The Evolution of Digital Engineering: Future Visions for GNC Model-Based Design

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Space Segment Manager, MathWorks

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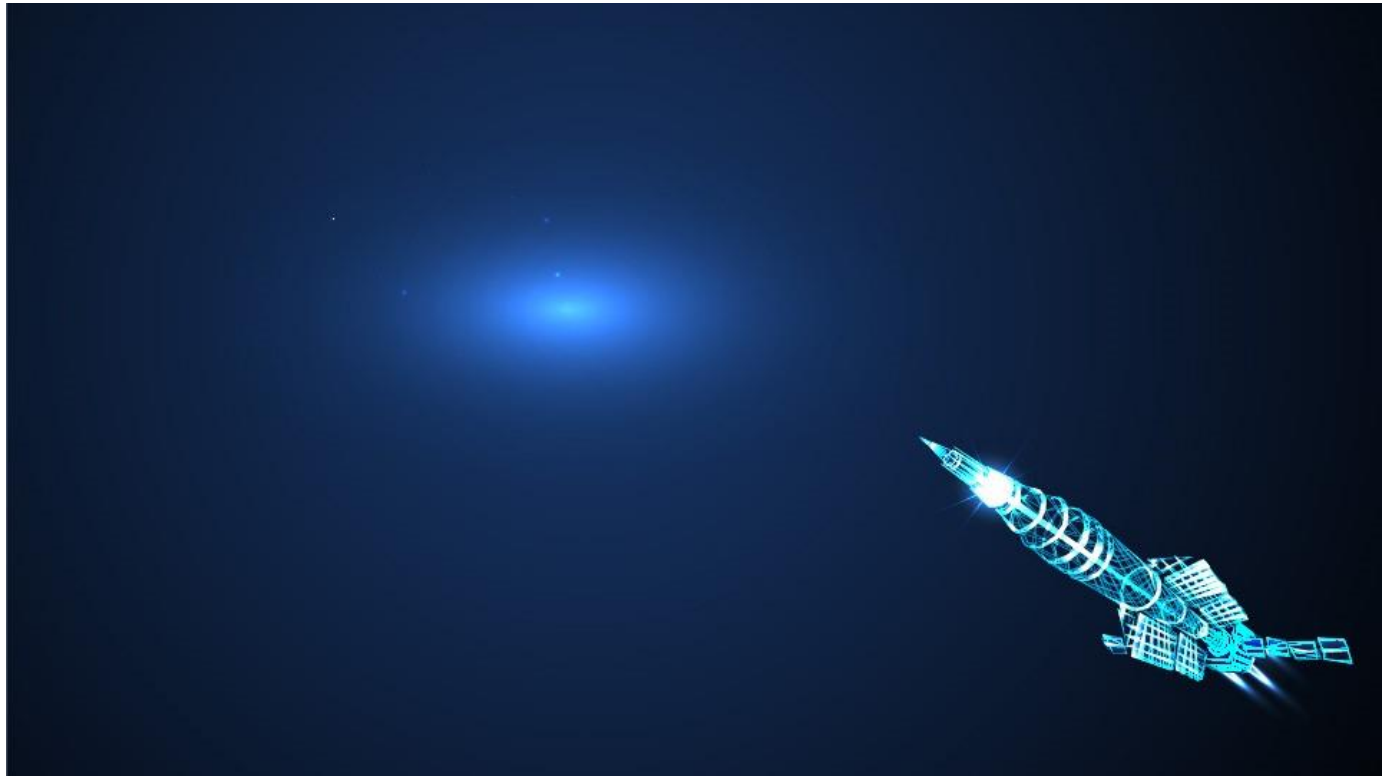
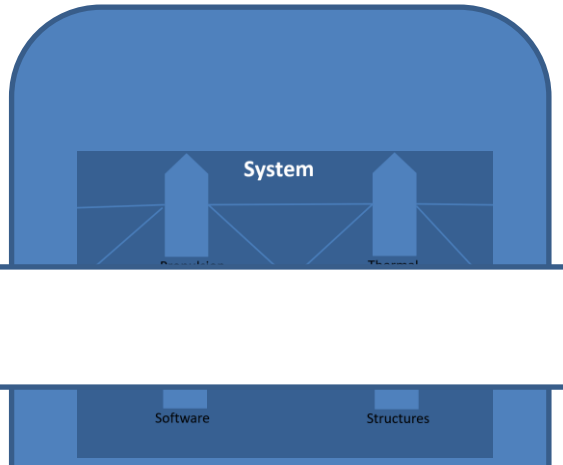
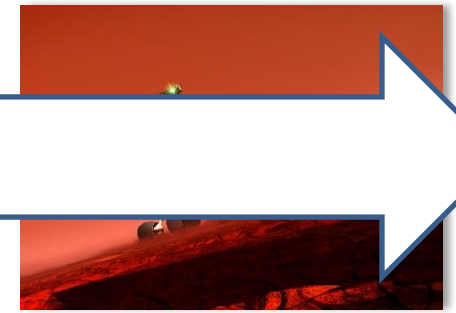


MathWorks®

For high integrity systems, failure is not an option

This talk explores how GNC engineers can design, verify and validate high integrity systems using digital engineering





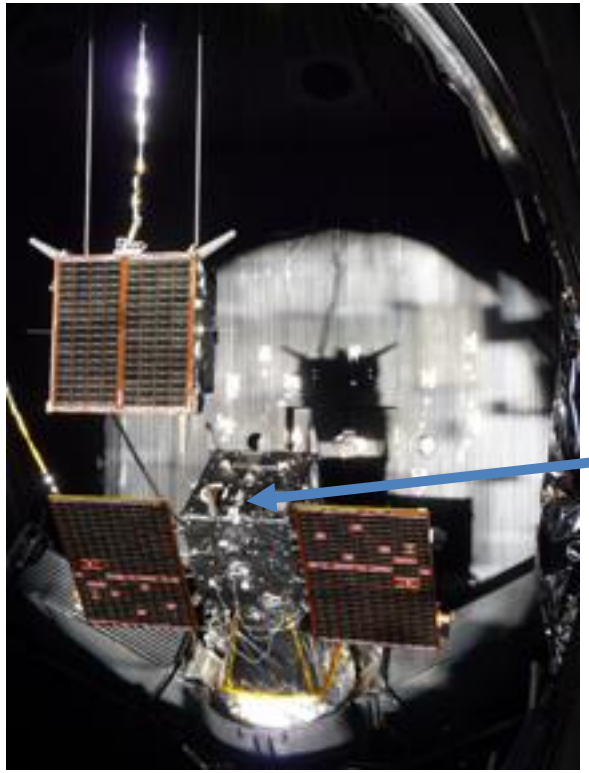
Verification and Validation

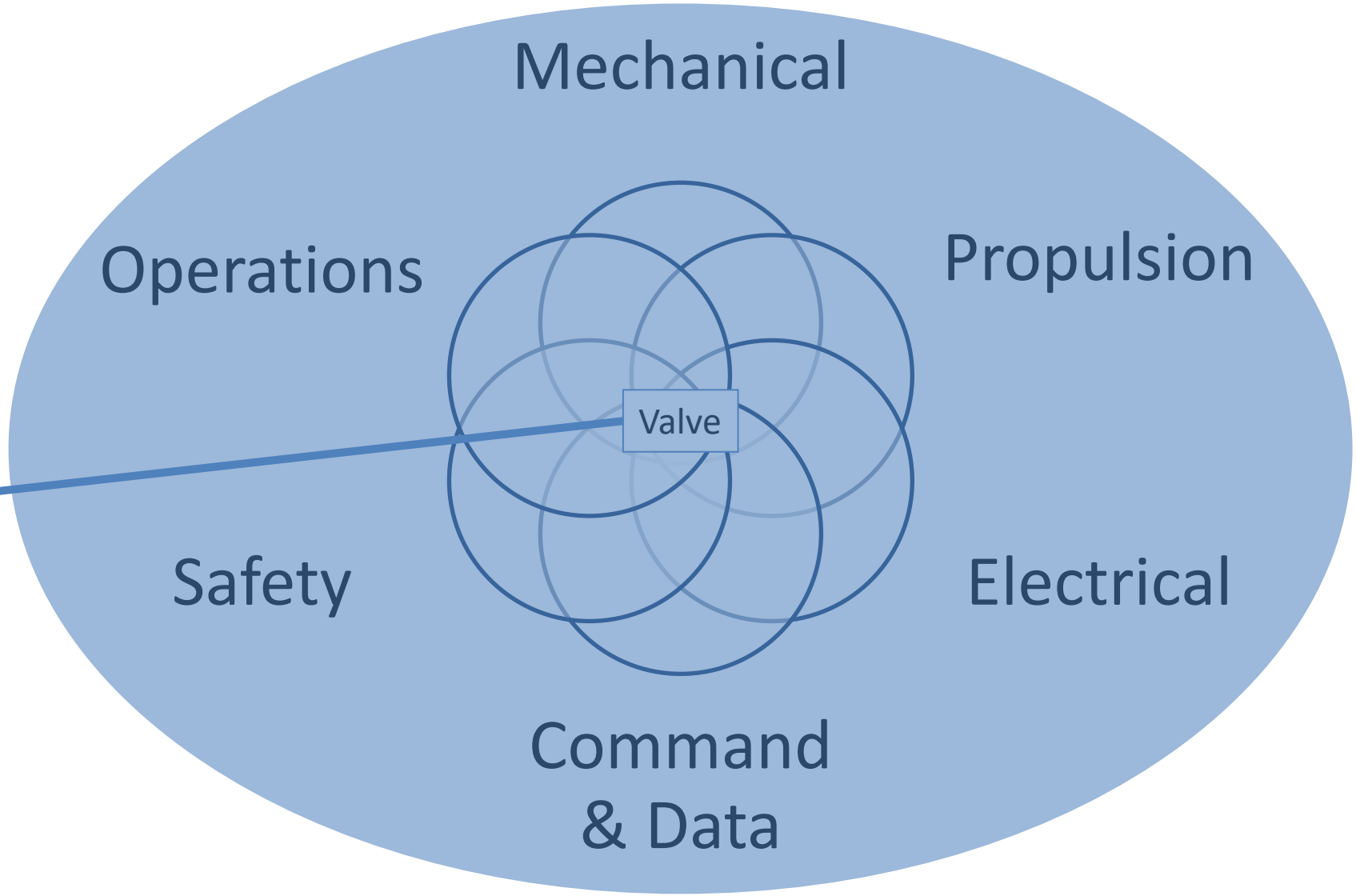
The role of GNC in systems design

The evolution of model-centric design

Dealing with adaptive systems and AI

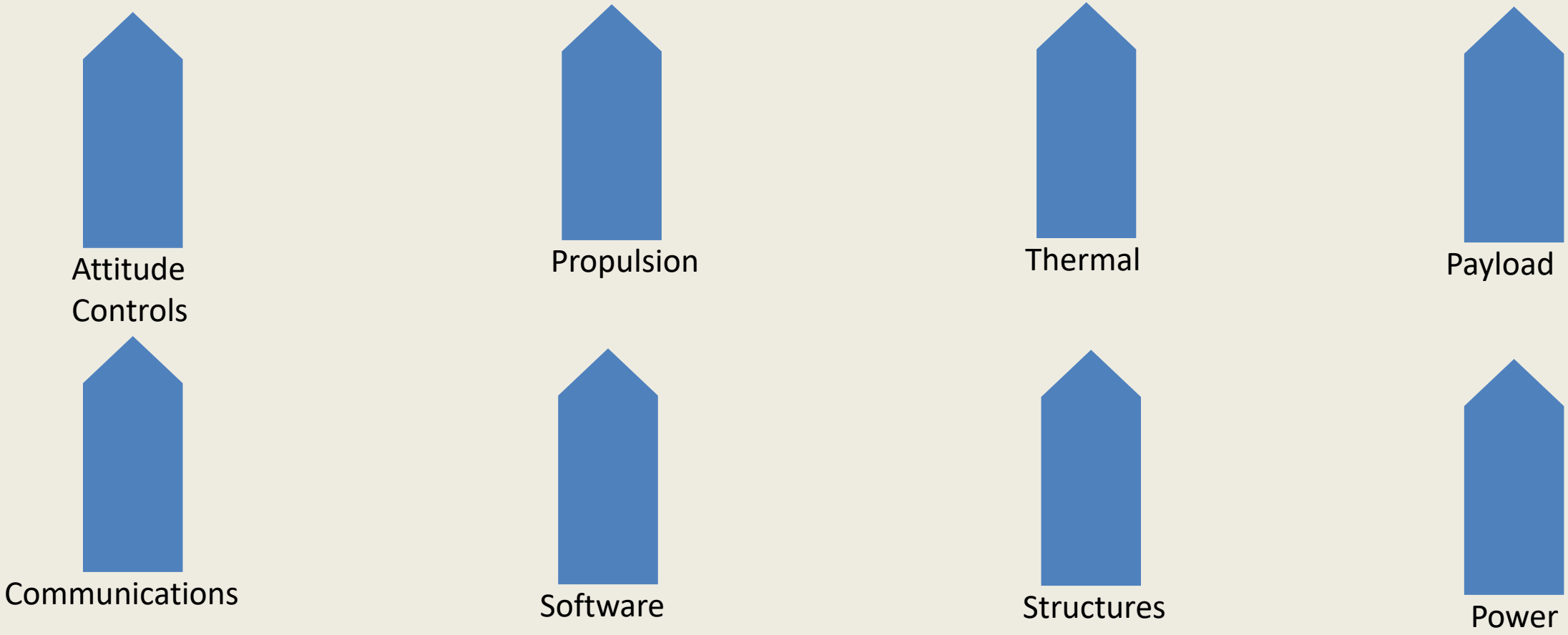
GNC is strongly coupled with many other disciplines



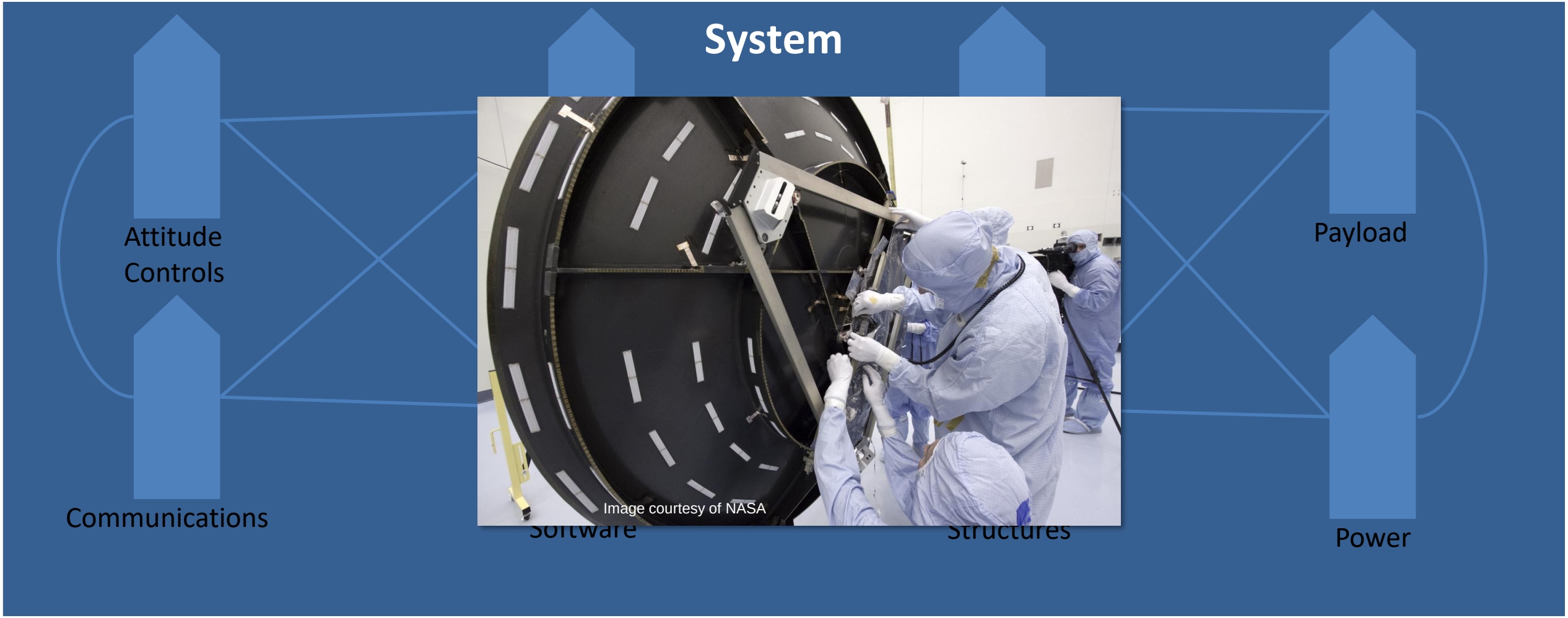


Change Spacecraft Attitude / Orbit

Engineering remains highly “siloed” within domains



Systems level thinking is a critical skill for GNC engineers



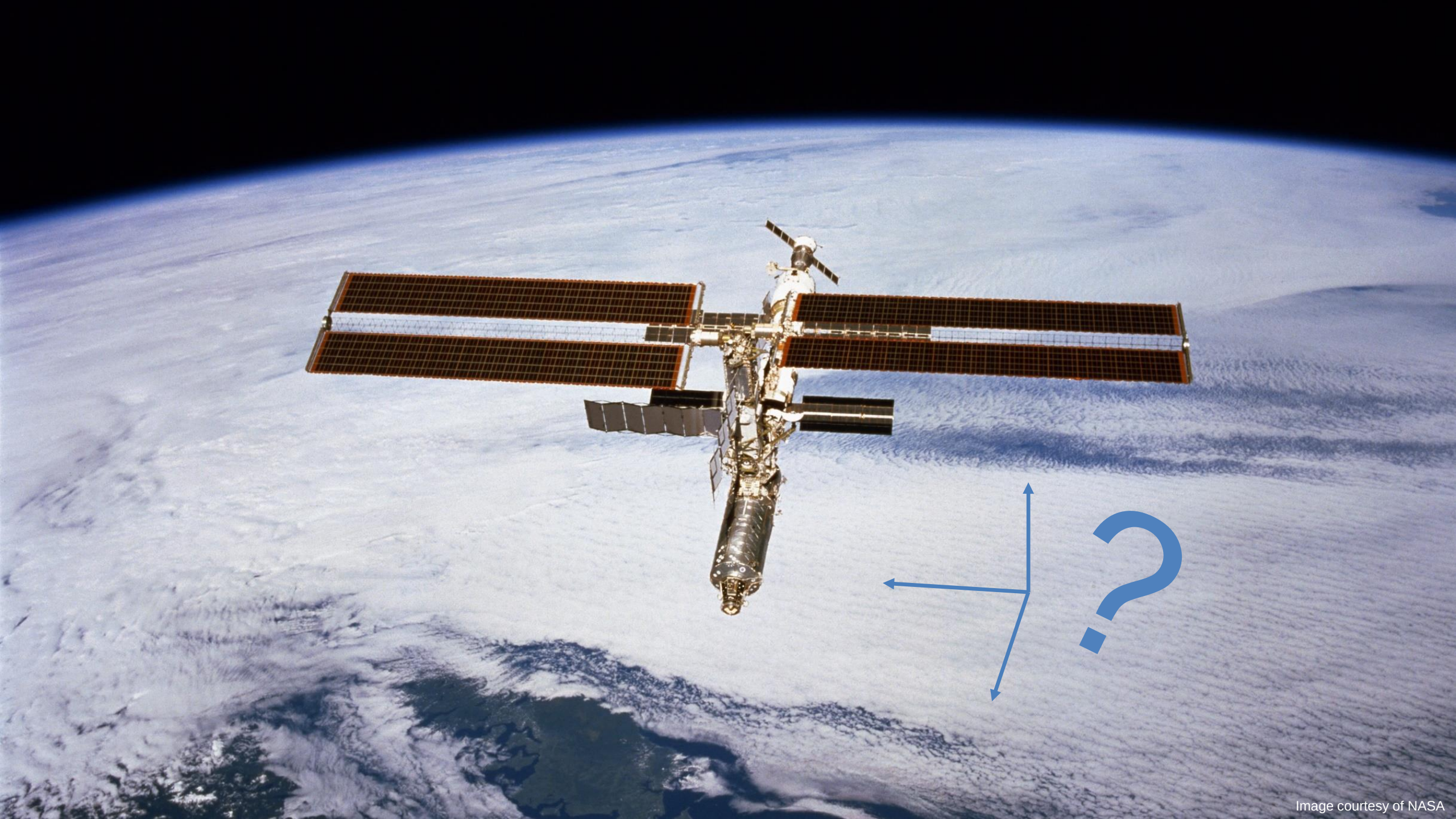


Image courtesy of NASA

Organizational culture impacts the ability to do systems thinking by controlling access to knowledge

