Digital Twins
A Little Bit of Everything

MBSE Symposium, Huntsville, AL | May 21-22, 2025

John Vickers | NASA, Marshall Space Flight Center
Principal Technologist, Advanced Manufacturing

NASA's Digital Transformation Strategic Framework

How we Synchronize DT Plans & Catalyze DT Progress

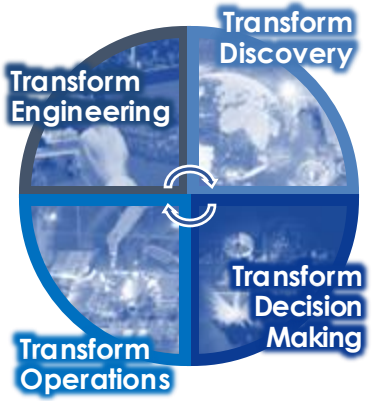
3 FUTURE STATE GOALS

4 TRANSFORMATION TARGETS

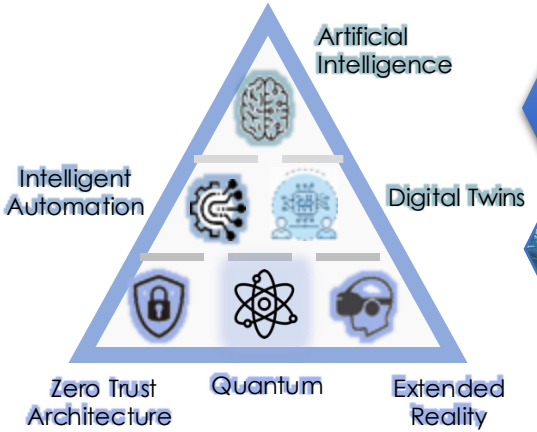
5 DIGITAL LEVERS

6 TECHNOLOGY FOUNDATIONS

7+ MISSION OUTCOMES



- Establish Interoperable *Architectures*
- Transform Critical *Processes*
- Maximize the Impact of our *Data*
- Adopt Common *Tools*
- Strengthen Inclusive[3] *Teaming*

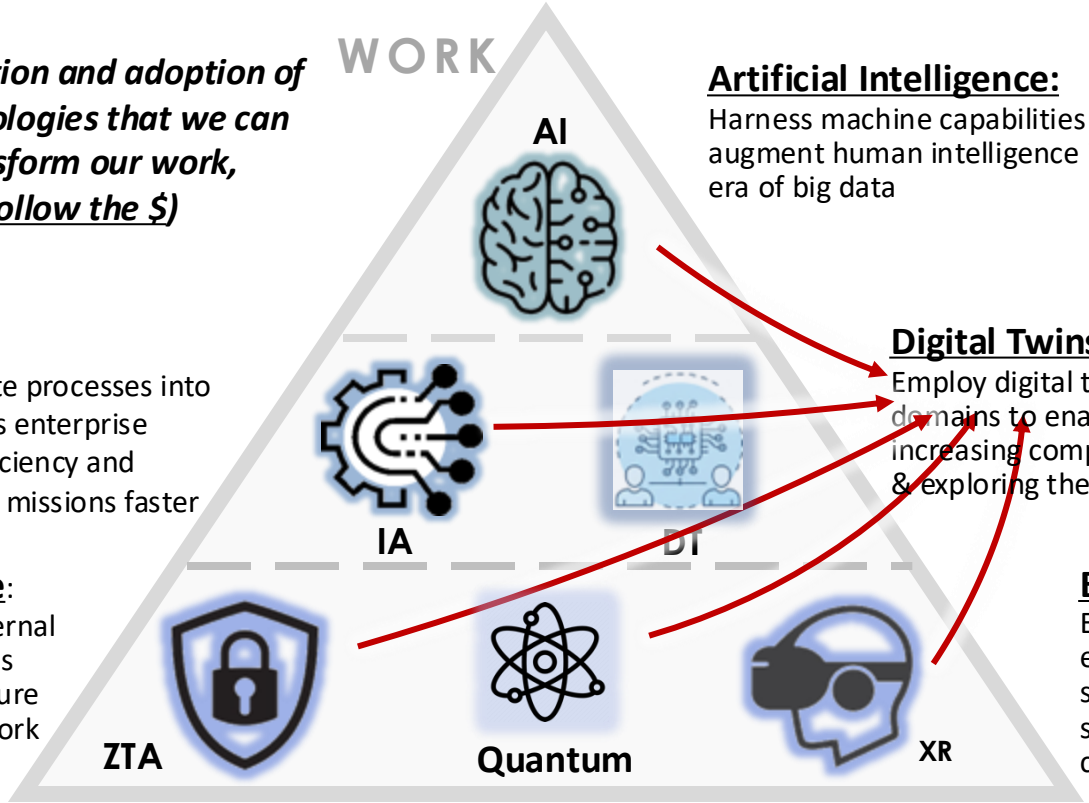


One Future NASA

NASA TM 20220018538

WHICH digital technologies will we use most?
6 Technology Foundations

DT will catalyze investigation and adoption of the next key digital technologies that we can & should leverage to transform our work, workforce & workplace (<u>Follow the $</u>)



<u>Artificial Intelligence:</u>
Harness machine capabilities to augment human intelligence in an era of big data

<u>Intelligent Automation:</u>
Eliminate, optimize & automate processes into synchronized workflows across enterprise platforms to maximize our efficiency and effectiveness to enable bolder missions faster

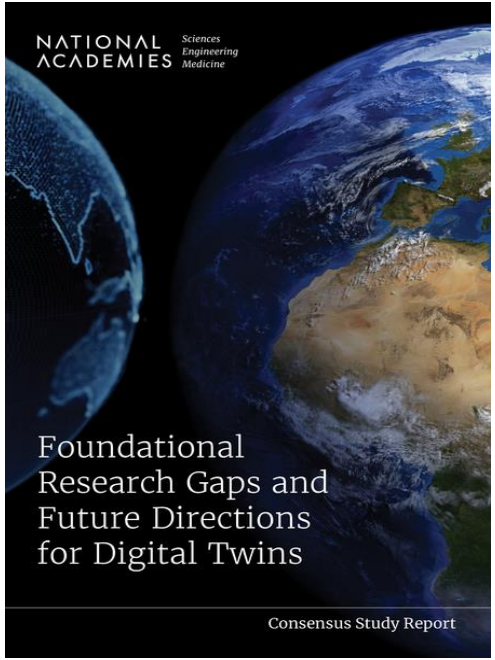
<u>Digital Twins:</u>
Employ digital twins across functional domains to enable our people to address increasing complexity, speed, uncertainty & exploring the unknown

