digital twins of the aircraft in question to isolate the issue to installation boresight angles. We can then use the simulation to determine if a SW update can compensate, avoiding EXPENSIVE HW CHANGES!