Tribal knowledge culture

hides and hoards information

Information sharing culture

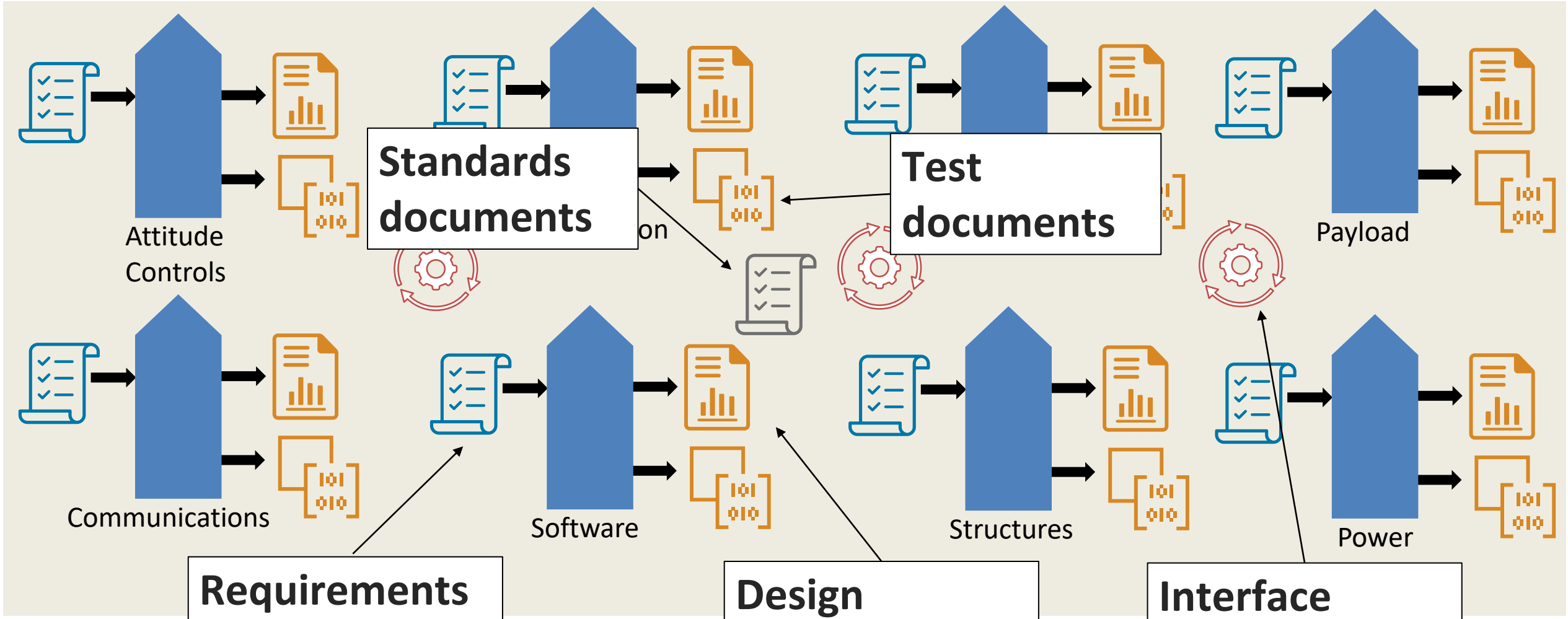
exposes and shares information

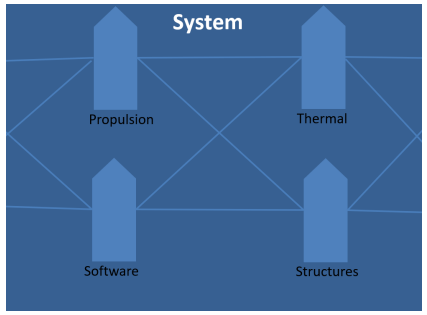
Processes and standards have evolved to avoid repeating past mistakes

Processes and standards have evolved to avoid repeating past mistakes

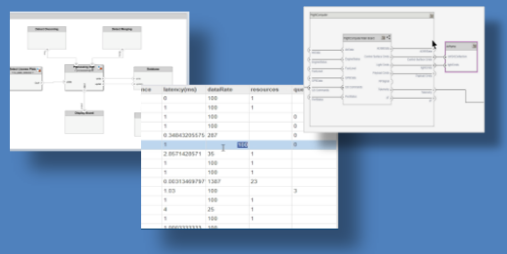
NASA Software Engineering Requirements NPR 7150.2

Our engineering processes have become document-intensive and challenging to manage, which can stifle systems thinking





The role of GNC in systems design



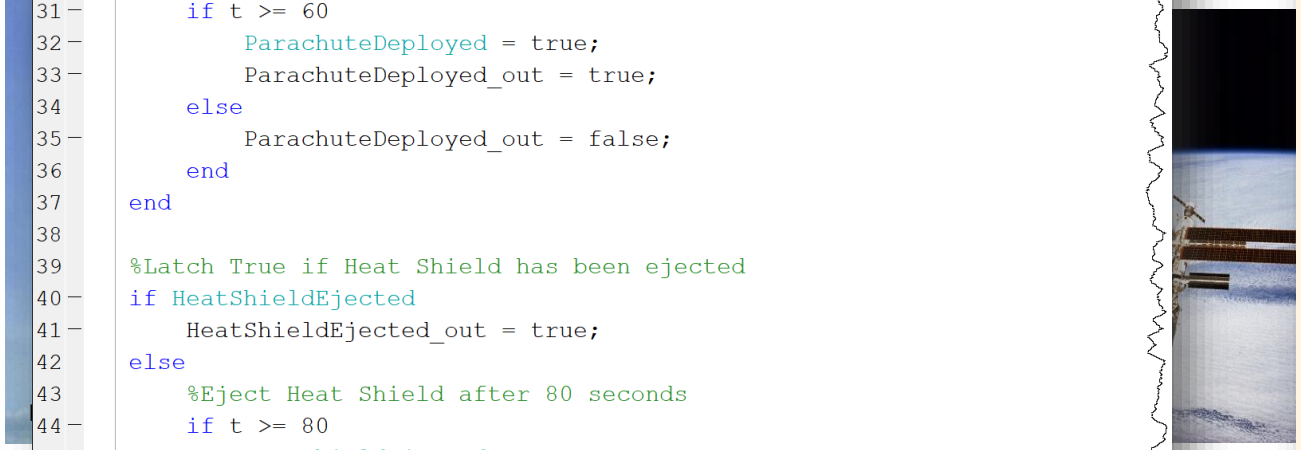
The evolution of model-centric systems design

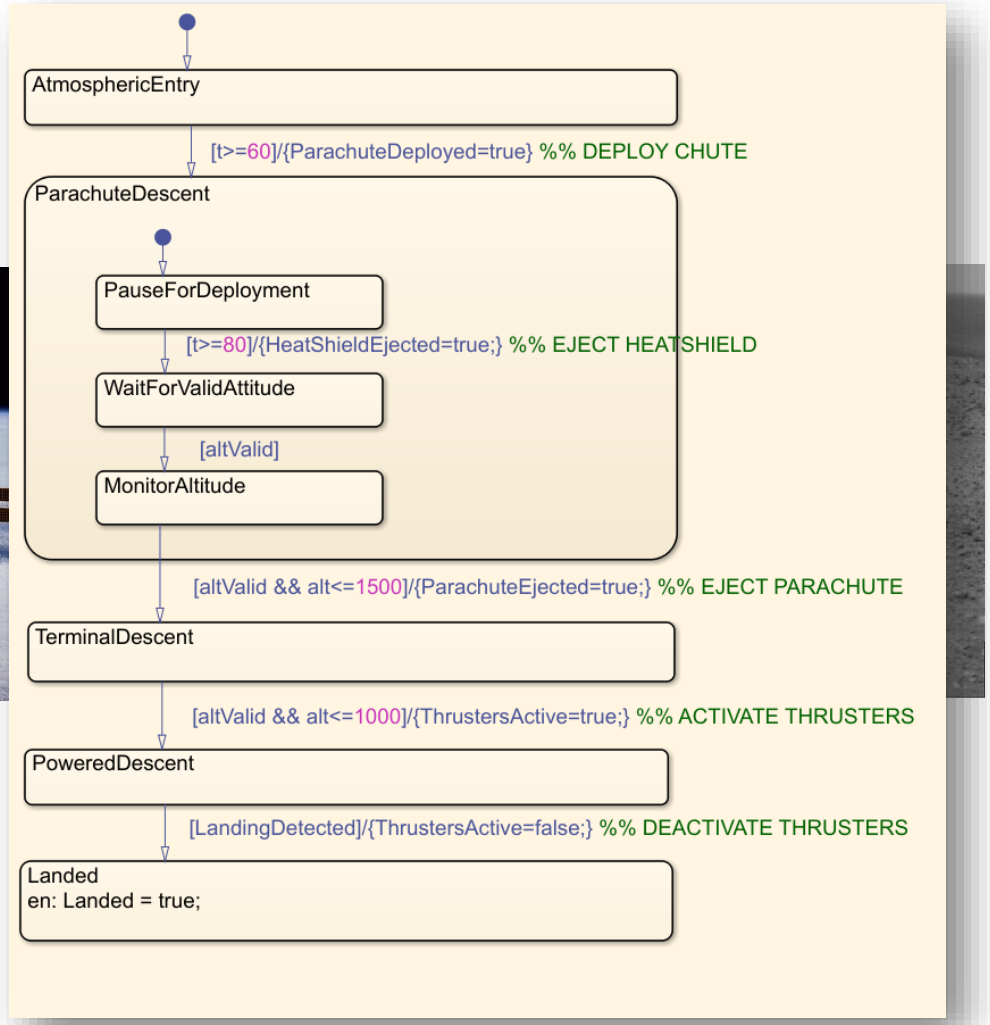
Dealing with adaptive systems and AI

Digital engineering is enabling the industry to evolve from hardware-centric, to software-centric, to model-centric

```
25
26    %Latch True if Parachute has been deployed
27    if ParachuteDeployed
28        ParachuteDeployed_out = true;
29    else
30        %Deploy Parachute after 60 seconds
31        if t >= 60
32            ParachuteDeployed = true;
33            ParachuteDeployed_out = true;
34        else
35            ParachuteDeployed_out = false;
36        end
37    end
38
39    %Latch True if Heat Shield has been ejected
40    if HeatShieldEjected
41        HeatShieldEjected_out = true;
42    else
43        %Eject Heat Shield after 80 seconds
44        if t >= 80
45            HeatShieldEjected = true;
46            HeatShieldEjected_out = true;
47        else
48            HeatShieldEjected_out = false;
49        end
50    end
51
52    %Latch True if Parachute has been ejected
```

Code





Model

Digital engineering is central to the space industry agenda

NASA HLS Requirements Document:

Revision: Initial Release	Document No HLS-RQMT-001
RELEASE DATE: September 27, 2019	Page: 7 of 315
Title: HLS Requirements Document (SRD)	

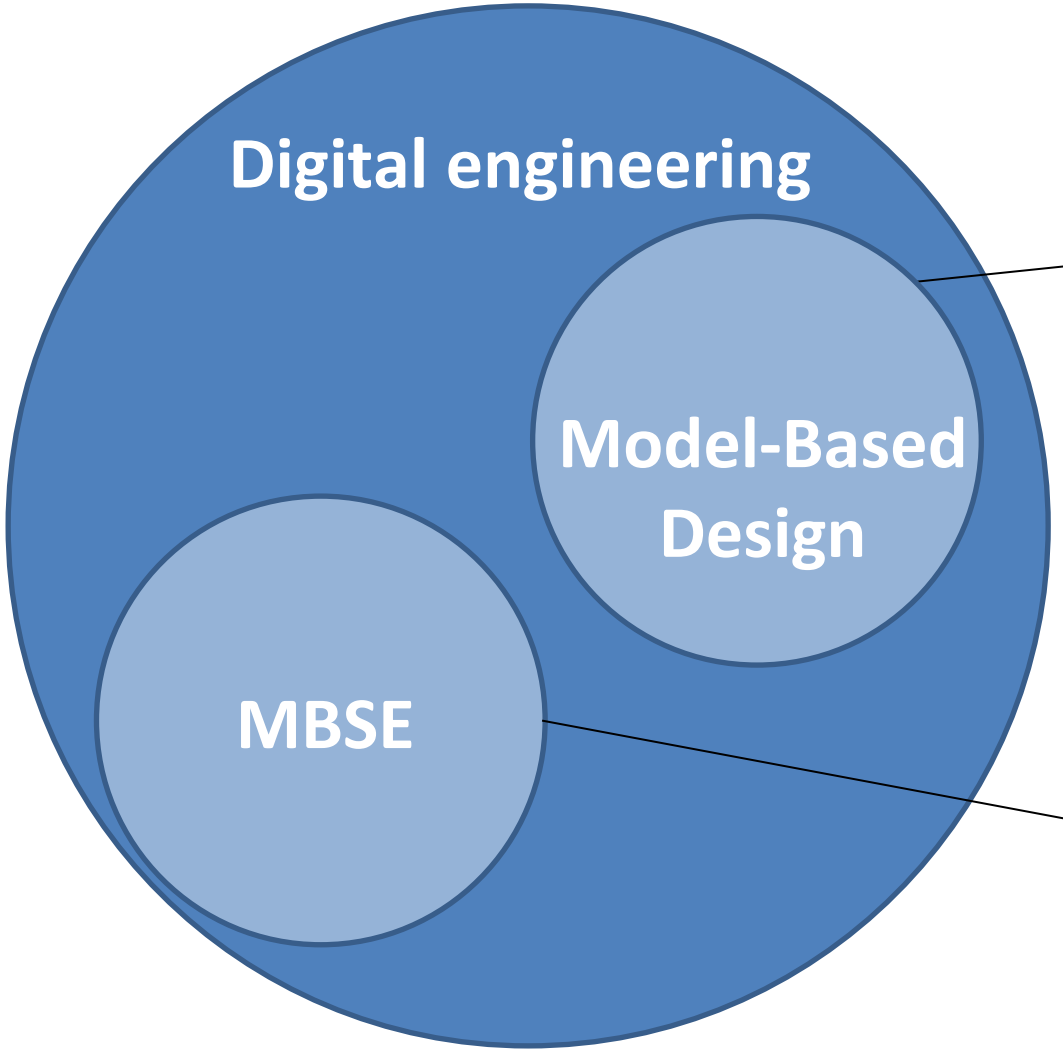
2 Documents

For the purpose of this document, the term 'document' can also refer to 'digital artifacts,' 'models,' or 'viewpoints' as needed to convey and exchange configuration managed data or information. An objective of the HLS Program is to advance towards a digital engineering environment and away from the traditional document-based approach for capturing data, reports and baselines.

ESA Agenda 2025:

"ESA will therefore digitalise its full project management, enabling the development of digital twins, both for engineering by using Model Based System Engineering, and for procurement and finance, achieving full digital continuity with industry."