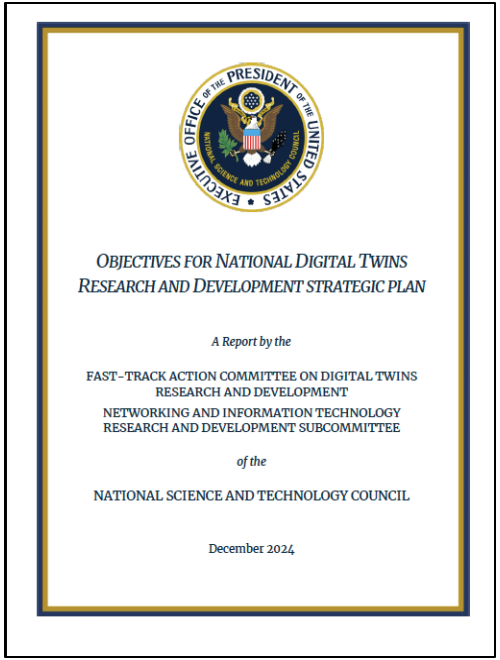
<u>Zero Trust Architecture</u>:
Enable dynamic internal/external collaboration wherever teams need to work, leveraging secure infrastructure, identity, network & data architecture

<u>Extended Reality</u>:
Enhance agile internal/ external teaming via seamless, immersive, secure visualization & collaboration

Leverage its potential for significantly enhanced missions by utilizing quantum computing and communication to solve complex challenges in areas like mission planning, materials science, and deep space travel

National Attention on Digital Twins





Summary of the National Academies Report

- Digital twins hold immense promise for revolutionizing various sectors…
- A digital twin is "a set of virtual information constructs that mimics the structure…
- Fit for Purpose Virtual Representation
- Modeling and Simulation/Physical Counterpart/Bidirectional Interaction?
- Improved Decision-Making/Enhanced Efficiency/Accelerated Scientific Discovery/Knowledge Preservation

Research Gaps

- Verification, Validation, and Uncertainty Quantification (VVUQ)
- Mathematical and Computational Gaps
- Data Integration and Management
- Interdisciplinary Collaboration
- Interagency Working Group

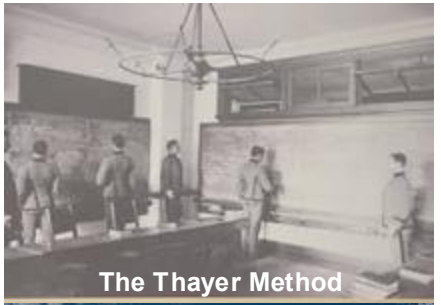
Fit for Purpose

Everything about a Digital Twin depends on its intended purpose!

(and your imagination)

Introduction

- ***Escaping the flatland of two-dimensionality of envisioning information for all the interesting worlds (physical, biological, imaginary, human) that we seek to understand… (Tuffe, 1990)***
- ***The goal of digital twins is to enrich our understanding and capabilities of the most complete and comprehensive reality.***
- ***A "Marvel of Technology" as the space station represents a pinnacle of physical innovation, engineering, and technology, digital twins promise even more ambitious model-based achievements.***



The world is complex, dynamic, multidimensional; the paper is static, flat.
"Envisioning Information, Edward Tuffe"

What are These Digital Twins Anyway

What are Digital Twins?

A set of virtual information constructs that mimics the structure, context, and behavior of a natural, engineered, or social system (i.e., a real thing). *(NASEM, 2024)*

- **Empirical Reality vs Model-based Reality: observed, measured, and verified through experiments vs algorithms, mathematical equations, data, and simulations to represent a real-world system.**
- **Physical Existence: possess mass, energy, and occupies space-time, includes particles, forces, and fields that interact according to the laws of physics.**
- **Theoretical Existence: Nature/Science theoretical entities that are not directly observable (e.g., evolution, black holes, earth core, brain function).**
- **Social Existence: Life, Work, Business, Space, Defense, IT, Construction, Transportation, Energy, Financial, Health, Environment, Agriculture, Government, Law, Social…**
- **Probabilistic and Emergent Reality: uncertainty is ubiquitous; digital twins can be a powerful tool for understanding and predicting the behavior of complex and emergent systems. (Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems.) (Grieves/Vickers 2017)**

When a distinguished but elderly scientist states that something is possible, he is almost certainly right. When he states that something is impossible, he is very probably wrong. — Arthur C. Clarke

Digital Twin Definitions- A picture is worth a thousand words

A digital twin is a set of virtual information constructs that mimics the structure, context, and behavior of a natural, engineered, or social system (or system-of-systems), is dynamically updated with data from its physical twin, has a predictive capability, and informs decisions that realize value. The bidirectional interaction between the virtual and the physical is central to the digital twin.
National Academies Report 2024

Humpty Dumpty: *"When I use a word it means just what I choose it to mean, no more nor less."* **Lewis Carroll**

A digital twin is a digital replica of a physical object, person, system, or process, contextualized in a digital version of its environment. **McKinsey**

A Digital Twin is a virtual representation of an object or system that spans its lifecycle, is updated from real-time data, and uses simulation, machine learning, and reasoning to help decision-making.
IBM

"A poet would be overcome by sleep and hunger before being able to describe with words what a painter is able to in an instant."
Leonardo da Vinci

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.
Digital Twin Consortium

Virtual twins provide the ability to 3D model everything around you and then test and simulate to ensure your model is perfected. **Dassault**

A digital twin is a complete (holistic) computational (modeling and simulation) replica of a real-world application (purpose) that enables understanding of interconnected relationships(systems) and explores potential future outcomes(prediction). **John Vickers**

"Digital Twin" Google search ~70,000,000 and Google Scholar ~220,000 results (Definition ~12,000 vs ~900)

Does a Digital Twin require a Physical Counterpart? It's Debatable!

Apologies to my Friends!

- A Digital Twin is a virtual representation of a connected physical asset. A Digital Twin requires a physical asset. (AIAA)
- The bidirectional interaction between the virtual and the physical is central to the digital twin. (National Academies)
- Representation of real-world entities and processes, with synchronized interaction at a specified frequency and fidelity. (Digital Twin Consortium)

IMO, existing portrayal has too much bias to one side, is a critical limitation to future development

- Models can outperform the physical counterparts by orders of magnitude
- Unlimited conceptual design iterations, prediction of future states, learn/adapt/improve
- Intangible counterparts (e.g., Business processes, Cyber security, Government, Life)
- Limited physical sensor/device feedback
- So much more than a 3D model of a part
- "No Exceptions Camp" -- "Possible Exceptions Camp" -- "Depends on Purpose Camp"

It's very profound and even a little bit scary because it's happening very quickly and there is no upper bound over the next decade intelligence that is rare today will become free and commonplace. — Bill Gates

Verification, Validation, and Uncertainty Quantification

- Methods for ensuring continual VVUQ and monitoring of digital twins are required to establish trust. (*NASEM*)
- Validation with Physical Testing: importance of validating simulation results with physical testing and collaboration with industry specific customers and research institutions to conduct experiments and validate the accuracy of software.
- Many of the elements of VVUQ for digital twins are shared with VVUQ for other computational models. (e.g., CFD, FEM, Financial)
- Commercial companies employ rigorous and comprehensive V&V processes to ensure the quality, reliability, and accuracy that covers the entire software development lifecycle, from requirements to product release.
- Companies adhere to relevant industry standards and regulations.
- Universities are researching mathematical foundations of digital twins.