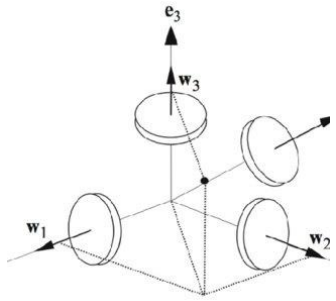
Model Based System Engineering and Model-Based Design are subsets of digital engineering



Subsystem (e.g., GNC) design and implementation

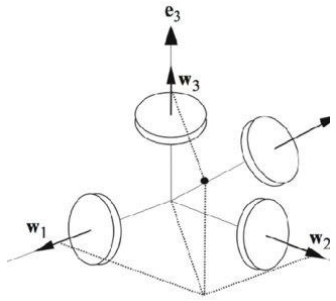
System requirements and architecture

Model-Based Design is well adopted within the GNC community



Model

Many of you are using Model-Based Design for components and subsystems



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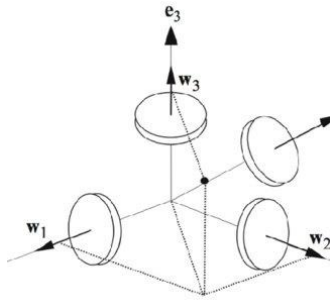
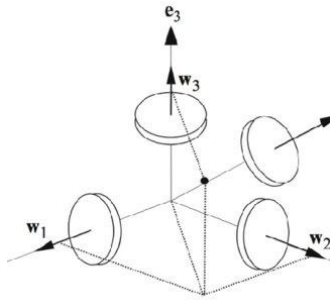


Model

Many of you are using Model-Based Design for rapid prototyping

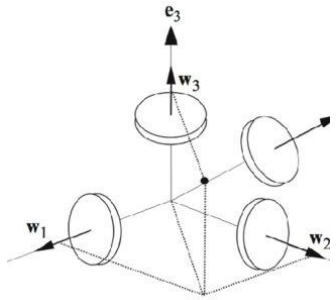


Hardware

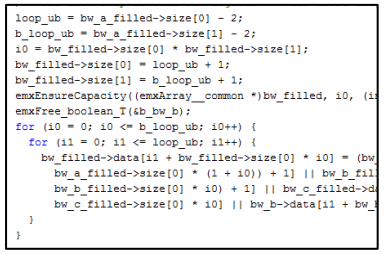
Many of you are using Model-Based Design for code generation

```
loop_ub = bw_a_filled->size[0] - 2;
b_loop_ub = bw_a_filled->size[1] - 2;
i0 = bw_filled->size[0] * bw_filled->size[1];
bw_filled->size[0] = loop_ub + 1;
bw_filled->size[1] = b_loop_ub + 1;
emxEnsureCapacity((emxArray__common *)bw_filled, i0, (i
emxFree_boolean_T(&b_bw_b);
for (i0 = 0; i0 <= b_loop_ub; i0++) {
  for (i1 = 0; i1 <= loop_ub; i1++) {
    bw_filled->data[i1 + bw_filled->size[0] * i0] = (bw_
      bw_a_filled->size[0] * (1 + i0)) + 1] || bw_b_fil
      bw_b_filled->size[0] * i0) + 1] || bw_c_filled->d
      bw_c_filled->size[0] * i0] || bw_b->data[i1 + bw_
  }
}
```

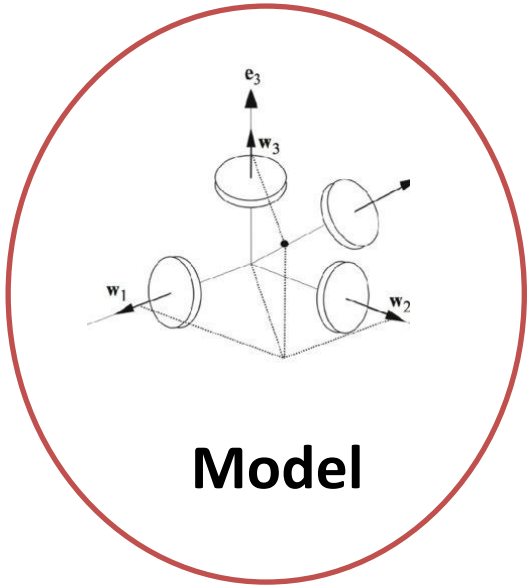
Software



Many of you are using Model-Based Design for components and subsystems



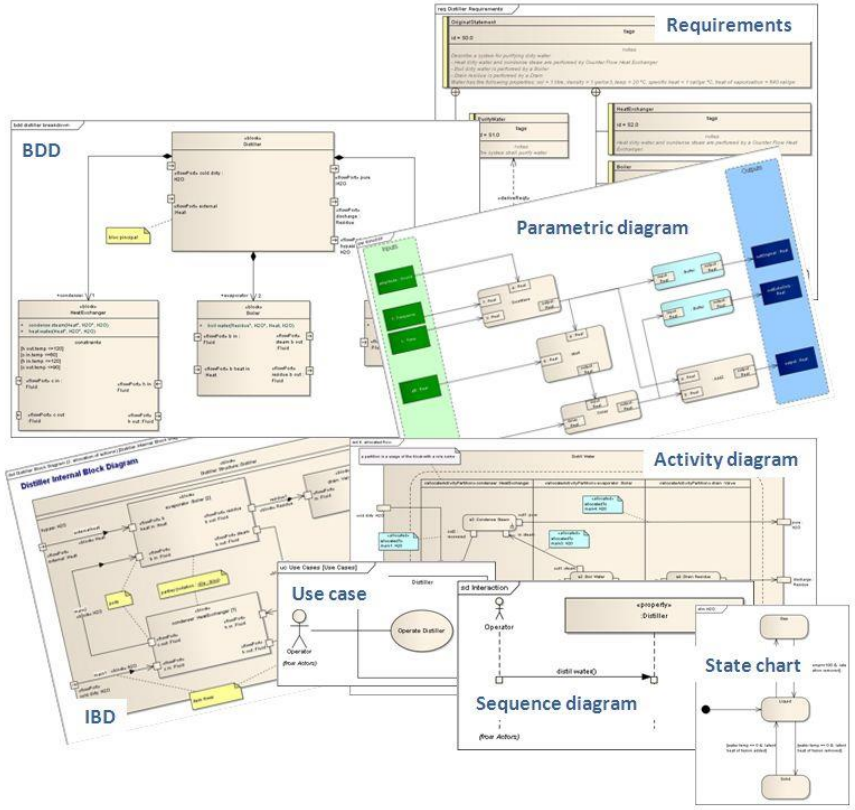
Software



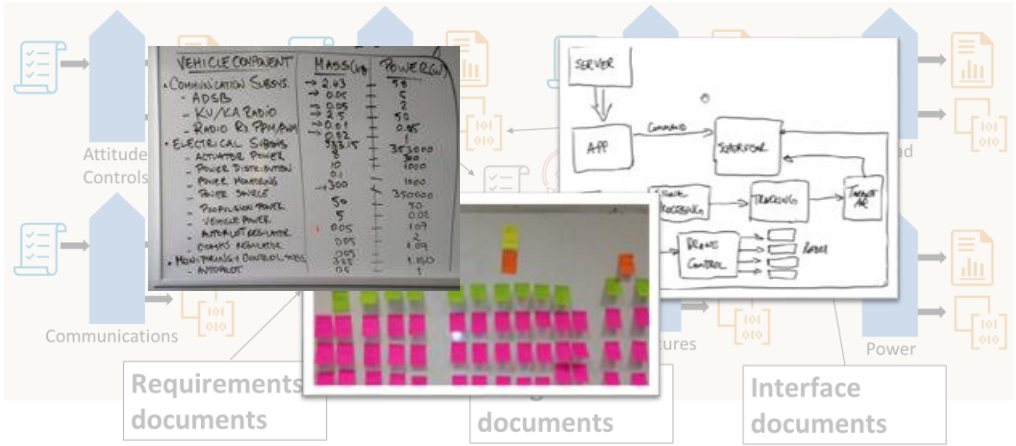
Model

Hardware

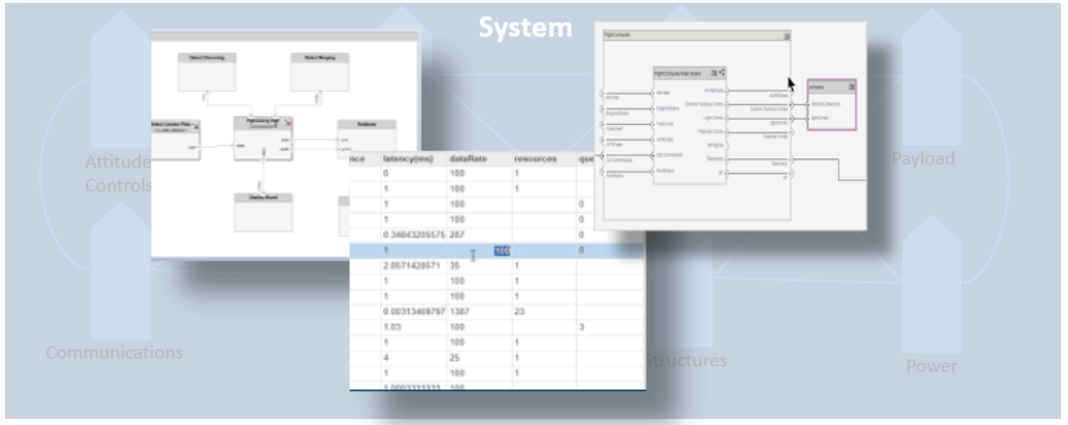
Model-Based System Engineering is also pervasive in the space industry



The goal of MBSE is to address disconnects in document-based systems engineering

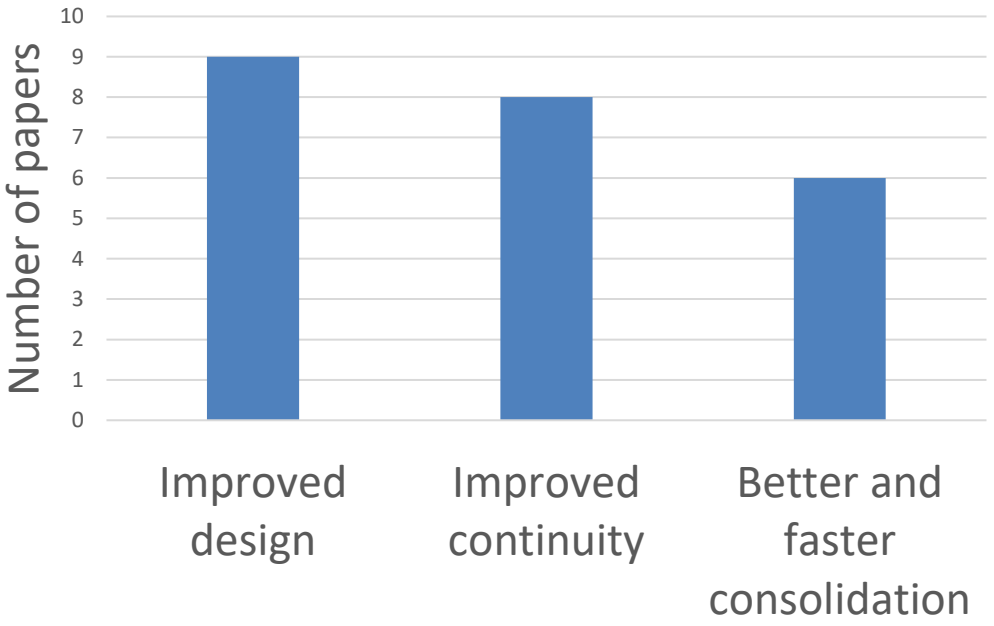


Paper documents are primary artifact

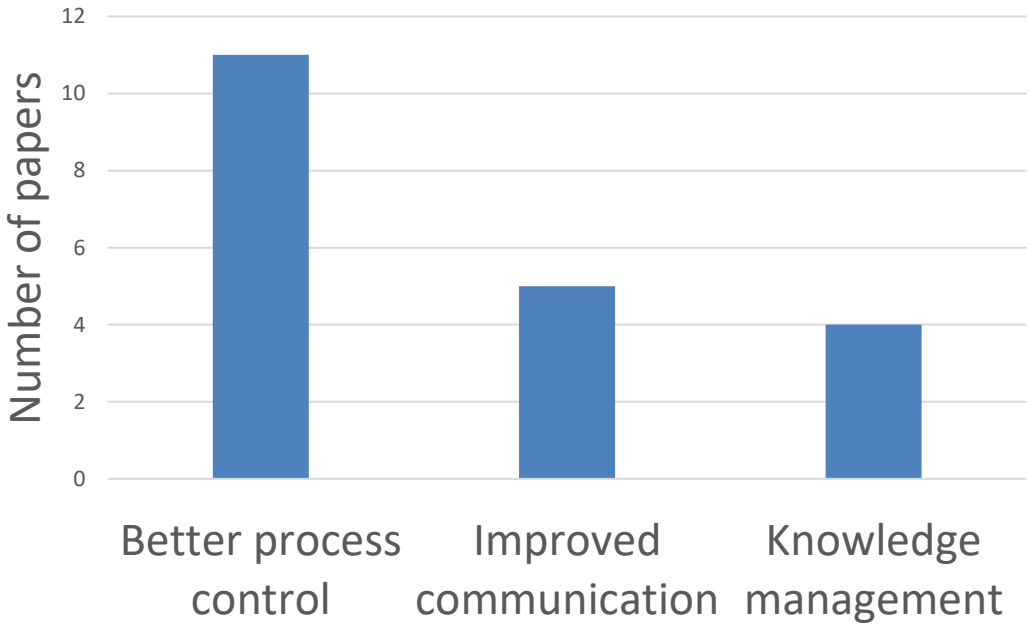


Digital model is primary artifact

MBSE can provide an improvement vs document-based systems engineering



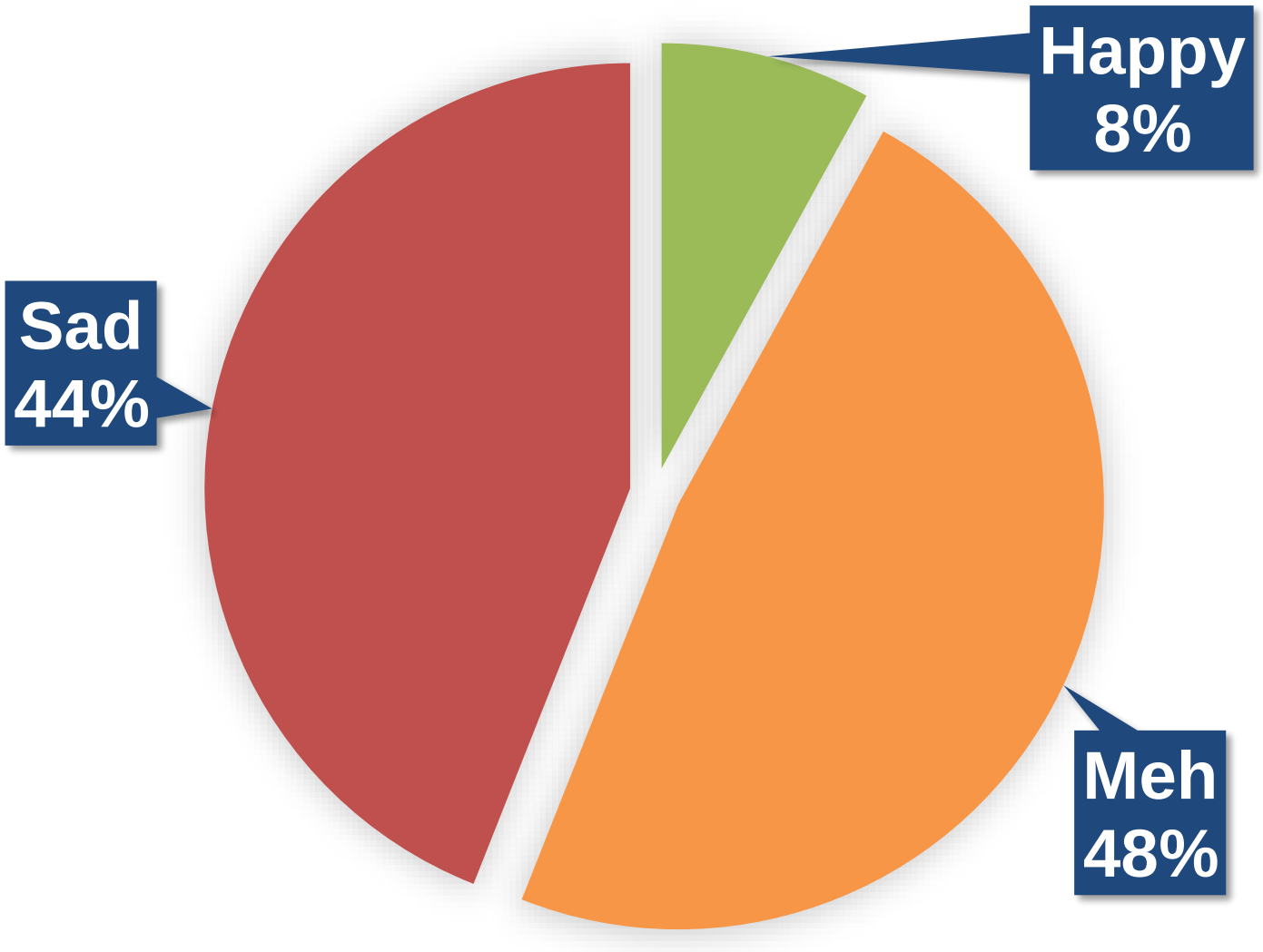
Technical benefits



Organizational benefits

Source: ESA MBSE 2020 Workshop, Wrap-Up / Conclusions by Mr. Jean-Loup Terrailon (ESA)

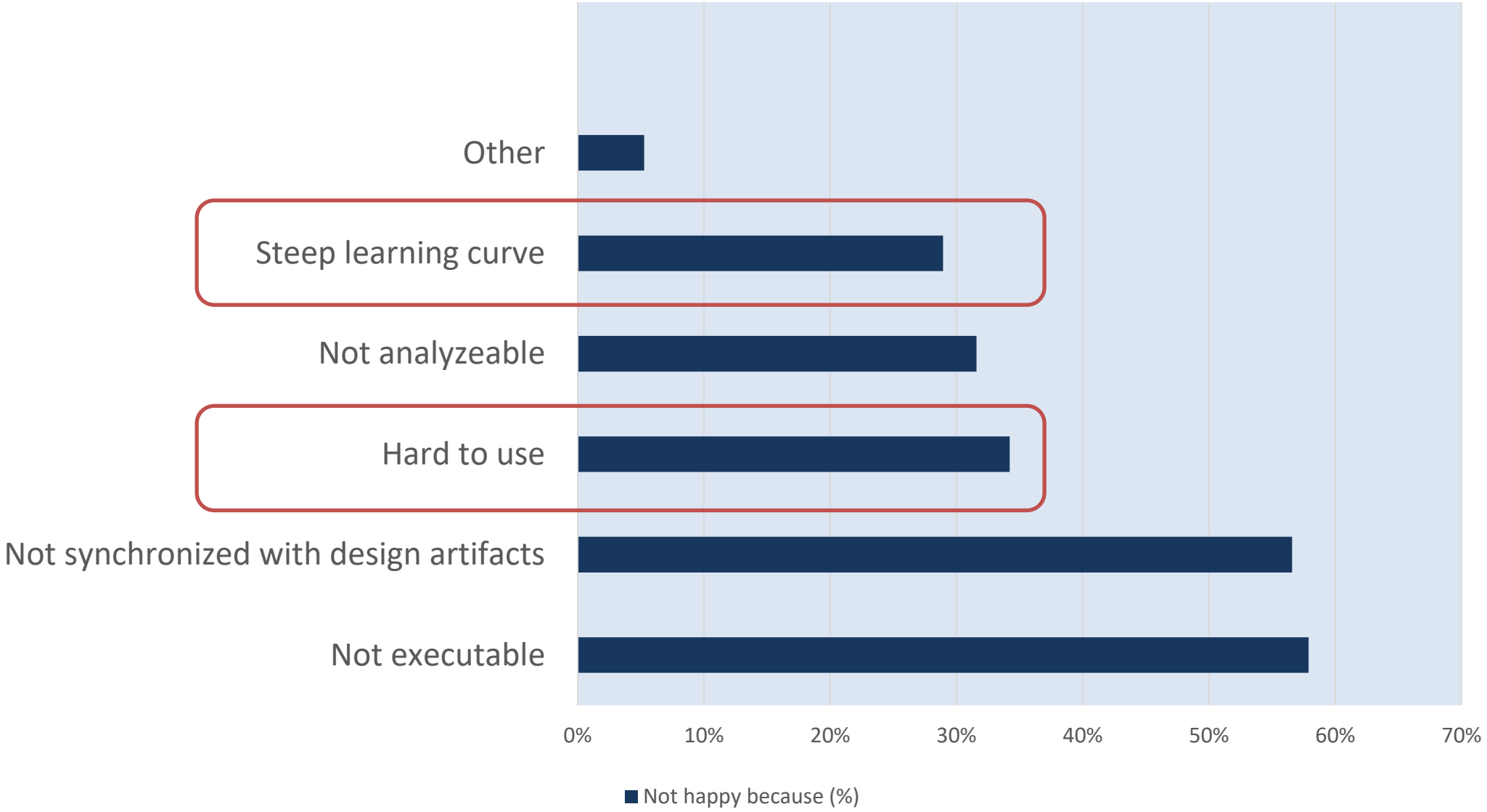
MBSE as practiced so far is not perfect



Are you happy with your current tool choices for Modeling System Architecture?
2018 MathWorks Survey