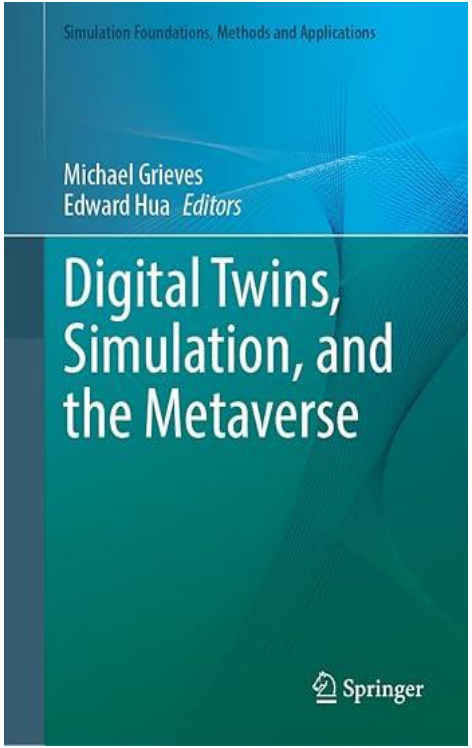
Universities Leading the Advancement of Digital Twin Research

- Louisiana State University: Digital Twin Media Arts & Engineering Program
- Carnegie Mellon University: NASA Digital Twin Institute
- Purdue University: Purdue Digital Twin Lab
- University of Central Florida: Digital Twin Initiative
- Stanford University: Mathematics of Digital Twins
- Texas A&M University: Texas A&M Digital Twin Project and Digital Twin Lab
- University of Florida: Digital Twins for Semiconductor Manufacturing
- Auburn University: The Interdisciplinary Center for Advanced Manufacturing Systems
- Southern Methodist University: Center for Digital and Human-Augmented Manufacturing
- University of Michigan: Mcity Test Facility Digital Twin
- Indiana University: Digital Twin Research Initiative
- University of Cambridge: Centre for Digital Built Britain

From Hype to Commercial Solutions

- NVIDIA: Omniverse Digital Twins are Solving the World's Greatest Challenges
- Siemens: Transforming Industries with Digital Twin Technology
- PTC: Digital Twins Transforming How we Make Sense of Data
- Ansys: Transform your Operations with AI Driven Simulation based on Digital Twin Software
- Dassault: Virtual Twin Experiences Going Beyond Digital Twin Technology
- Microsoft: Azure Digital Twins Enables the Creation of Twins based on Models of Entire Environments
- Bentley Systems ITwin Project/Construction/Capture software
- Autodesk Digital Twin Technology

My Reading Digital Twin Books



Summary of "Twin Systems"

- Practical applications of digital twins across various stages of infrastructure projects…
- The level of fidelity depends on the purpose
- Not only physical assets but also behaviors and processes
- Emphasis on a systems thinking and more holistic approach to implementation
- Capacity to extrapolate forwards and backwards
- Ability to outlive intended purpose
- Not merely digital replicas but dynamic, living systems
- Digital twin lifecycle, from its origins in design stages to its maturity in the operational phase
- Interconnected forecasting, forensics, AI, and IoT
- Security challenges associated with digital twins, particularly in large-scale infrastructure projects

🚫 More than an expansion of DT concept

Snead State Career Technical & Workforce Development

Additive Manufacturing

Machine Tool Technology

Industrial Systems Technology

Computer Design

Welding Technology

Digital transformation isn't about eliminating hands-on manufacturing (Planes, Trains, and Automobiles)

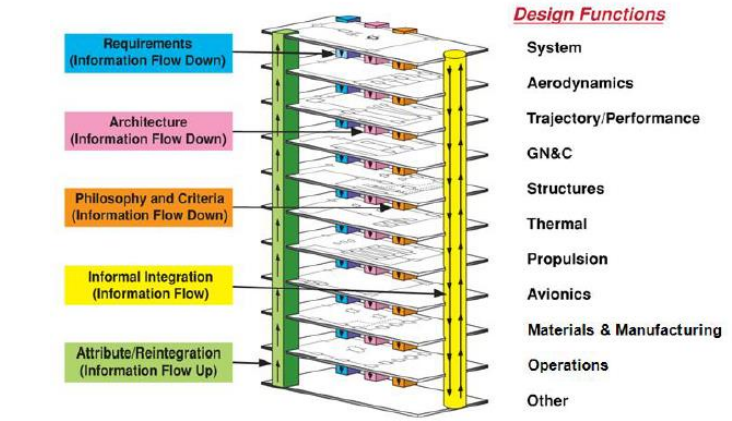
Legacy vs Transformation

Artificial Intelligence Verbal Requirements Definition

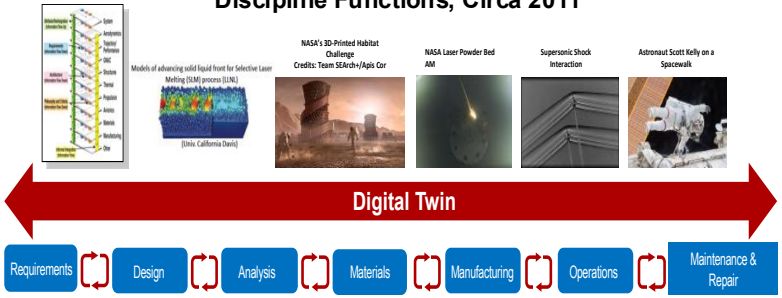
Auburn University

- Training an AI agent to accept verbal commands to generate system requirements in minutes
- Identifies relationships between requirements
- Provides the purpose of the requirement
- Can be used to classify the type of requirement and the priority of the requirement
- Integrated Technical, Policy, and Standards requirements
- Human evaluation is still important, to verify the generated requirements are correct and complete

(*Auburn University: Dr. Gregory Harris, Dr. Edward Huang, and Md Mehedi Hasan, 2025*)



NASA Technical Integration of System, Design, and Discipline Functions, Circa 2011



Properly understood, system engineering is concerned with context over structure, with interactions over elements, and with the whole over the sum of the parts. (Michael Griffin, University of Alabama in Huntsville, 2010)

NASA Space Technology Research Institute -- Institute for Model-Based Qualification & Certification of Additive Manufacturing (IMQCAM)

Vision

Our vision is to deliver a Digital Twin (DT) platform comprising a powerful set of integrated computational models and simulation tools that can be used with confidence by NASA researchers and practitioners for Q&C of AM processes and products. This DT will promote a holistic, cradle-to-grave model-based approach for unraveling complex subtleties in the materials-processes-structure-property performance and life relationships in the metals additive manufacturing domain.

Mission

The goal of the IMQCAM is to develop an end-to-end model or Digital Twin of the LPBF process, connecting feedstock, 3D printing conditions, and post-print microstructural state to part response and location-specific properties, as well as fatigue life that is crucial to the aerospace community.

$15M/5-year grant

Partner Institutions: Carnegie Mellon University, Johns Hopkins University (JHU), JHU-Applied Physics Laboratory, Vanderbilt University, University of Texas-San Antonio, Southwest Research Institute, University of Virginia, Pratt & Whitney (PW), Case Western Reserve University

Carnegie Mellon University,
Johns Hopkins University

Group photograph from the IMQCAM Continuation Review, Oct 3-4 at CMU. Photo credit: CMU

Major Focus Areas:

- Process Modeling
- Multiscale Modeling &
- Life Prediction
- Digital Twin Assisted Qualification & Certification
- Data & Software Integration

Branch Technology and Foster + Partners Lunar Power Tower

The Kennedy Center

National

What's On Visit Digital Stage Support Education Our Story Memorial Shop Rentals

EARTH TO SPACE

Foster + Partners

From Earth to Space and Back

STUDIO F

Foster + Partners is a global studio for architecture, urbanism, and design, rooted in sustainability, which was founded over fifty years ago in 1967 by Norman Foster. With scale models, 3D-printed structures, and captivating films, Foster + Partners presents groundbreaking projects that explore the potential of 3D printing in the construction of lunar and Martian habitats. (UK)

Mar. 28-Apr. 13, 2025

https://www.youtube.com/watch?v=T78kP6_GM7s

NASA'S LunaRecycle Centennial Challenge

"Everything that we do on the moon: we've got to figure out how to dispose of it or it's there forever…" *Pam Melroy, Deputy NASA Administrator*

The LunaRecycle Challenge is a $3 million, two track, two-phase competition focused on the design and development of recycling solutions that can reduce waste and improve the sustainability of longer-term lunar missions.

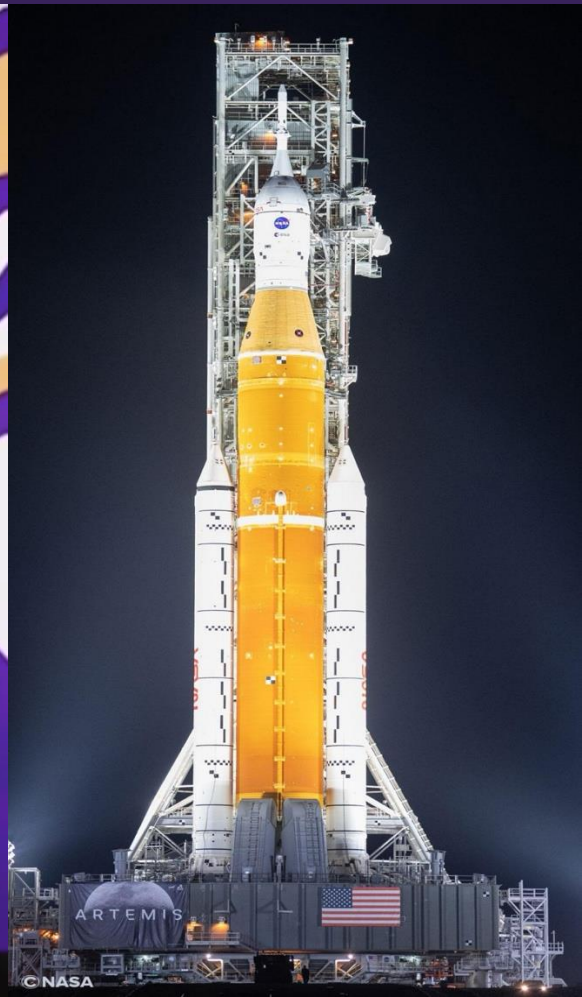
Digital Twin track, focused on designing a digital twin of a complete system for recycling one or more waste categories on the lunar surface and manufacturing one or more end products. Teams in this track must include the manufacturing of one or more finished end products in their design.

NASA | Michoud Assembly Facility, New Orleans, Louisiana

LSU

CREATIVE CAPABILITY | "What can you do with that?"