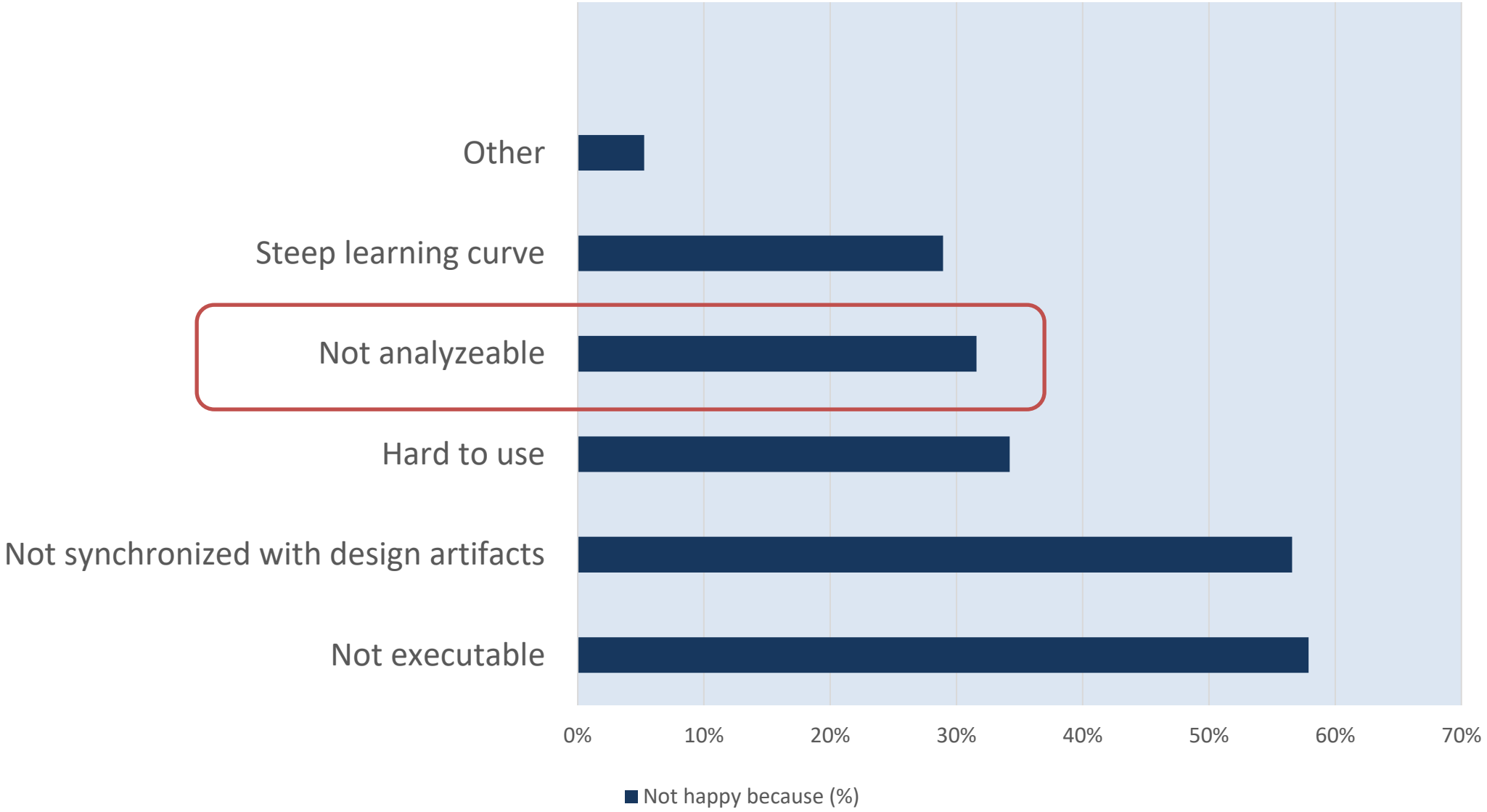
Source: 2018 MathWorks Advisory Board Survey

Many modeling tools are complex to use on a day to day basis



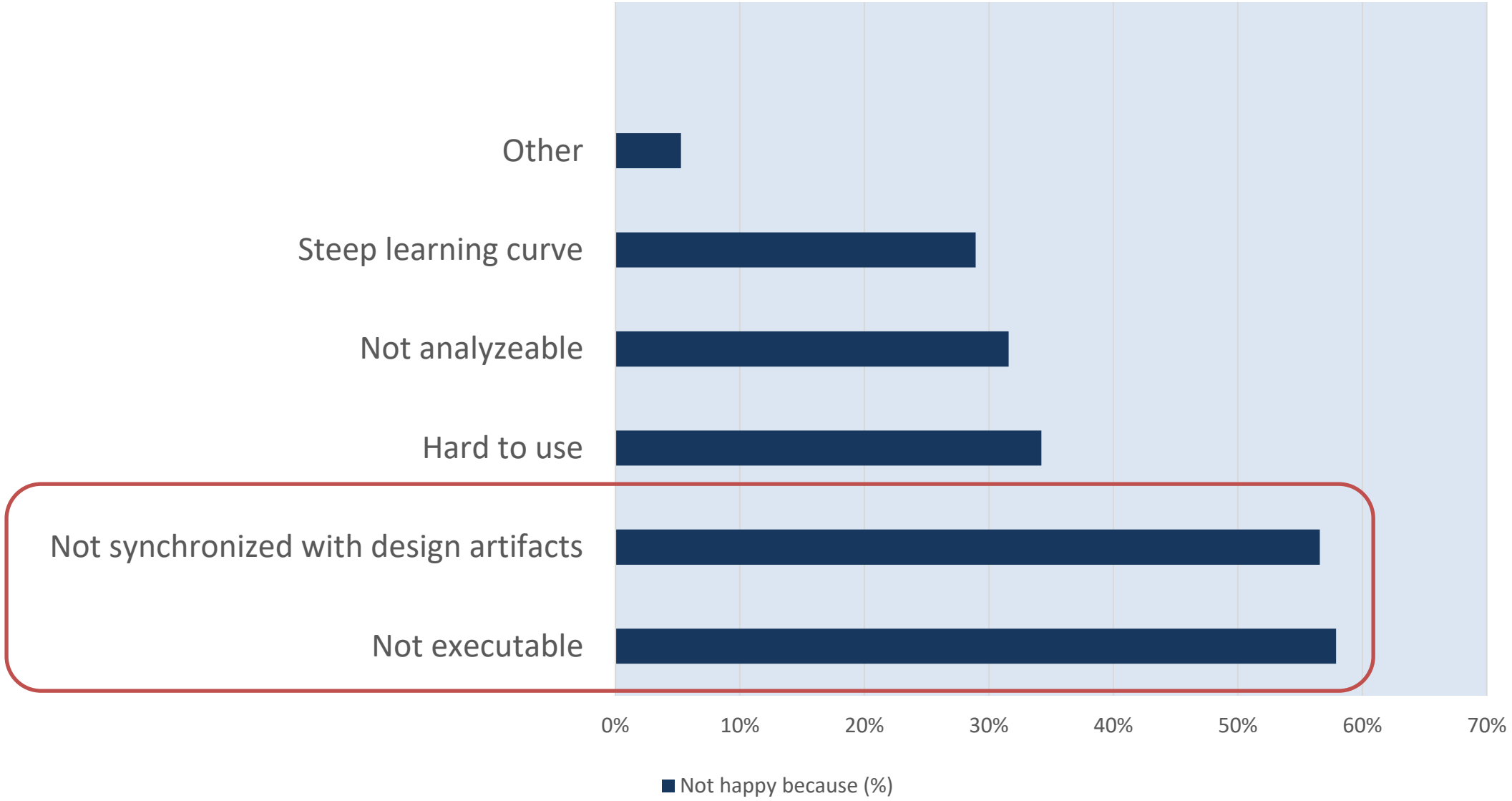
Source: 2018 MathWorks survey

Modeling languages do not always present data in a form that engineers can use for engineering analysis



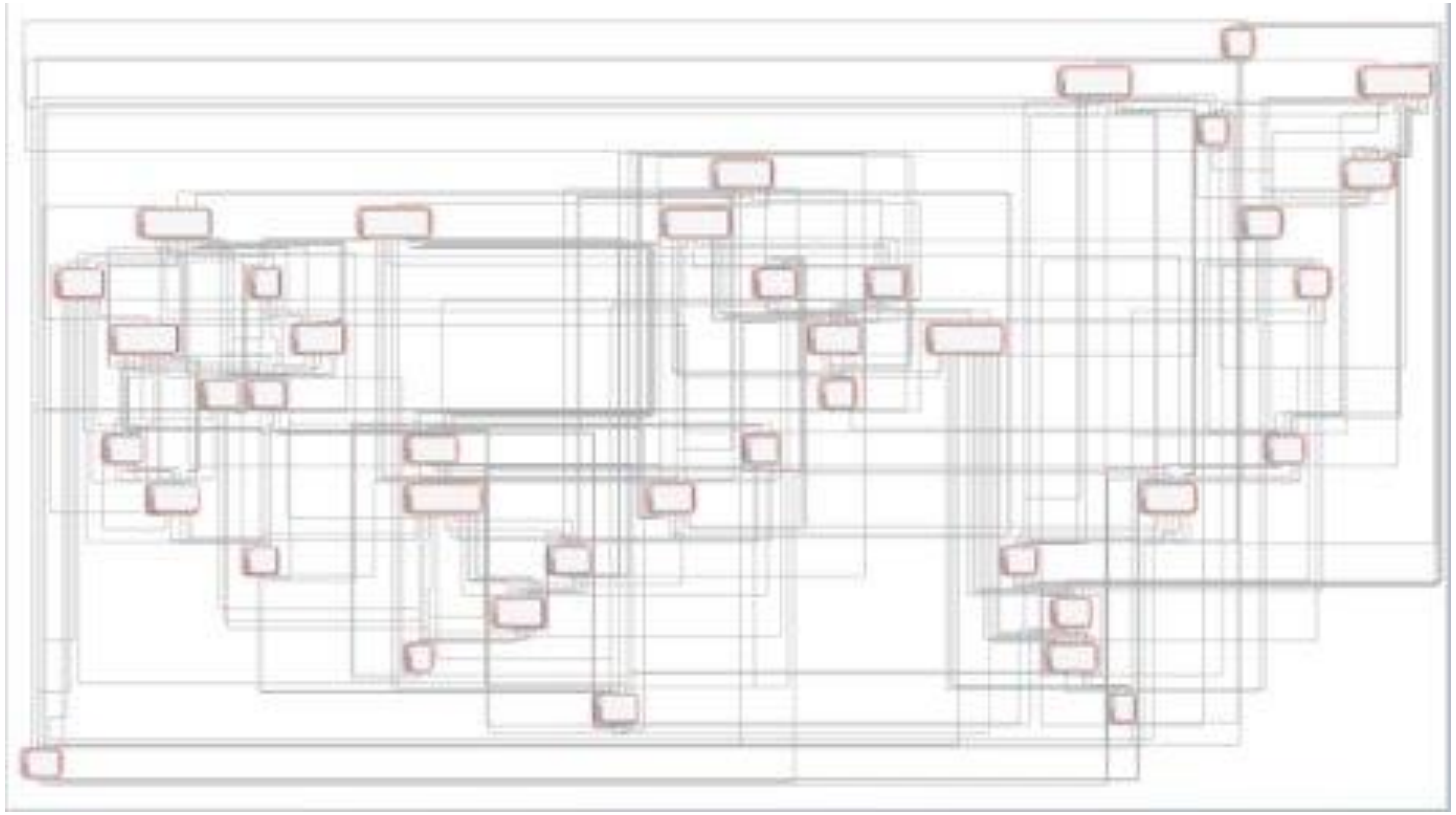
Source: 2018 MathWorks survey

Integration between descriptive models and simulation models is challenging

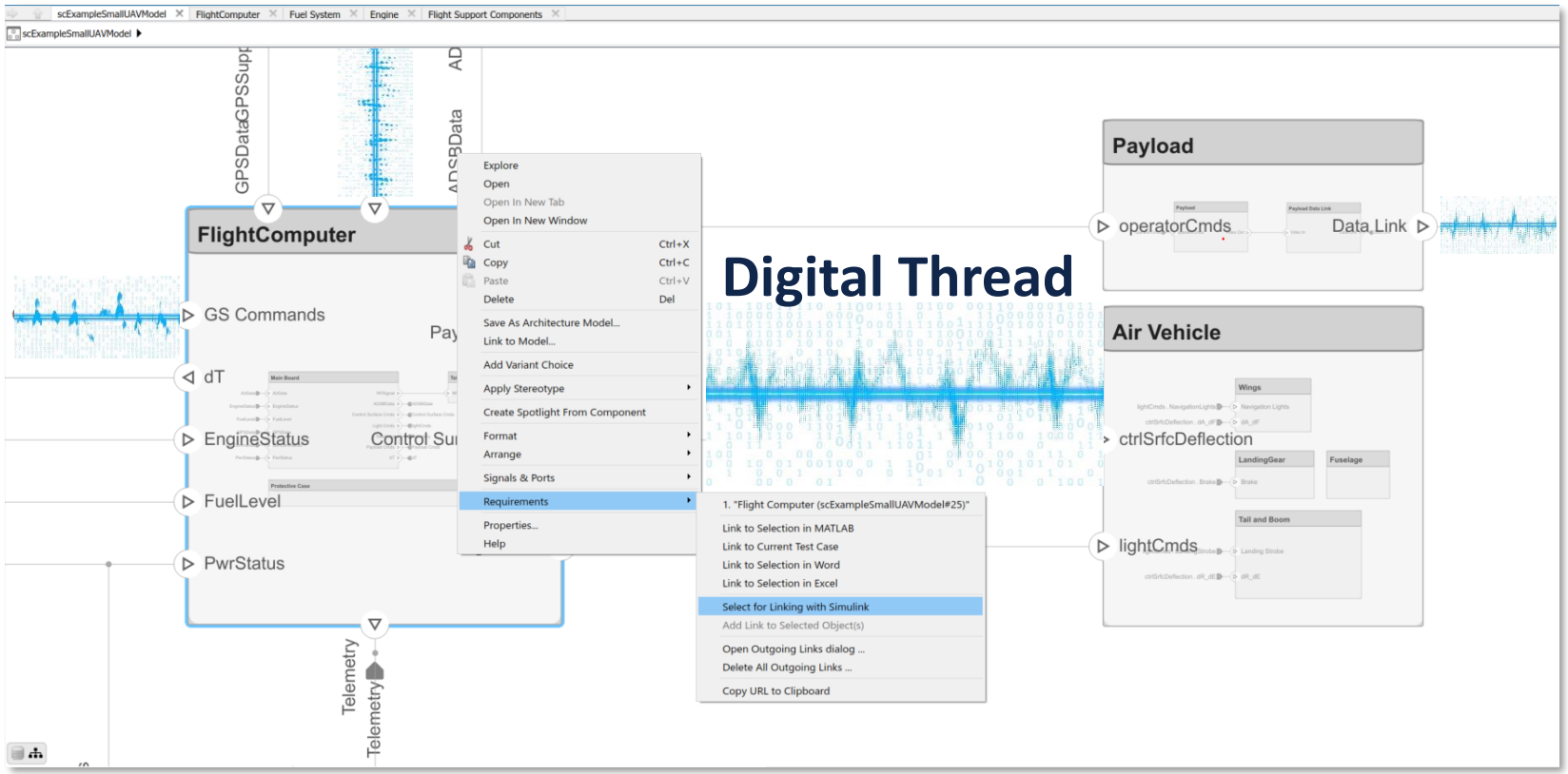


Source: 2018 MathWorks survey

MBSE can benefit your systems engineering organization, but there is more to a complete digital engineering solution



One definition of digital engineering is the connected use of models to digitally represent a system in the virtual world

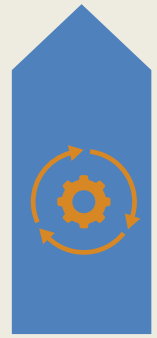


This vision of digital engineering is larger than what we have done before


Attitude Controls


Propulsion

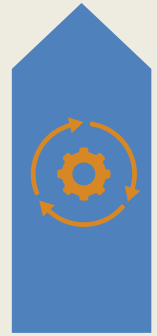

Thermal


Payload

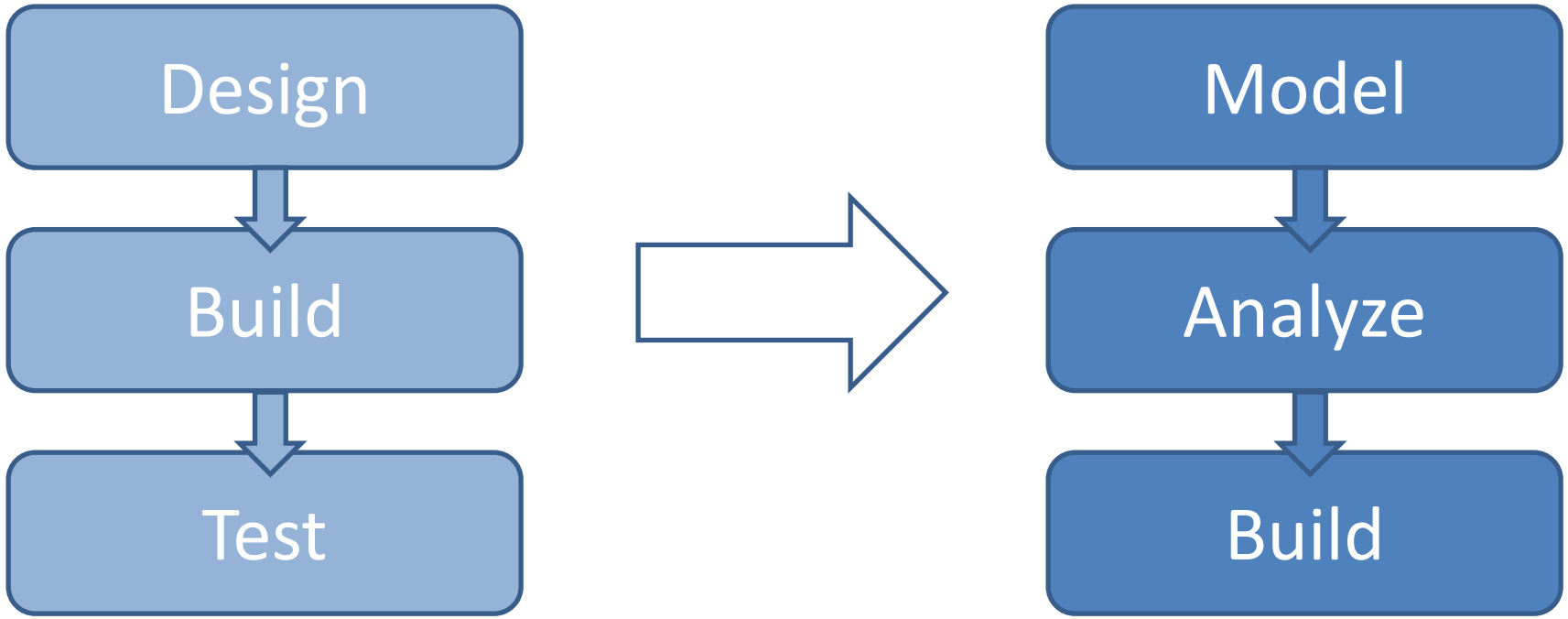

Communications


Software


Structures

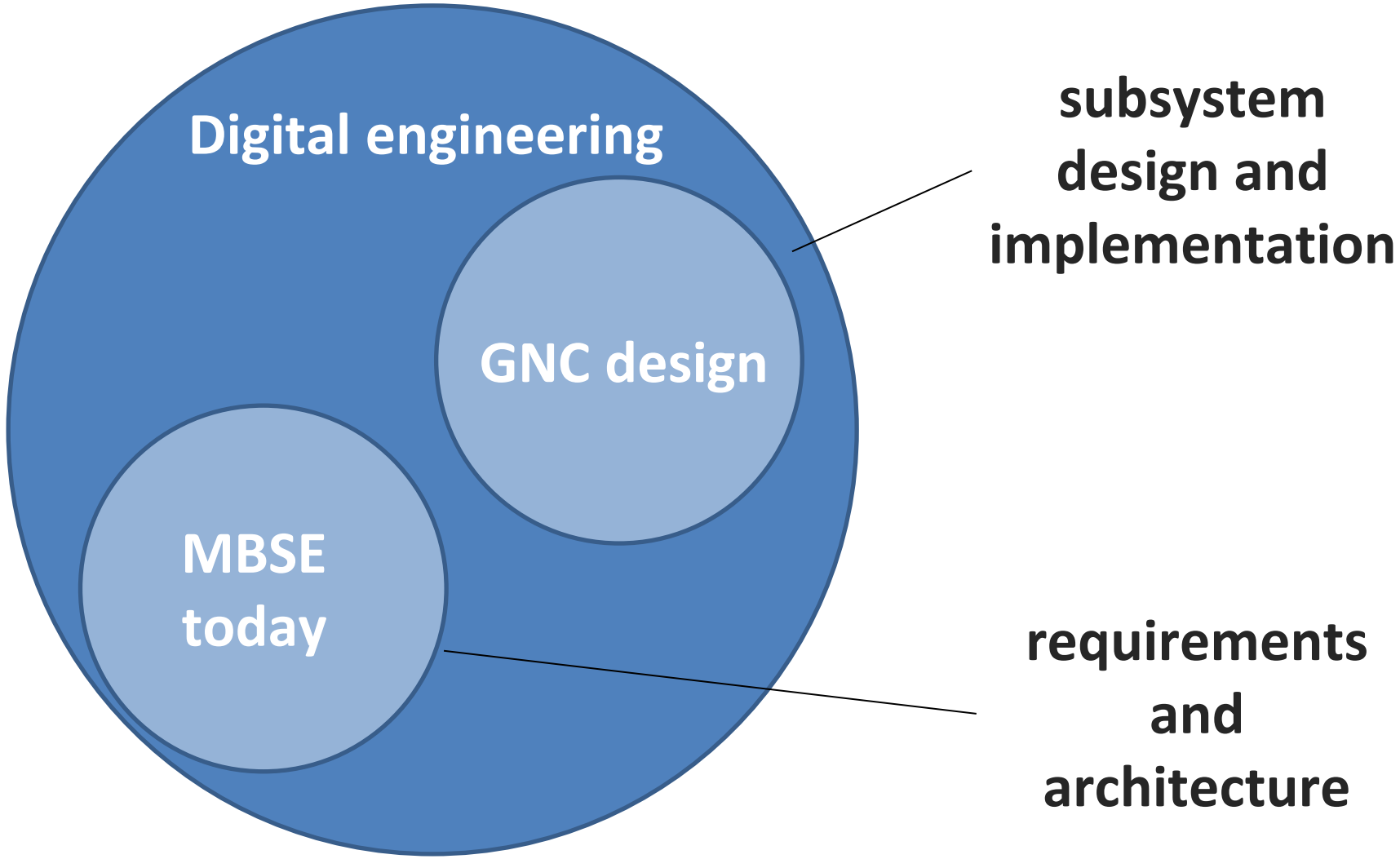

Power

Digital engineering may fundamentally change the way we design, build and verify systems

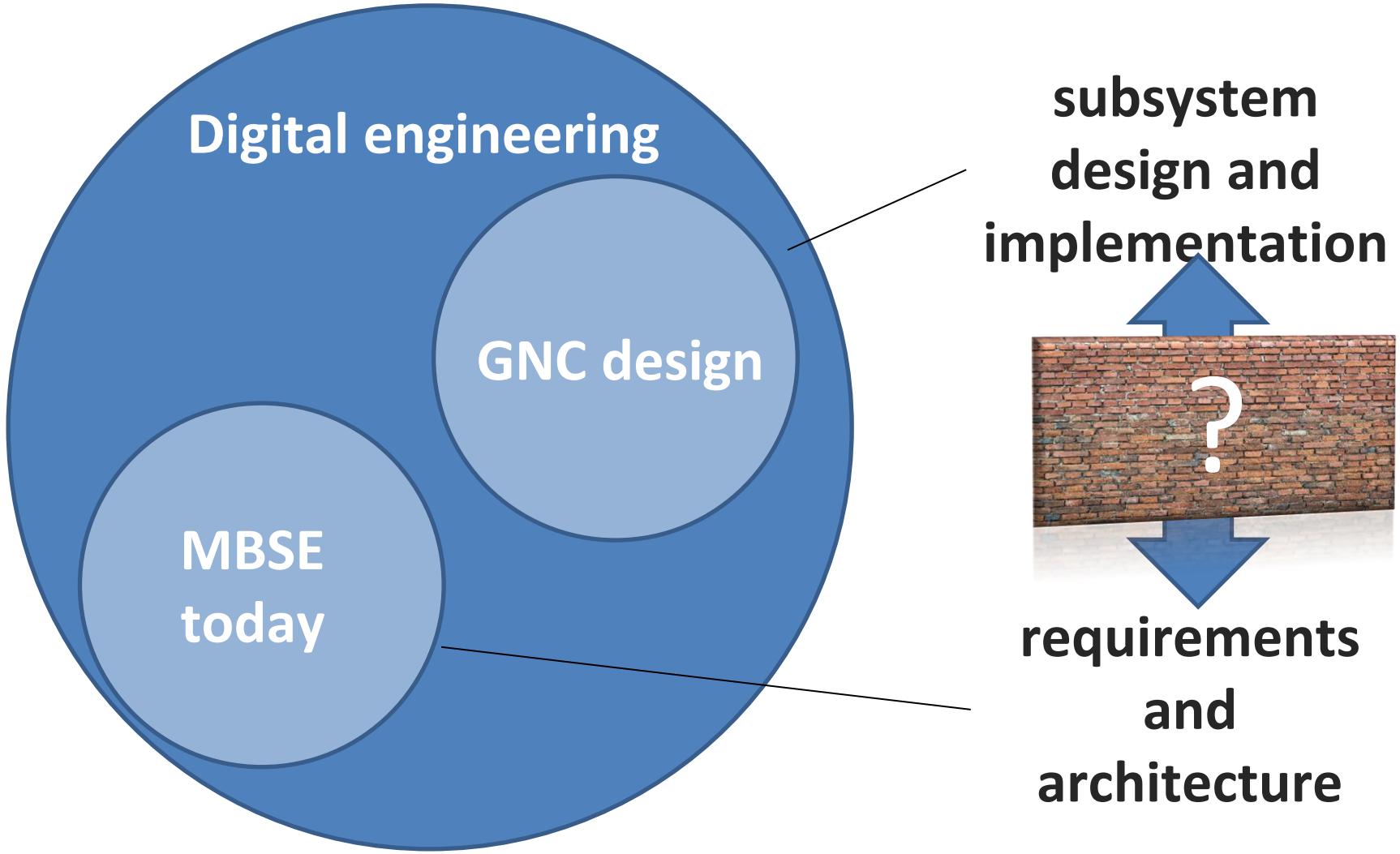


~50% of cost

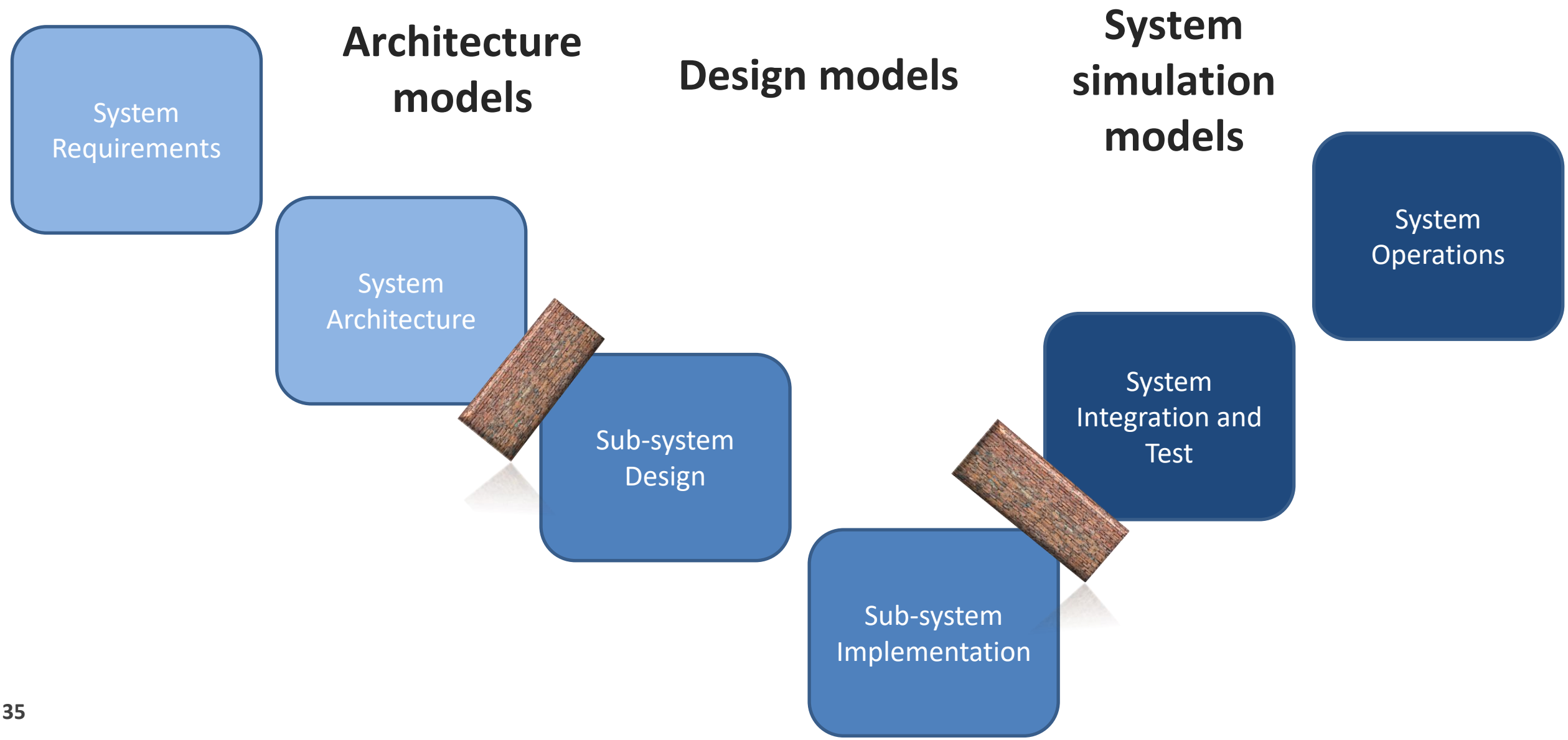
Most digital engineering efforts today have a gap between systems engineering and algorithm design & implementation



This gap impedes verification and validation, which requires traceability between requirements and design



Full model-based engineering needs a digital thread connecting *all* the models



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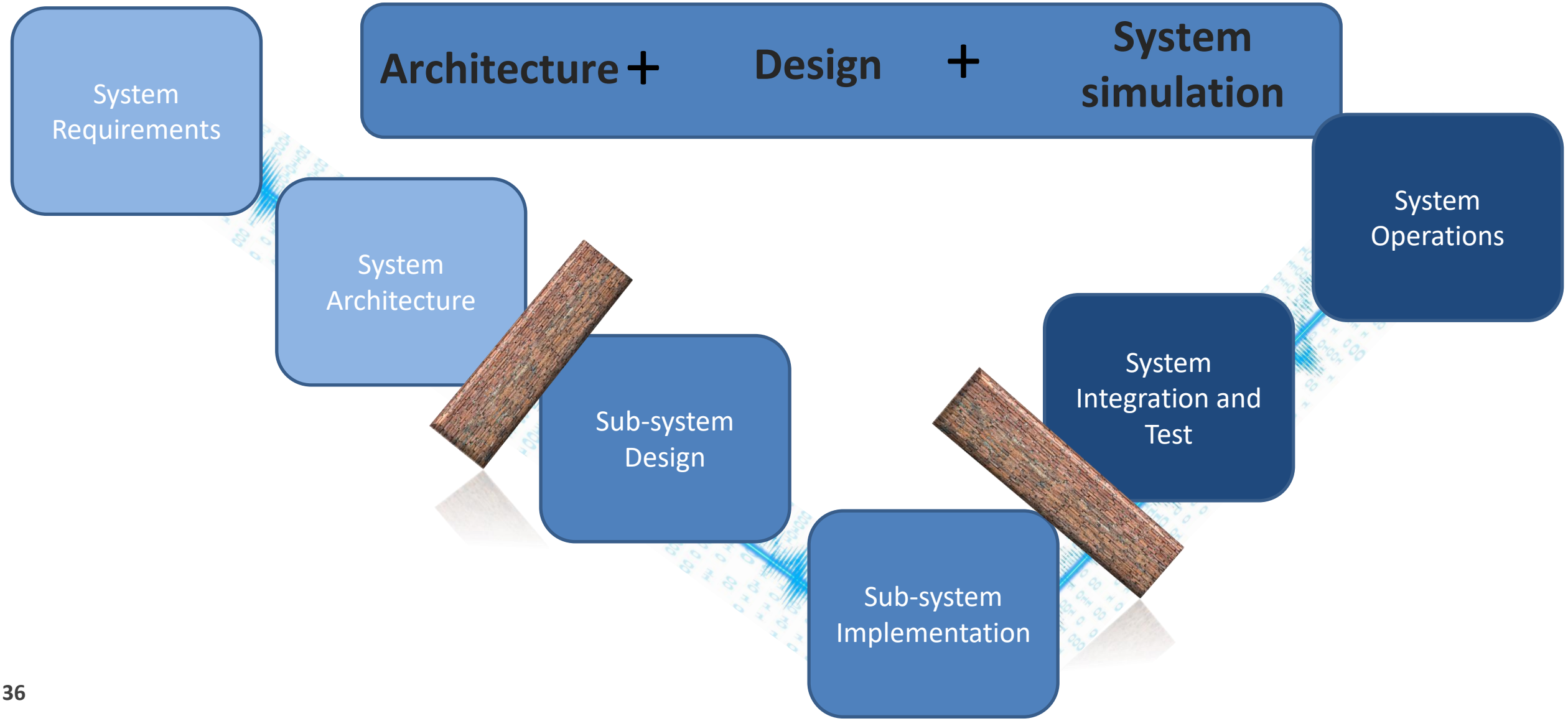

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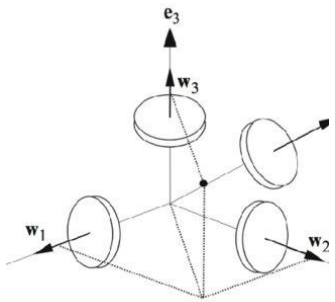

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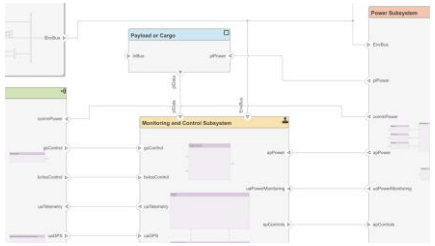

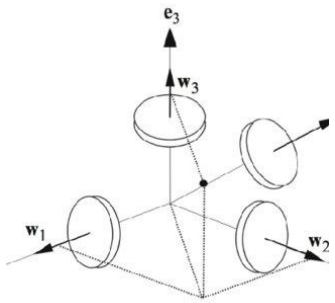

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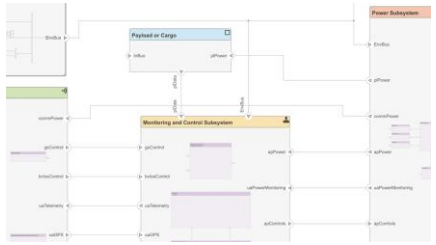
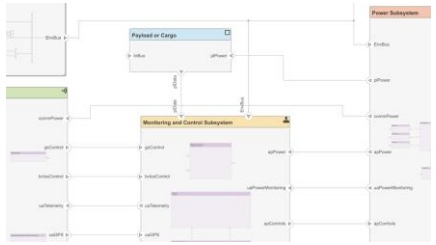


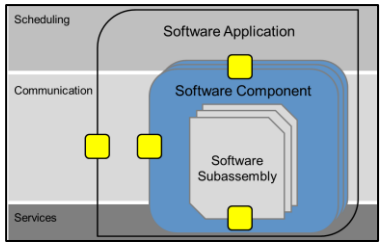
Architecture model

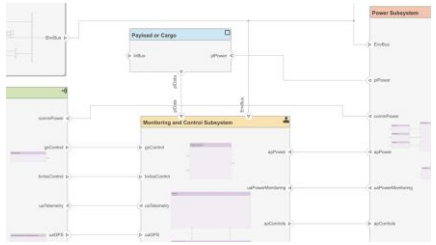
Full model-based engineering needs a digital thread connecting *all* the models