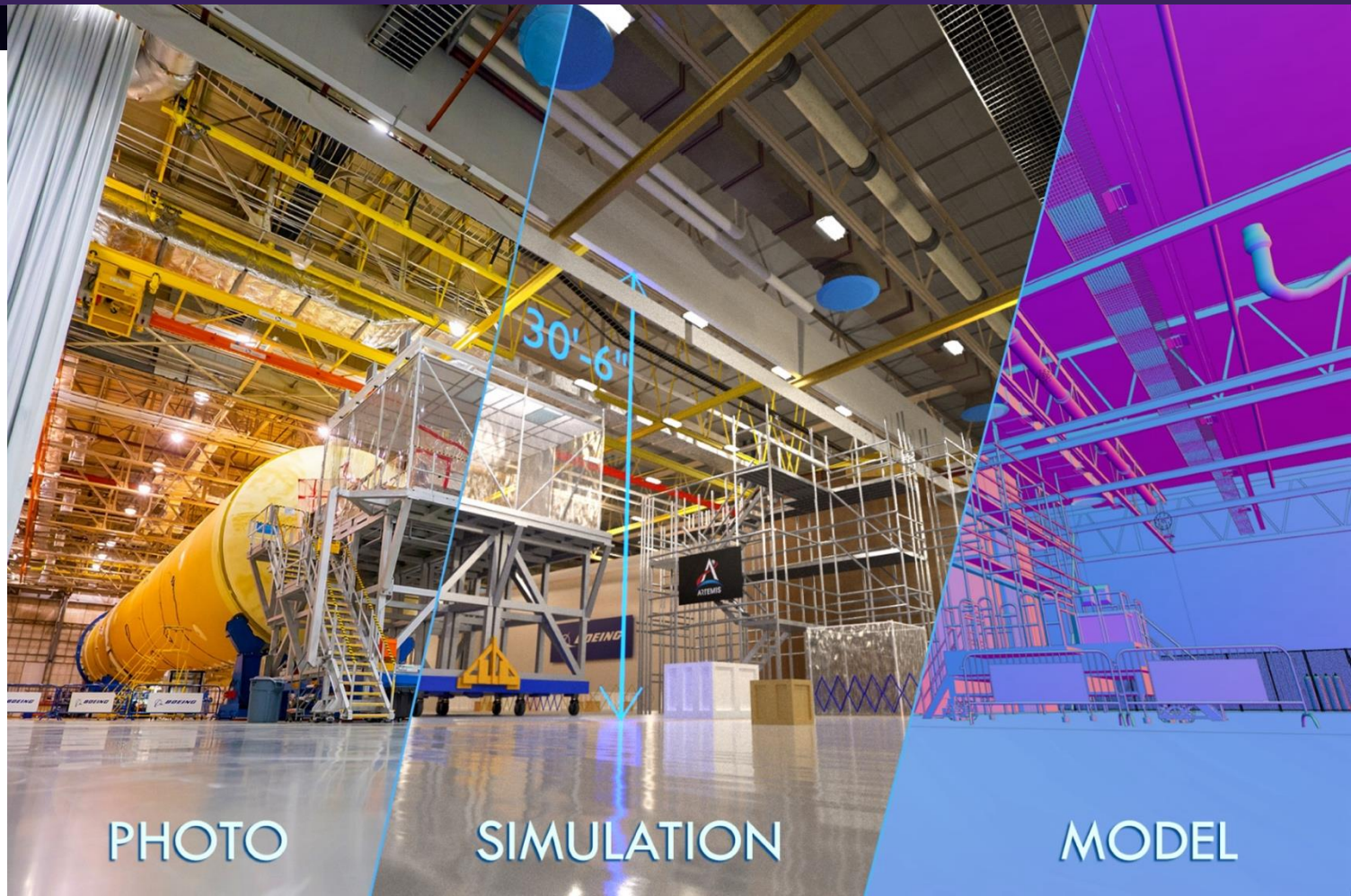
LSU



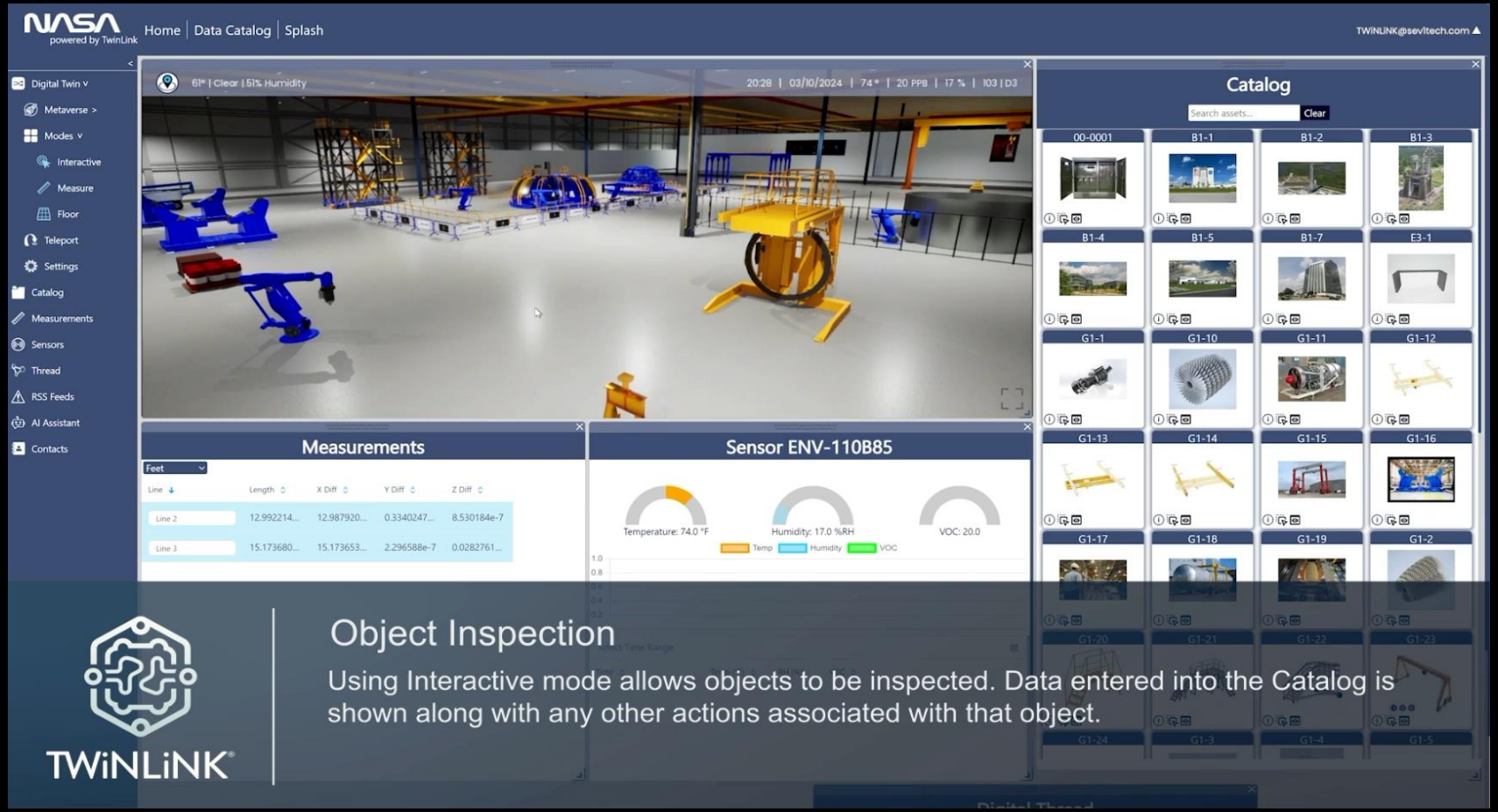
THE DIGITAL TWIN | Art + Technology for Insight

LSU

- Scan and Model
- Factory Engineering Analysis and Interrogation
- Environment Data Overlay
- Real Time Location Tracking
- Sensor Data Overlays



FEATURE | Object Inspection and Interrogation

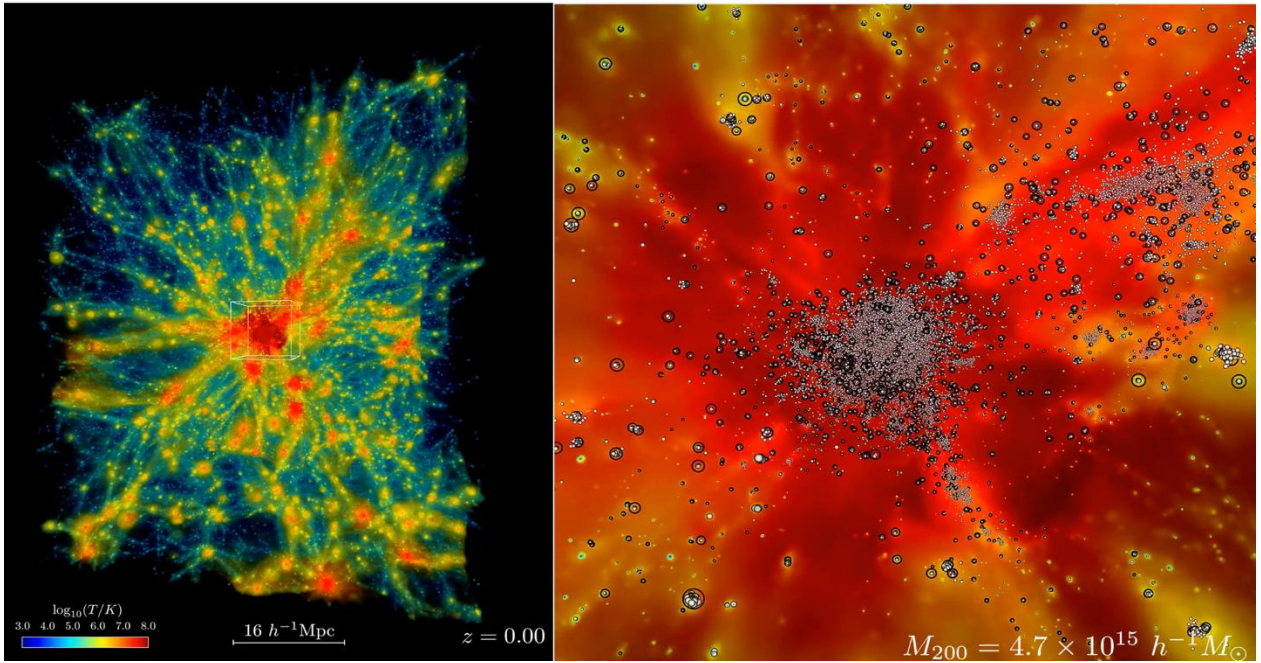


“Digital Twins are Helping Scientists Run the World’s Most Complex Experiments”