HIL

Full model-based engineering needs a digital thread connecting *all* the models

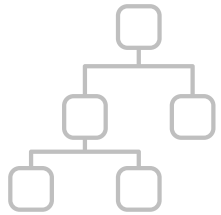


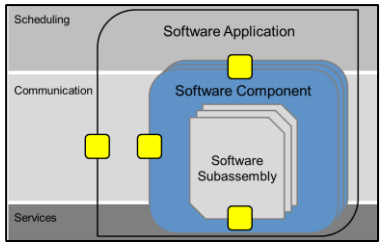


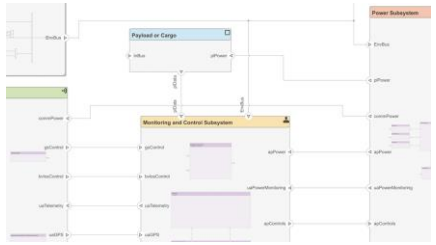
Full software application

Full model-based engineering needs a digital thread connecting *all* the models

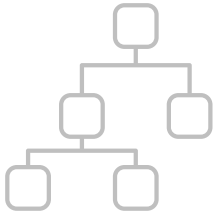
Software Architecture

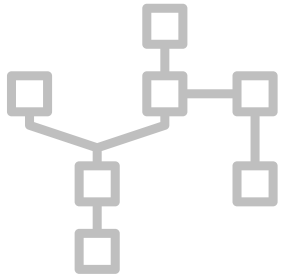




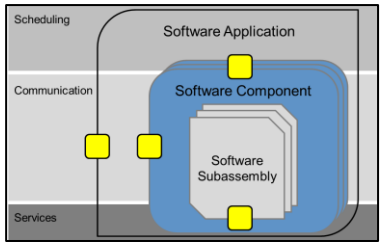


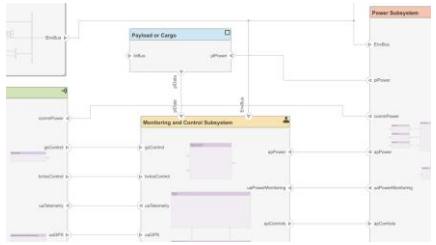
Full model-based engineering needs a digital thread connecting *all* the models



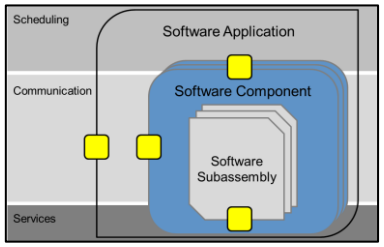


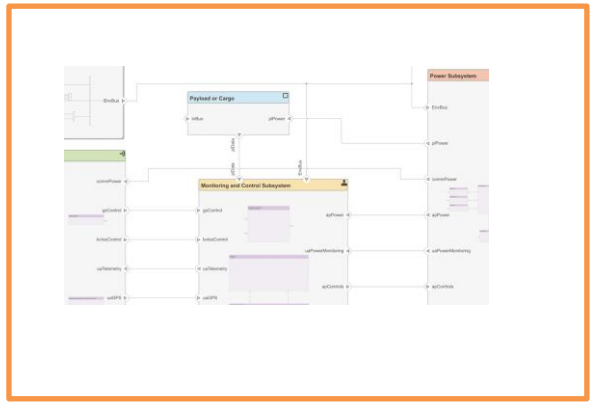
System Architecture

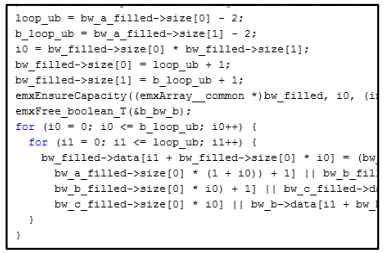


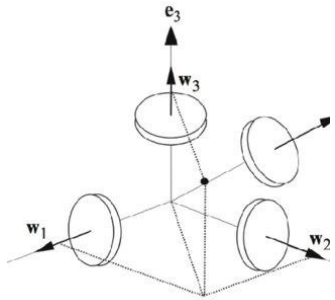


Full model-based engineering needs a digital thread connecting *all* the models



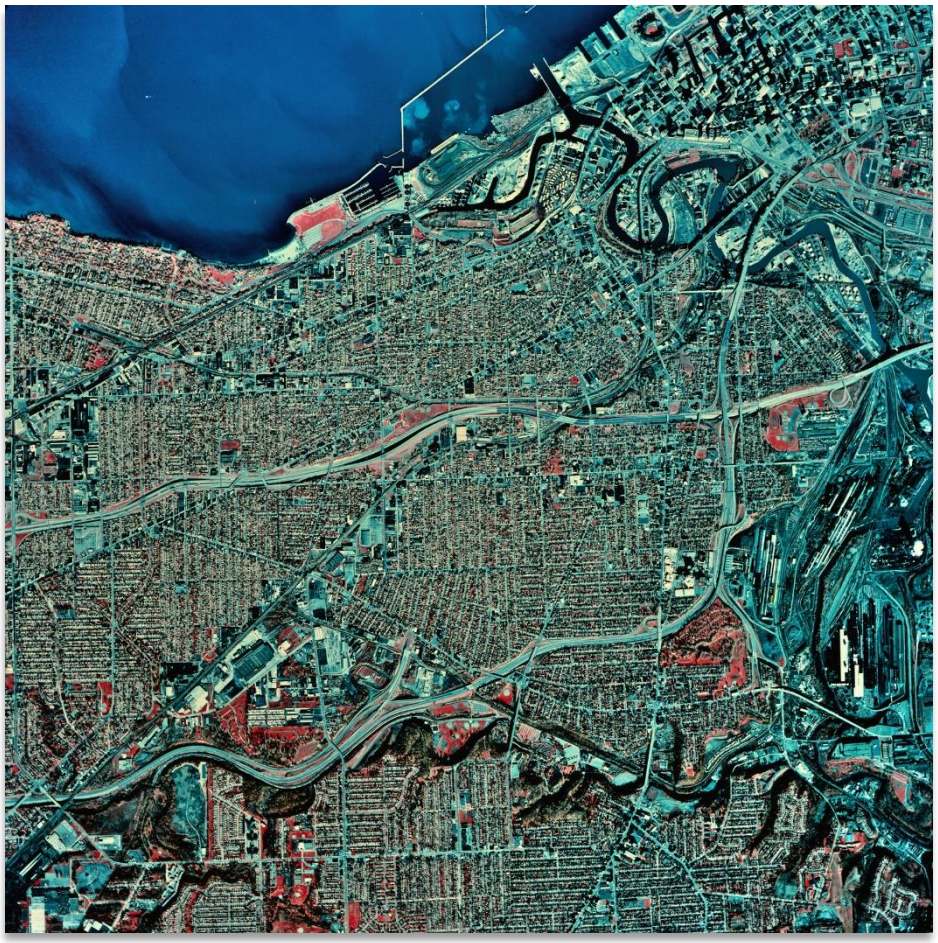






Full model-based engineering needs a digital thread connecting *all* the models

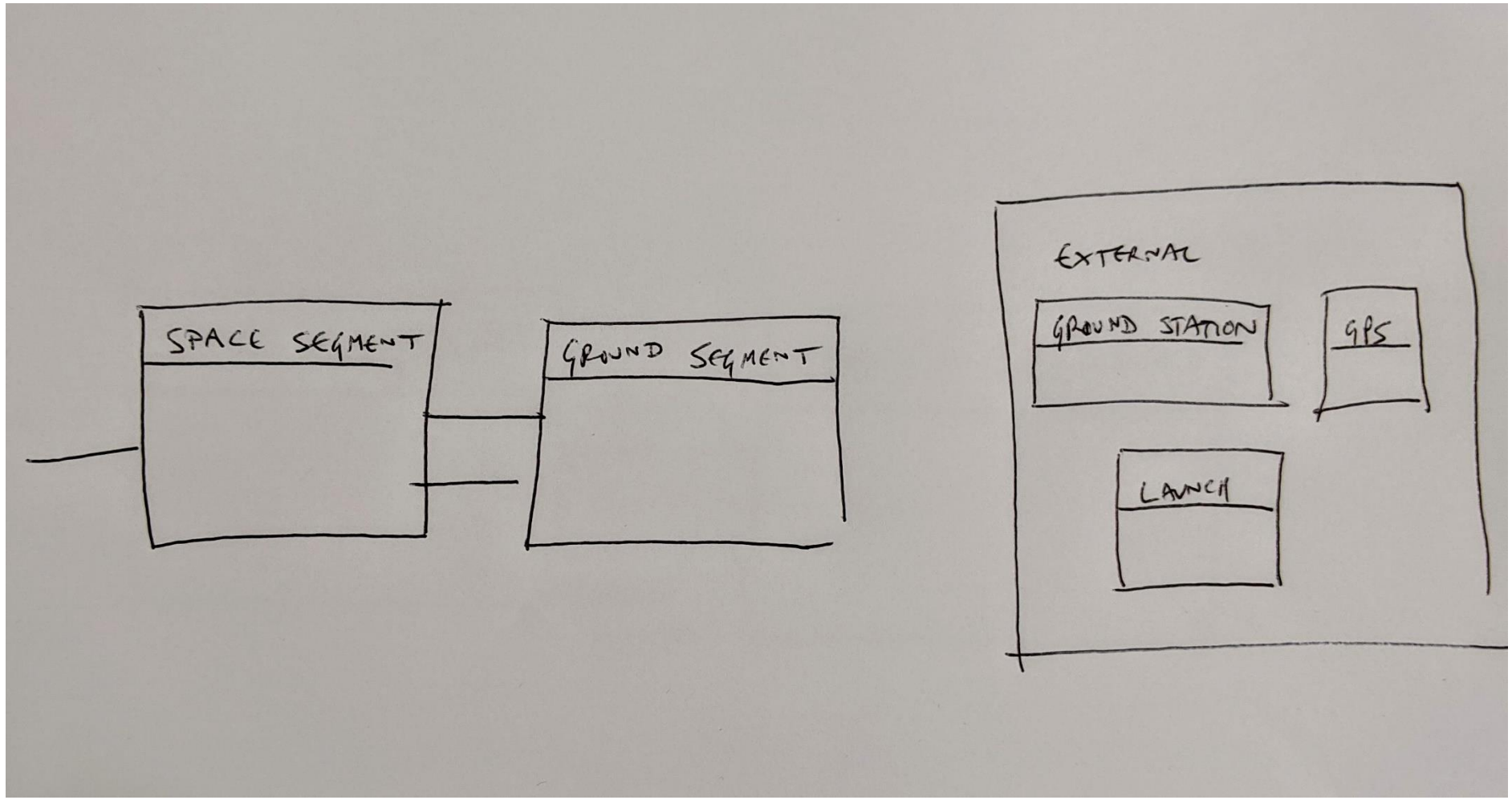
Let’s say we wanted to develop an imaging satellite system

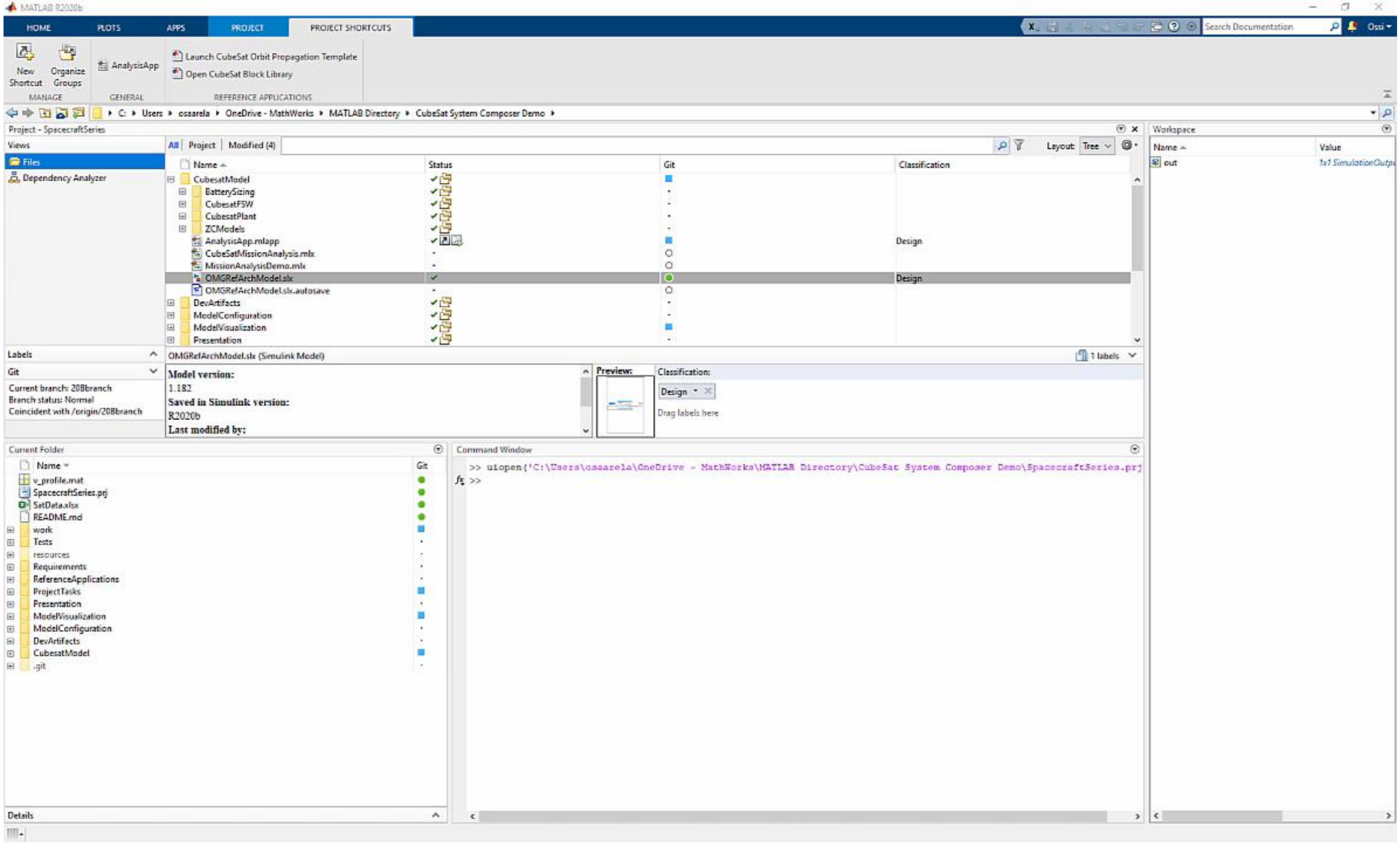


High level requirement:

The system shall provide and store visual imagery of MathWorks headquarters [42.2775 N, 71.2468 W] 1 times daily at 10 meters resolution

Let’s say we wanted to develop an imaging satellite system




MATLAB R2020b
HOME
PLOTS
APPS
PROJECT
PROJECT SHORTCUTS
Search Documentation
Ossi
New Shortcut
Organize Groups
MANAGE
AnalysisApp
GENERAL
Launch CubeSat Orbit Propagation Template
Open CubeSat Block Library
REFERENCE APPLICATIONS
C: ▸ Users ▸ osaarela ▸ OneDrive - MathWorks ▸ MATLAB Directory ▸ CubeSat System Composer Demo ▸
Project - SpacecraftSeries
Views
Files
Dependency Analyzer
All
Project
Modified (4)
Layout: Tree
Name
Status
Git
Classification
CubesatModel
BatterySizing
CubesatFSW
CubesatPlant
ZCModels
AnalysisApp.mlapp
Design
CubeSatMissionAnalysis.mlx
MissionAnalysisDemo.mlx
OMGRefArchModel.slx
Design
OMGRefArchModel.slx.autosave
DevArtifacts
ModelConfiguration
ModelVisualization
Presentation
Labels
Git
Current branch: 20Bbranch
Branch status: Normal
Coincident with /origin/20Bbranch
OMGRefArchModel.slx (Simulink Model)
1 labels
Model version:
1.182
Saved in Simulink version:
R2020b
Last modified by:
Preview:
Classification:
Design
Drag labels here
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Git
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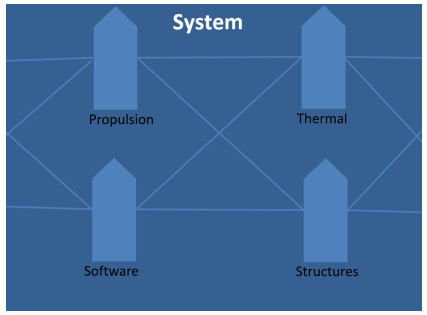
SatData.xlsx
README.md
work
Tests
resources
Requirements
ReferenceApplications
ProjectTasks
Presentation
ModelVisualization
ModelConfiguration
DevArtifacts
CubesatModel
.git
Command Window
>> uiopen('C:\Users\osaarela\OneDrive - MathWorks\MATLAB Directory\CubeSat System Composer Demo\SpacecraftSeries.prj
>>
Details

Digital engineering requires investments in people as well as technology

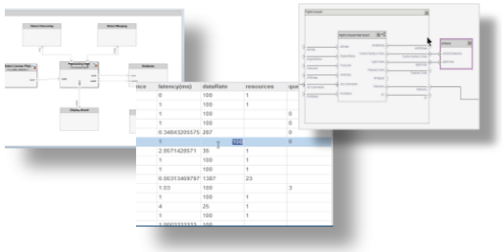
Figure it out yourself

Be enabled by training

Fully realized digital engineering connects system engineering, sub-system engineering and operations



The role of GNC in systems design



The evolution of model-centric systems design

Dealing with adaptive systems and AI

AI is the capability of a machine to imitate intelligent human behavior

ARTIFICIAL INTELLIGENCE

Any technique that enables machines to mimic human intelligence

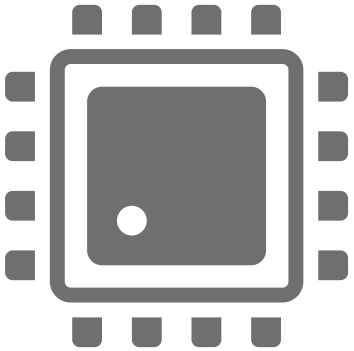
MACHINE LEARNING

Statistical methods that enable machines to "learn" tasks from data without explicitly programming

DEEP LEARNING

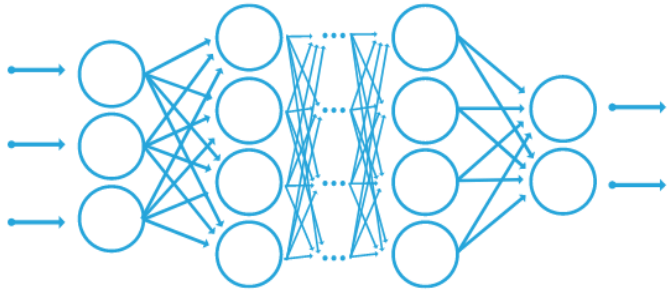
Neural networks with many layers that learn representations and tasks "directly" from data

The ingredients for practical applications of deep learning have only become available in the last decade