“Digital twins hold exciting potential for exploring the unknown. Digital twins can create virtual replicas of unexplored environments. They can push the boundaries of knowledge, unveil the unexplained, and enhance our ability to respond to the unexpected, leading to a more resilient and informed future.”

https://www.technologyreview.com/2024/06/10/1093417/how-digital-twins-are-helping-scientists/

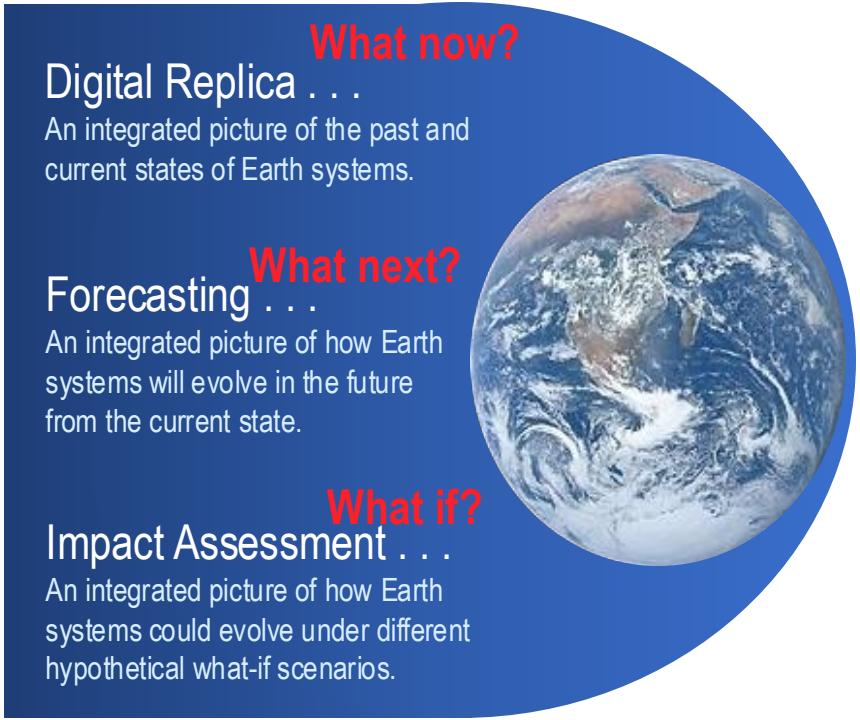
Digital Twins: Expanding our Understanding



World's largest simulation of the cosmos lays new computational foundation for simultaneous extreme-scale dark matter and astrophysical investigations. The universe just got a whole lot bigger… or at least in the world of computer simulations. Used the fastest supercomputer on the planet to run the largest astrophysical simulation of the universe ever conducted, 1.1 exaFLOPS, which is equal to 1.1 quintillion floating-point operations per second. (Frontier, Oak Ridge National Laboratory)

Earth System Digital Twins

NASA Earth Science Technology Office (ESTO), Advanced Information Systems Technology (AIST)
Earth Systems Digital Twins (ESDTs) are an emerging capability for understanding, forecasting, and conjecturing the complex interconnections among Earth systems, including anthropomorphic forcings and impacts to humanity.



An Earth System Digital Twin or ESDT is a dynamic and interactive information system that first provides a digital replica of the past and current states of the Earth or Earth system, as accurately and timely as possible, second allows for computing forecasts of future states under nominal assumptions and based on the current replica, and third offers the capability to investigate many hypothetical scenarios under varying impact assumptions.

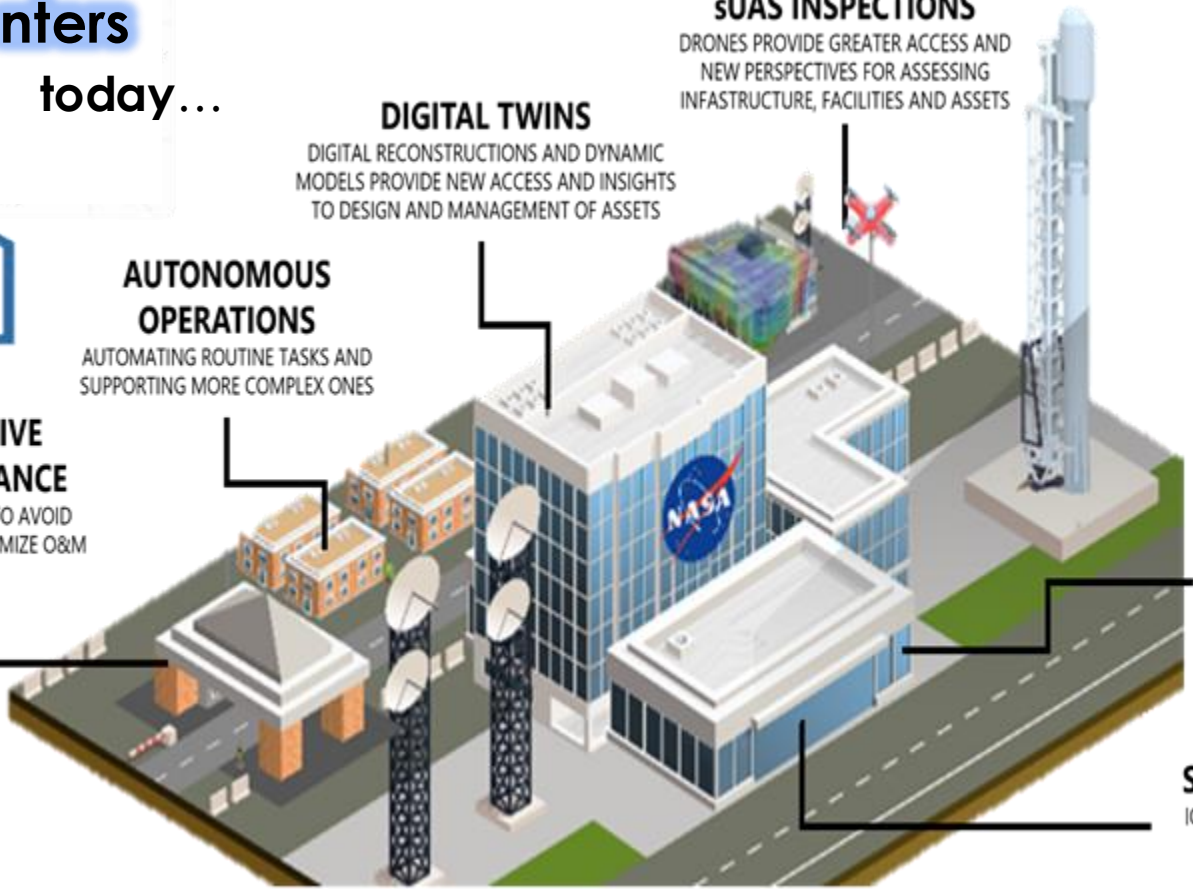
=> What Now? What Next? What If?