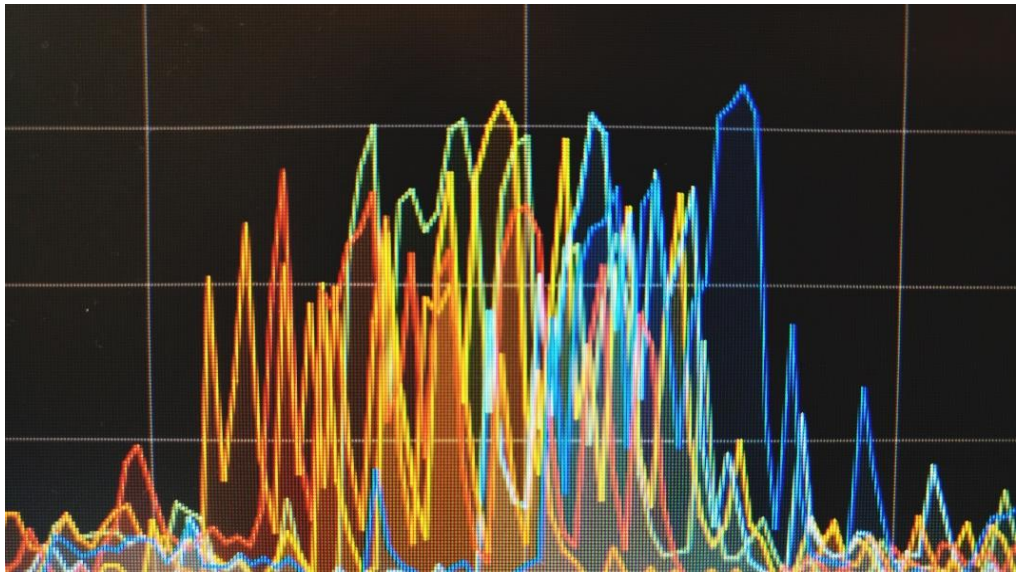
COMPUTING POWER

DATA



ALGORITHMS

Machine learning has been deployed on ground segment applications for several years

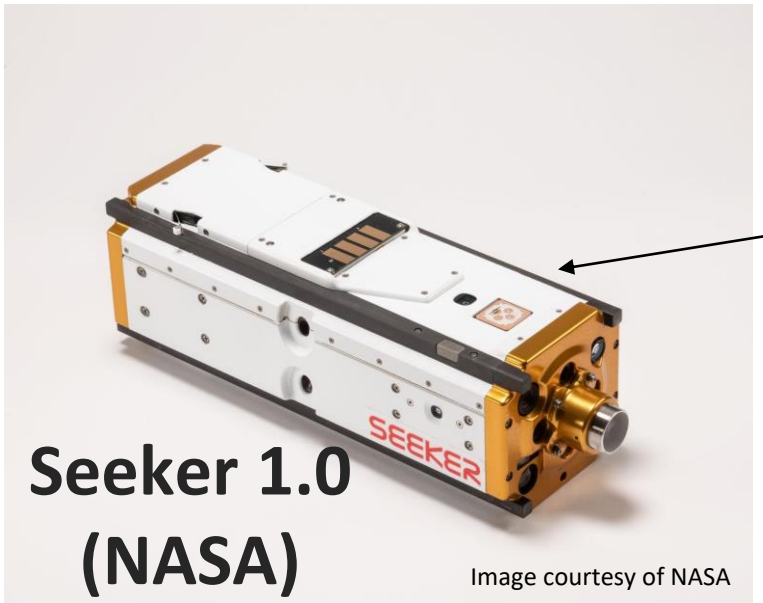


Telemetry Outlier Detection

Geospatial Analytics

Recently, machine learning has also been deployed in space

PhiSat-1
(ESA)

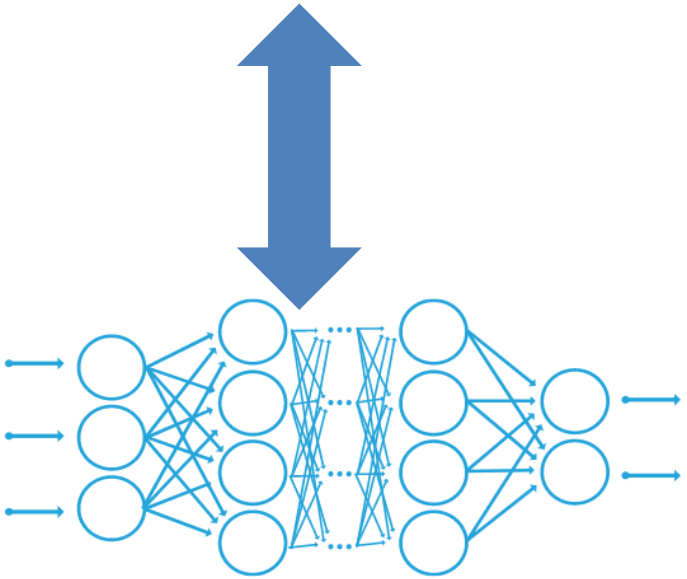


Seeker 1.0
(NASA)

CNN

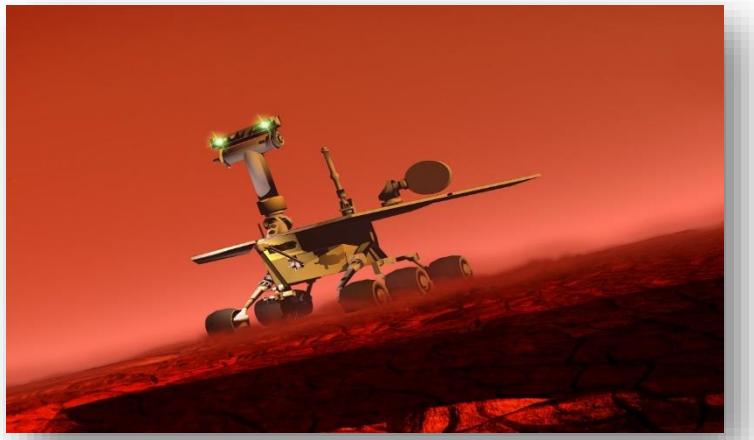
Cygnus

What is the relationship between machine learning and GNC?



Deploying machine learning in space requires pragmatic applications

Deploying machine learning in space requires pragmatic applications

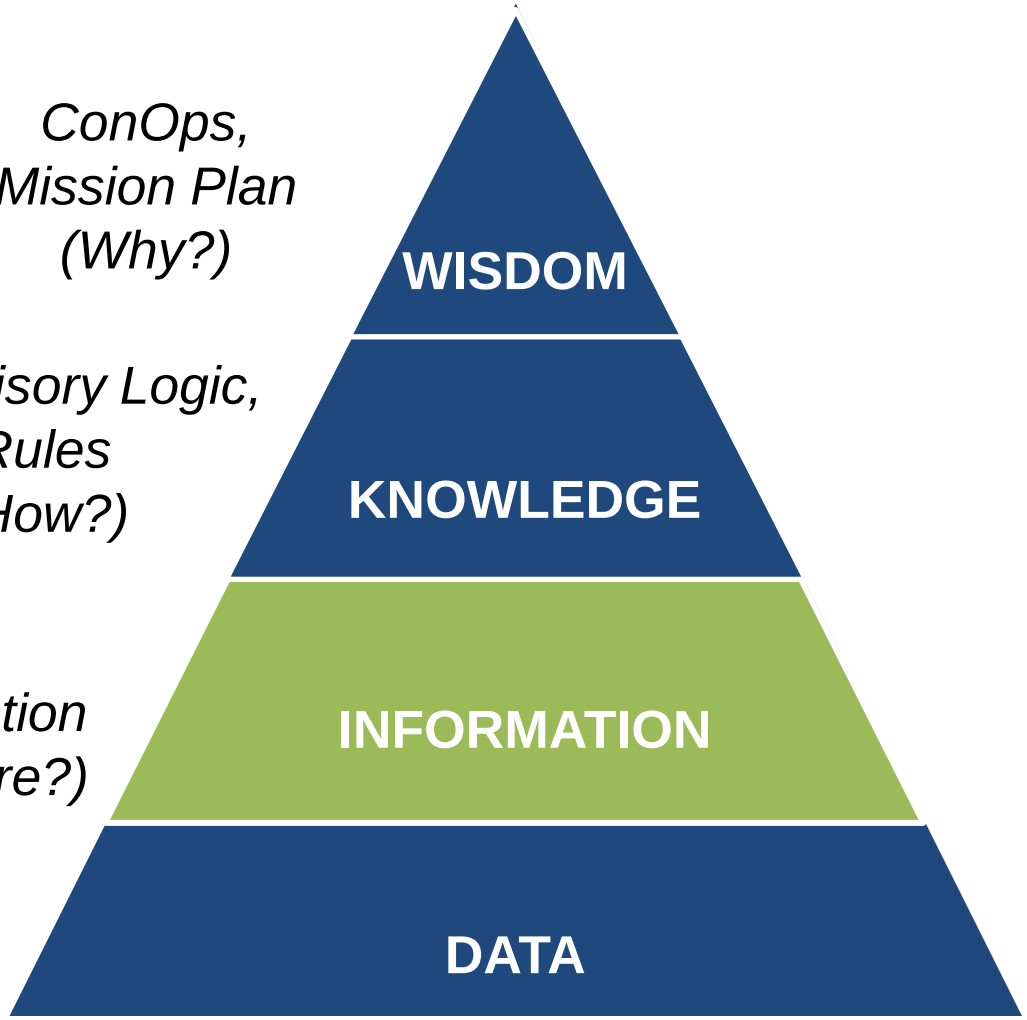


ConOps,
Mission Plan
(Why?)

Supervisory Logic,
Rules
(How?)

Sensing,
State Estimation
(What? Where?)

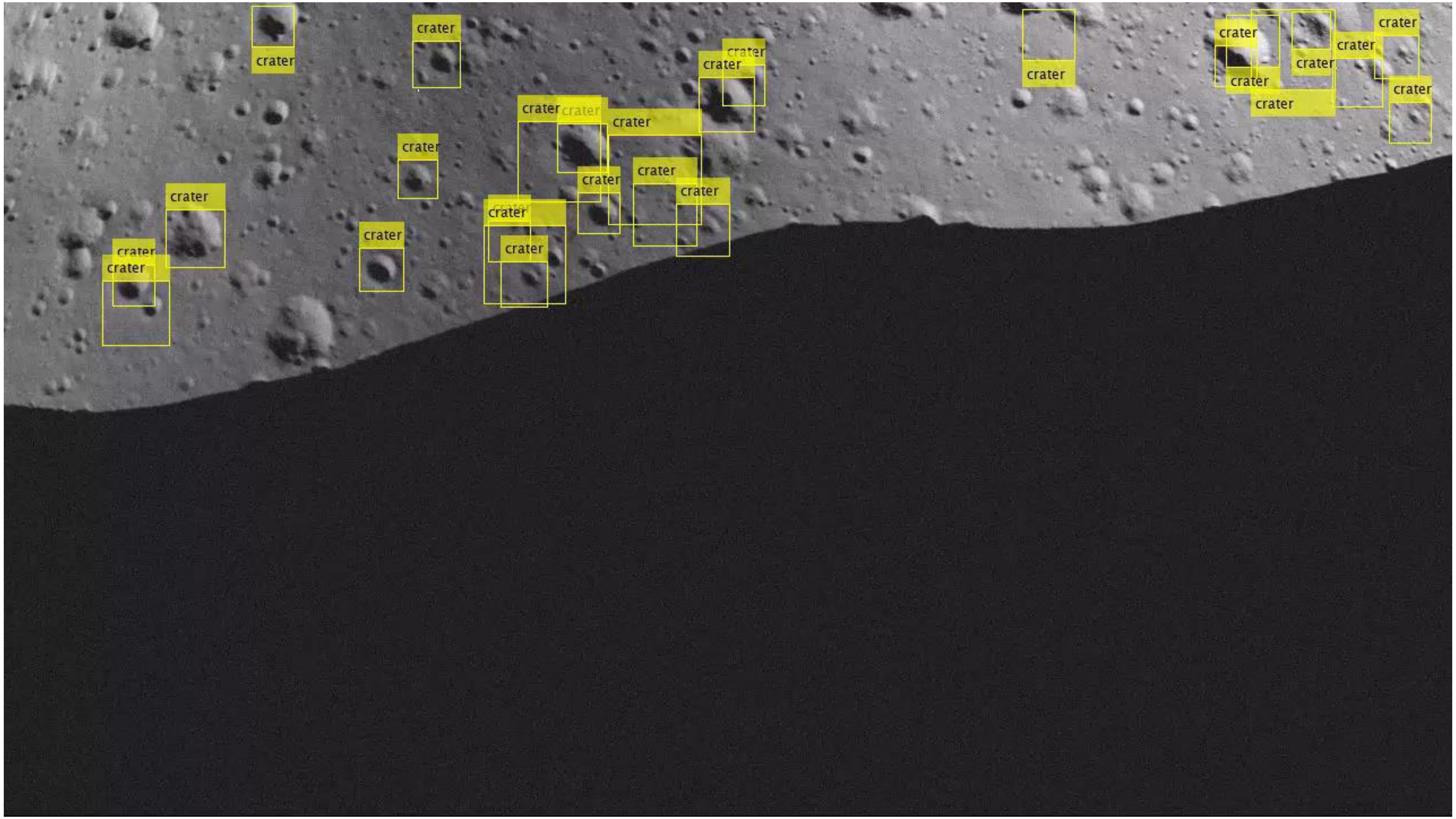
Raw inputs



Lunar landing is a potential future use case for machine learning

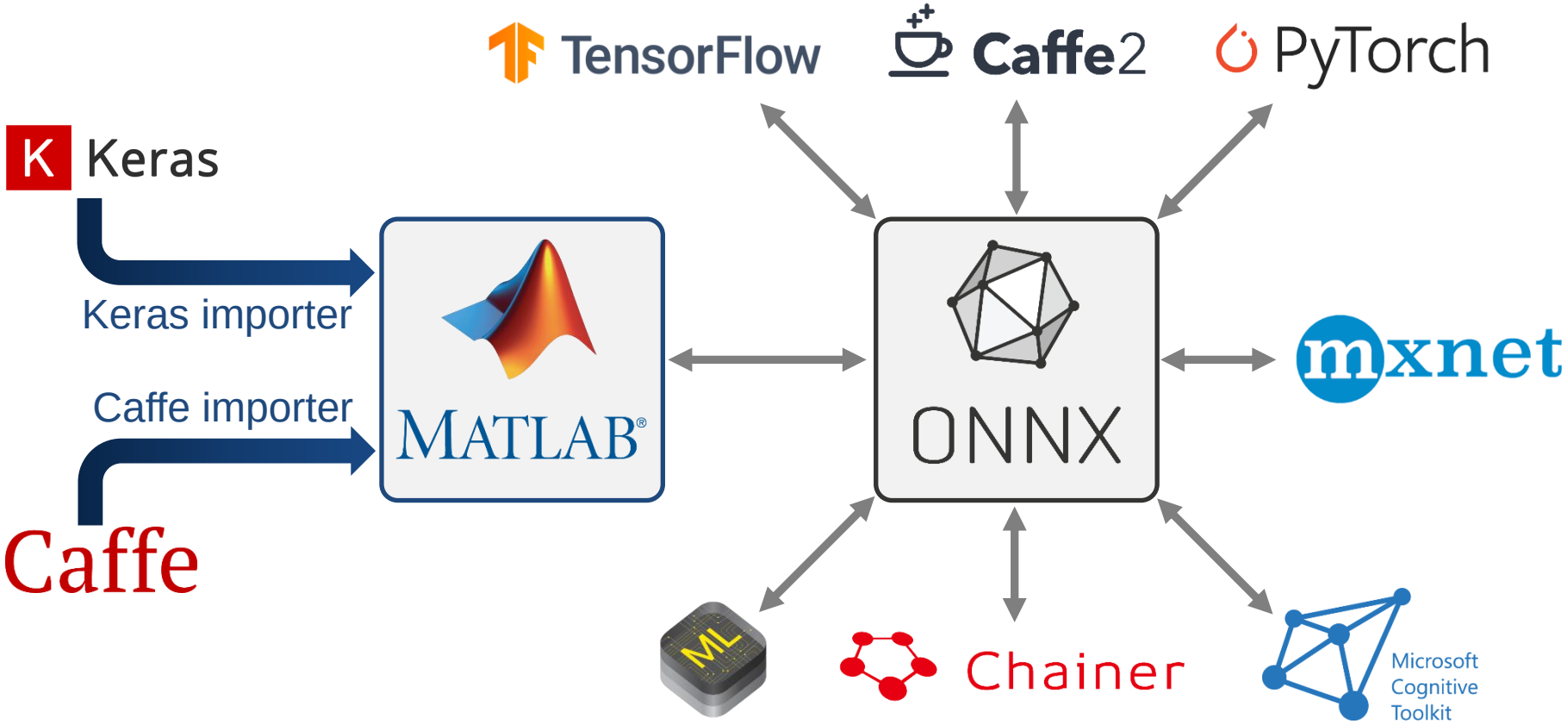
Image from Apollo 17 courtesy of NASA

Lunar landing is a potential future use case for machine learning



Images and video generated by PANGU and courtesy of the University of Dundee and STAR-Dundee.