An ESDT includes:

- Continuous observations of interacting Earth & human systems
- From many disparate sources
- Driving inter-connected models
- At many physical and temporal scales
- With fast, powerful and integrated prediction, analysis & visualization capabilities
- Using Machine Learning, causality and uncertainty quantification
- Running at scale in order to improve our science understanding of those systems, their interactions and their applications

Digital Twins of our Workplace (SimCity)

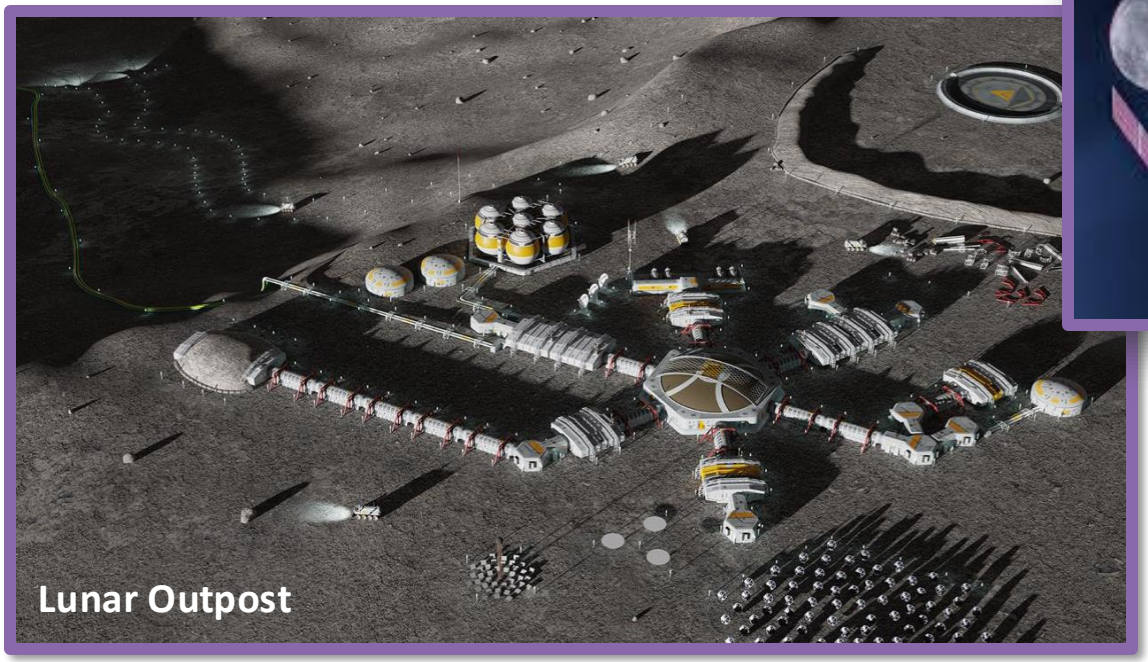
Smart Centers today…



Integrating Smart Cities technologies to ***optimize services*** *for our "citizens," "business partners" and "city managers"*

Cislunar & Lunar Surface Mission Planning

Leveraging digital twins to design, manufacture, test and operate mission elements from multiple nations >1000x before attempting real missions to speed design cycles & reduce costs



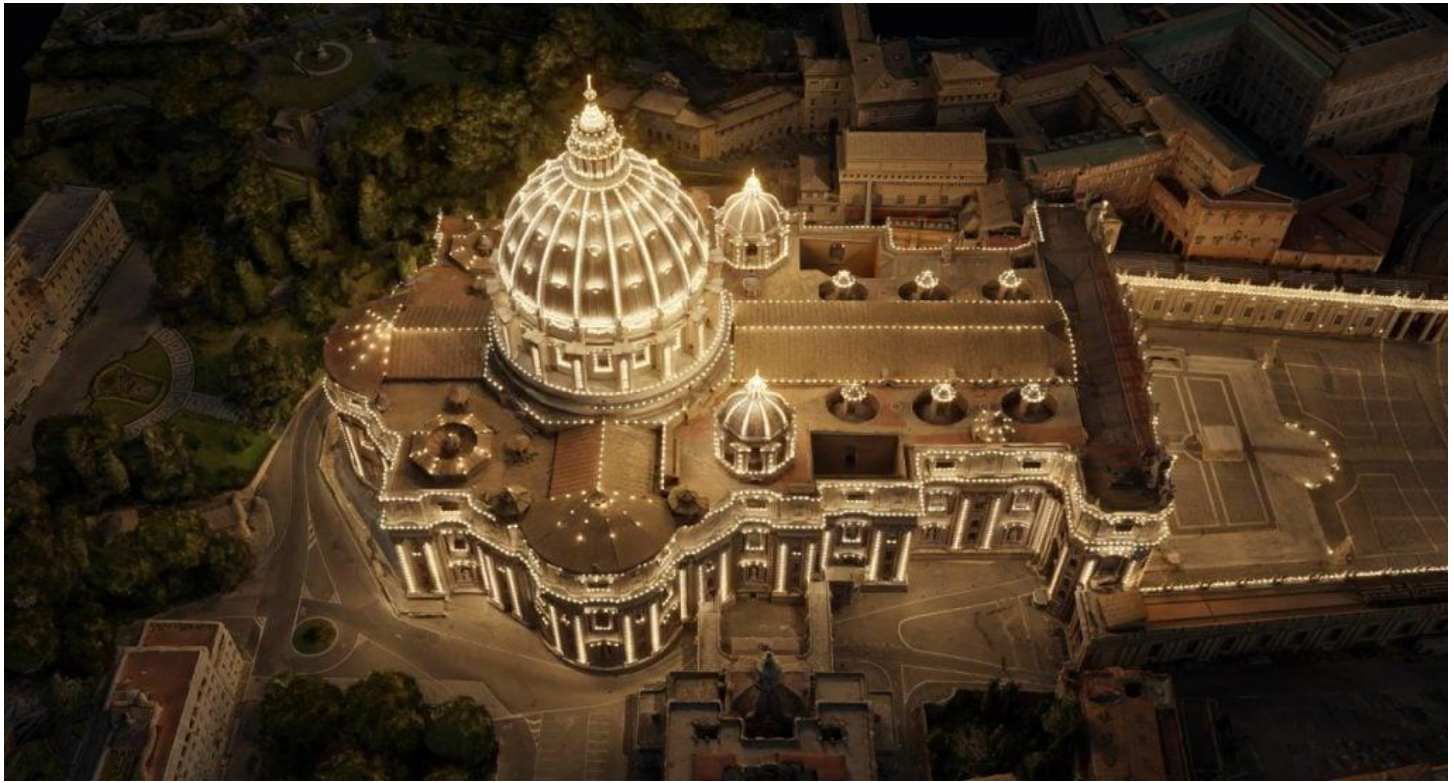
Gateway Lunar Space Station

Smart Bases tomorrow

[Digital Twins for Cislunar and Lunar Enterprise Integration Workshop #3]

Award to Semiconductor Research Corporation Manufacturing Consortium Corporation in North Carolina, $285 Million CHIPS Manufacturing USA Institute for Digital Twins. Total investment of over $1 billion, SMART USA (Semiconductor Manufacturing and Advanced Research with Twins USA). Focus on digital twin efforts to more rapidly develop, validate, and improve domestic semiconductor design, manufacturing, advanced packaging, assembly, and test processes.

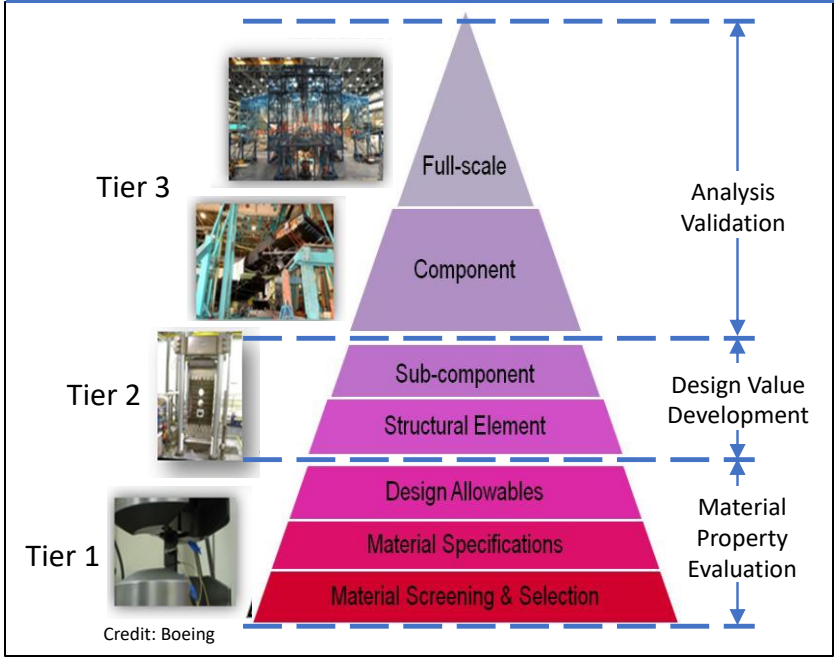
St. Peter’s Basilica Digital Twin (Microsoft)



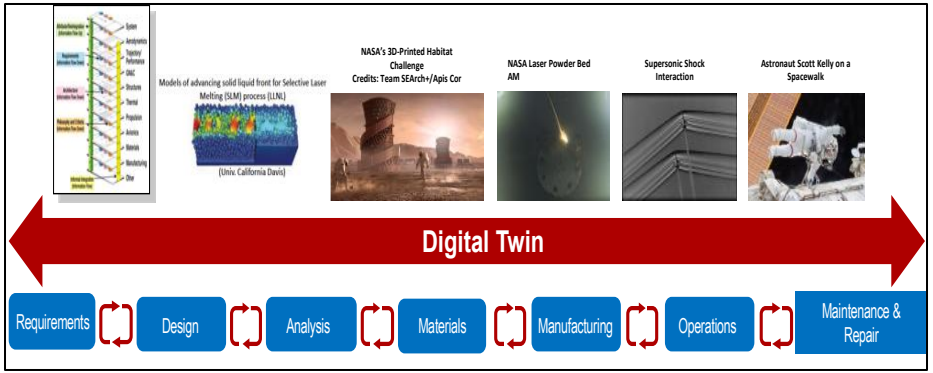
The 3D replica of St. Peter's Basilica. 400,000 images taken by drones and cameras. (Microsoft)
https://virtual.basilicasanpietro.va/en

A Little Less Conversation A Little More Action Please

Product Development, Testing and Certification Today

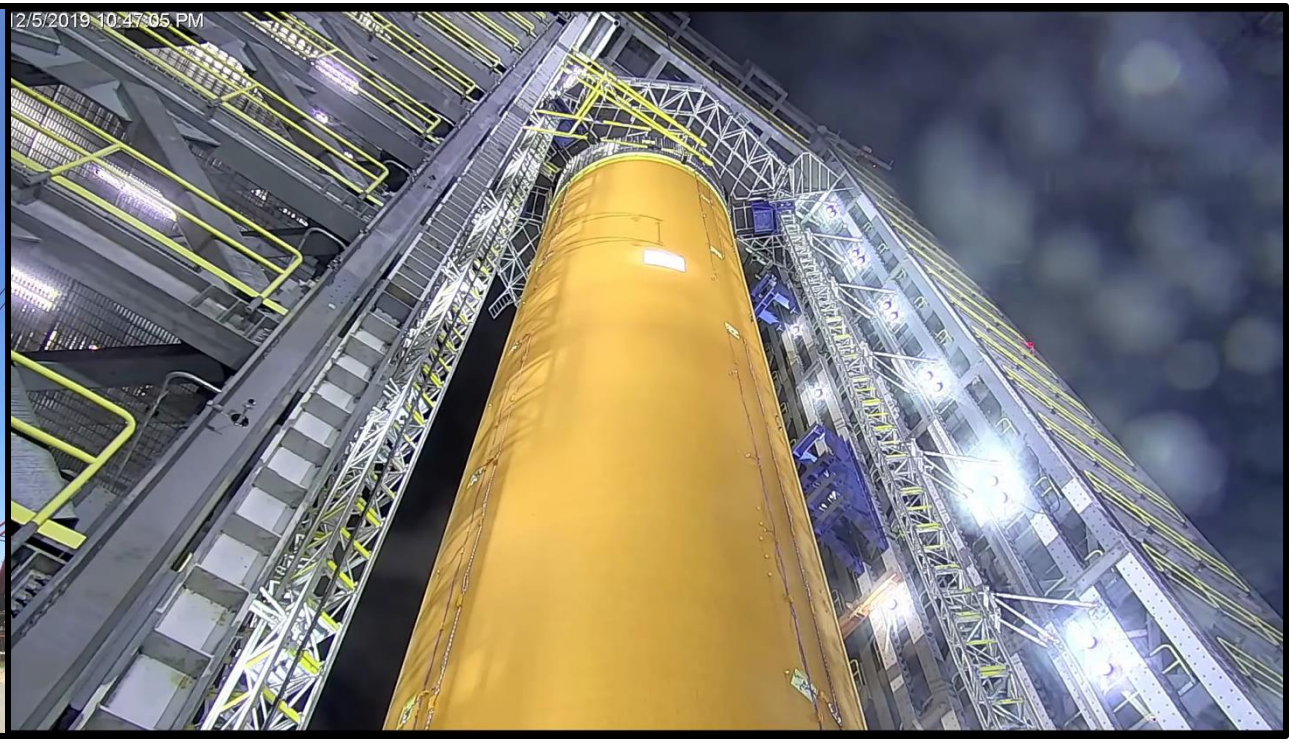


Credit: Boeing



"It takes too long and costs too much to certify aerospace structures"
Exhaustive testing done to support analysis

Testing and Certification Today



"One good test is worth a thousand expert opinions." Wernher Von Braun

QUESTIONS?

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