There are many machine learning models to start from available from the broader community



Productization of AI is more than a model or algorithm

Data Preparation

- Data cleansing and preparation
- Human insight
- Simulation-generated data

AI Modeling

- Model design and tuning
- Hardware accelerated training
- Interoperability

Simulation & Test

- Integration with complex systems
- System simulation
- System verification and validation

Deployment

- Embedded devices
- Enterprise systems
- Edge, cloud, desktop

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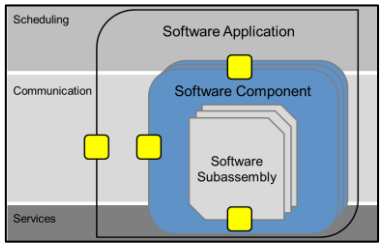
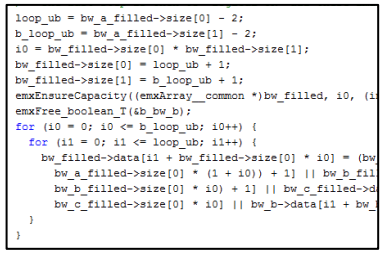
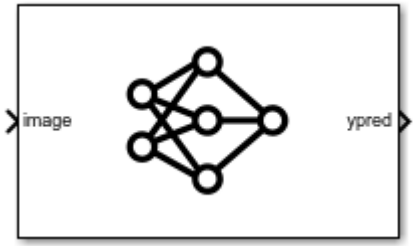
- Edge, cloud, desktop

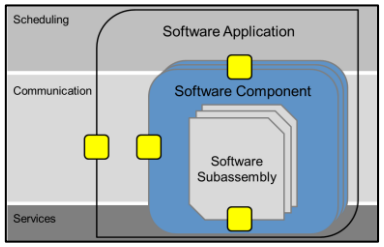
AI models need to be integrated within existing designs and processes



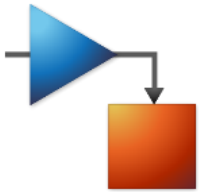




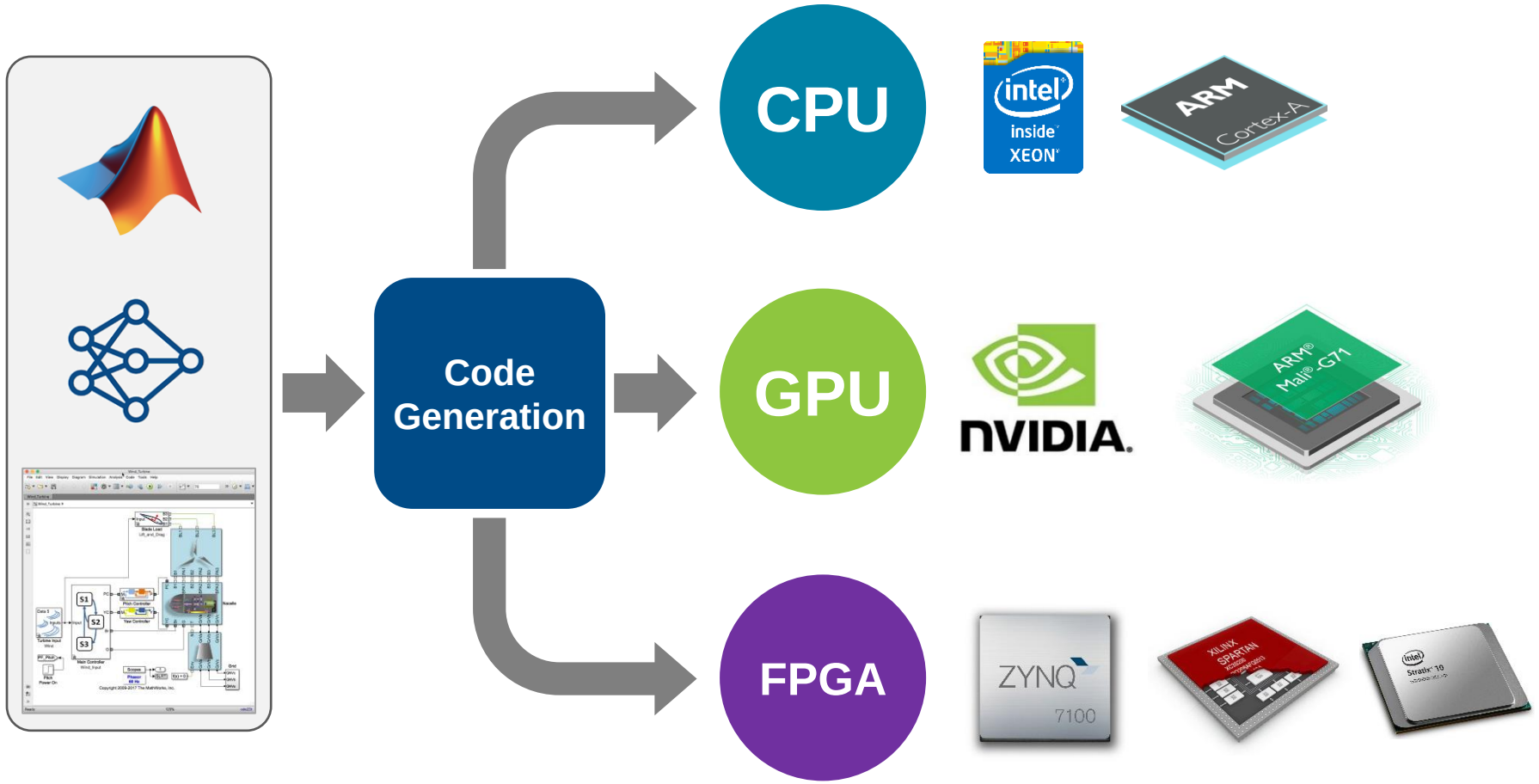
There is a growing interest in modeling at the systems level



```
loop_ub = bw_a_filled->size[0] - 2;
b_loop_ub = bw_a_filled->size[1] - 2;
i0 = bw_filled->size[0] * bw_filled->size[1];
bw_filled->size[0] = loop_ub + 1;
bw_filled->size[1] = b_loop_ub + 1;
emxEnsureCapacity((emxArray__common *)bw_filled, i0, (i
emxFree_boolean_T(&b_bw_b);
for (i0 = 0; i0 <= b_loop_ub; i0++) {
  for (i1 = 0; i1 <= loop_ub; i1++) {
    bw_filled->data[i1 + bw_filled->size[0] * i0] = (bw
      bw_a_filled->size[0] * (1 + i0)) + 1] || bw_b_fil
      bw_b_filled->size[0] * i0) + 1] || bw_c_filled->d
      bw_c_filled->size[0] * i0] || bw_b->data[i1 + bw_
  }
}
```

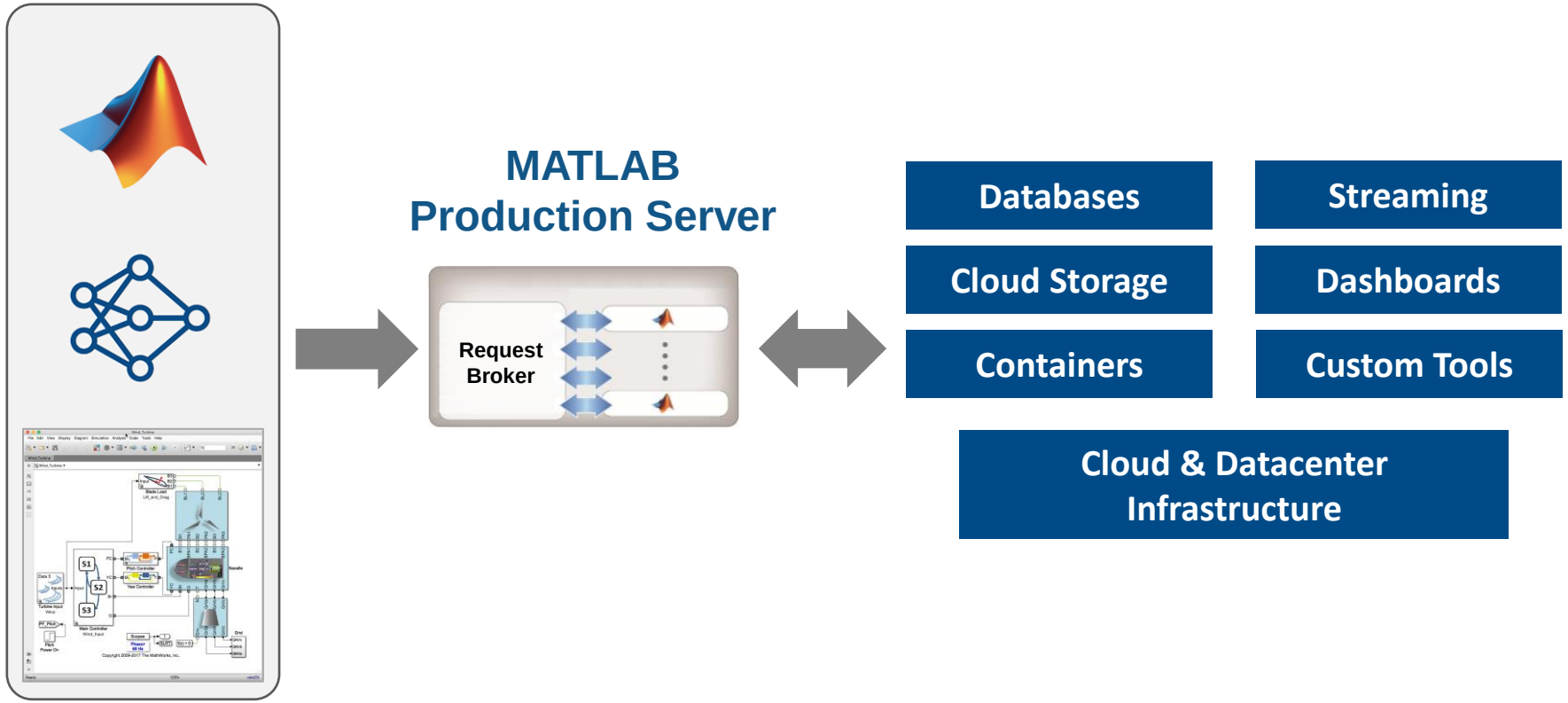


Ease of integration and deployment is key to productization of AI



Embedded deployment

Ease of integration and deployment is key to productization of AI



Ground-based deployment

MathWorks®

is a **Leader** in the 2021 Gartner Magic Quadrant for Data Science and Machine Learning Platforms for the Second Year in a Row

Figure 1: Magic Quadrant for Data Science and Machine Learning Platforms

Source: Gartner (March 2021)

Gartner Magic Quadrant for Data Science and Machine Learning Platforms, Peter Krensky, Carlie Idoine, Erick Brethenoux, Pieter den Hamer, Farhan Choudhary, Afraz Jaffri, Shubhangi Vashisth,1st March 2021.

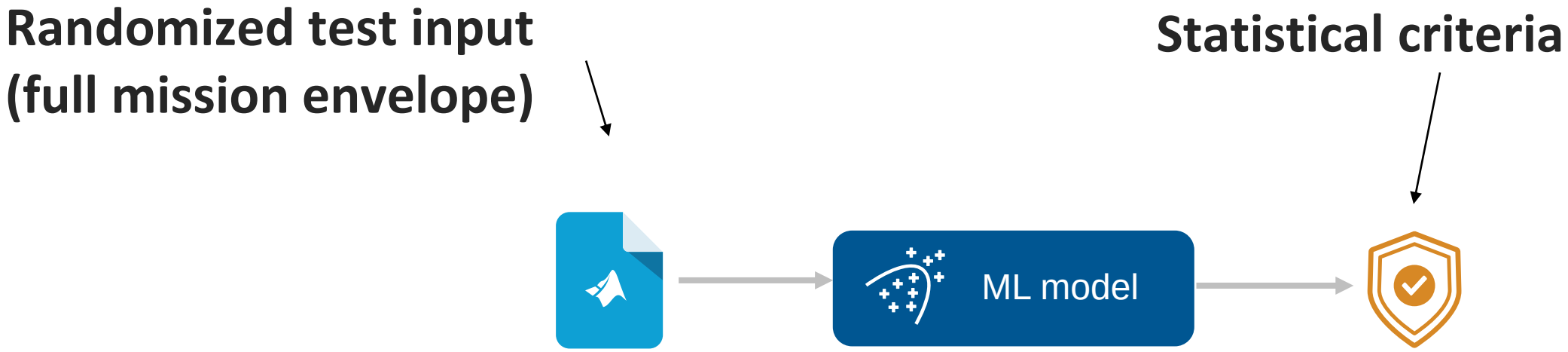
The biggest challenge to deploying AI algorithms for GNC may be verification and validation

Commercial Aviation

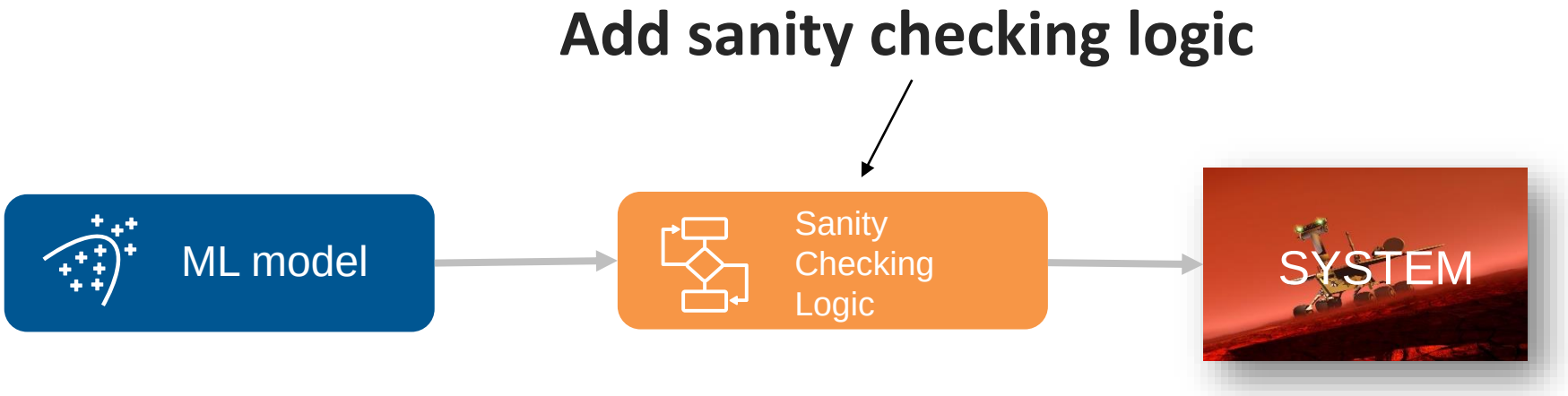
EUROCAE WG114 – SAE G34

EASA Concept Paper:
First usable guidance for Level 1
machine learning applications

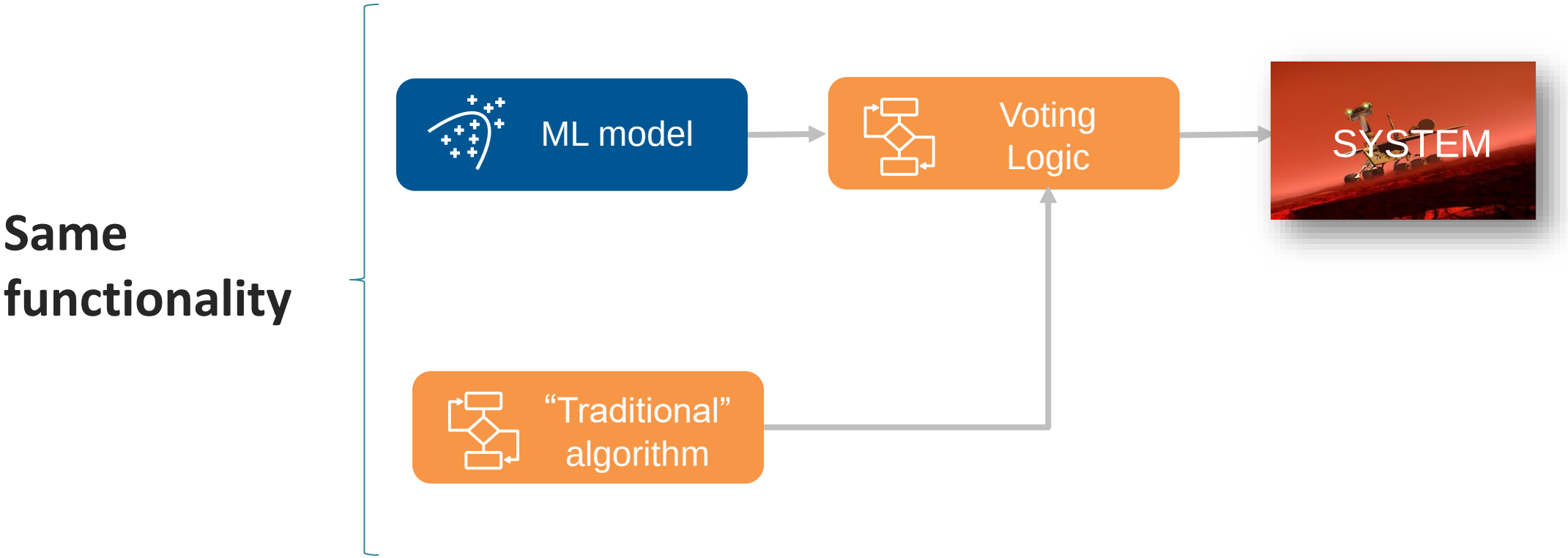
A statistical approach is one candidate for verifying machine learning algorithms



Statistical approaches can be made safer by bounding the algorithm outputs



Fallback mechanisms involving dissimilar redundancy are likely inclusions in a machine learning architecture

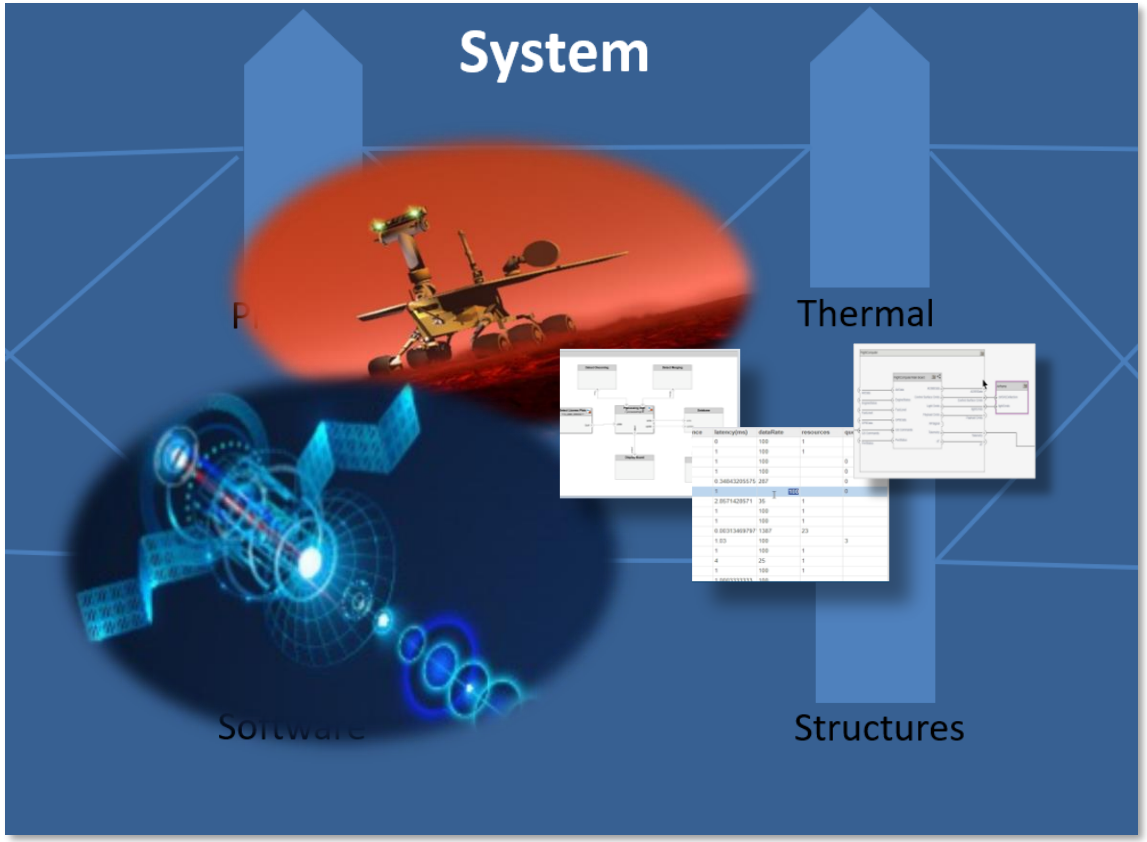


We have mentioned three methods that can be studied for the purpose of verifying machine learning algorithms

1. ***Black box*** **testing to** ***statistical requirements***
2. ***Sanity checking***
3. ***Dissimilar redundancy***

In summary

- **Systems thinking is more important than ever for GNC engineers**
- **Fully realized digital engineering includes and expands upon Model-Based Design**
- **GNC engineers should prepare for AI**



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