Modeling and Simulation for Space Missions at NASA

2022 SISO SIMposium

September 14, 2022

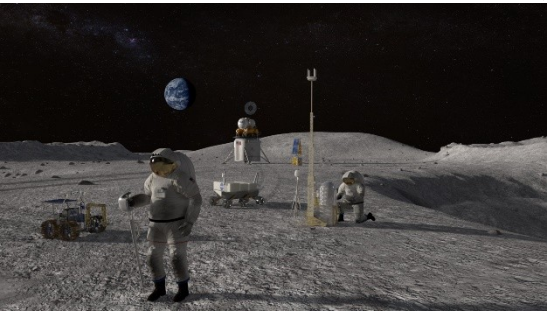
Presented by Michael Madden
Chief Engineer for Modeling and Simulation
NASA Langley Research Center

Content on Artemis Program created by Edwin “Zack” Crues, Johnson Space Center

Outline

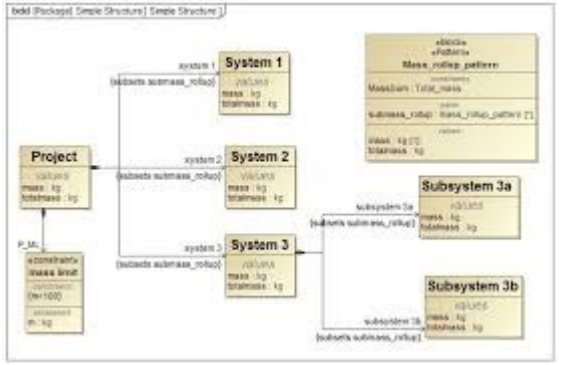
- How NASA Uses Modeling and Simulation
- ModSim and Apollo
- ModSim and Mars
- The Artemis Program
  - Overview and Program Elements
  - Integrated Simulation of Artemis Base Camp
  - Key Enablers: HLA and SpaceFOM
- Summary

How NASA Uses Modeling and Simulation



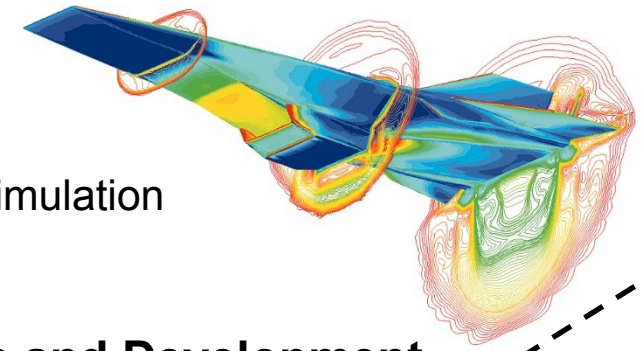
Mission/Systems Analysis

- System-scale simulations
- Mixture of parametric, algebraic, and reduced order physics models
- Monte-Carlo capable



- Logical modeling of system
  - Requirements
  - Architecture
  - Performance Measures
  - Verification & Validation

Model-Based Systems Engineering (MBSE)

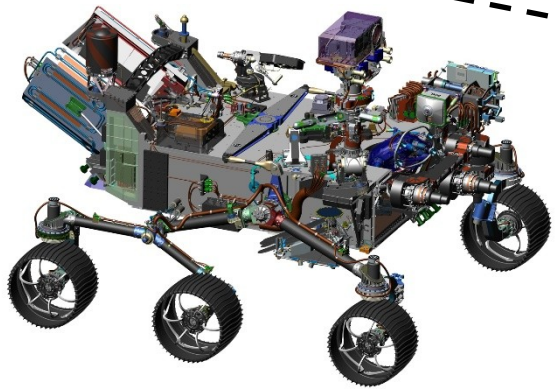


- Physics-based simulation
- Capability driven

Research and Development

Operations and Training

- Fusion of high-fidelity models with real systems
- live-virtual-constructive (LVC)
- Digital Twins



- Fusion of empirical, data-driven, and physics models
- Capacity driven
- Multi-discipline

Engineering of Systems

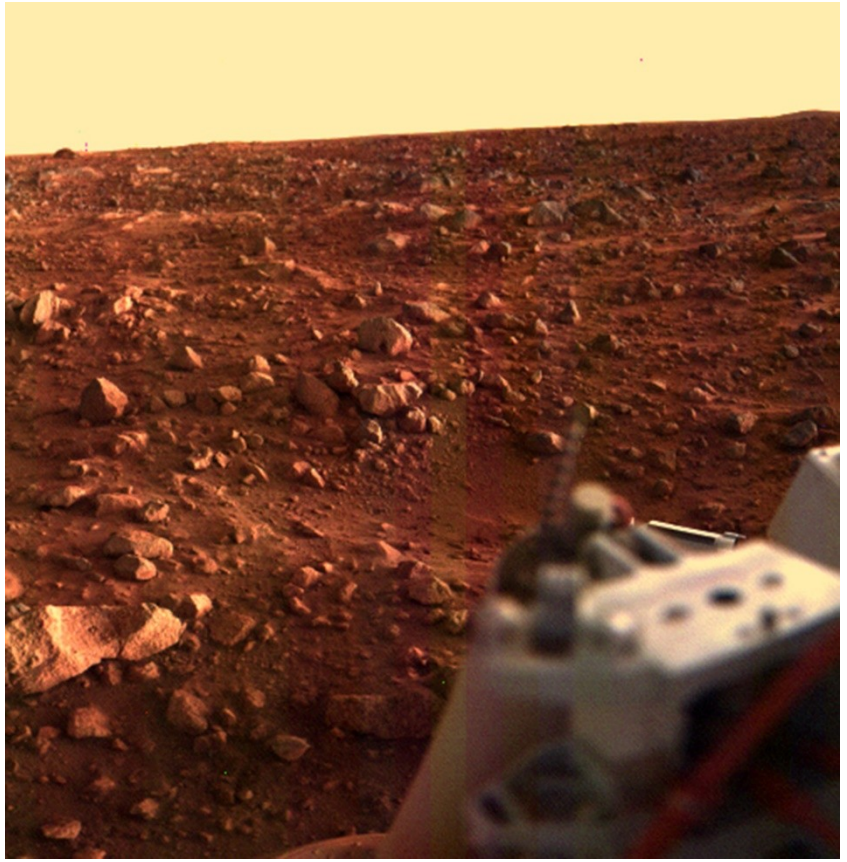
ModSim and Apollo

Neil Armstrong in the Lunar Module Simulator

- NASA built simulators to train every aspect of the Apollo mission
  - Mission training is essential to reduce failures due to crew mistakes and prepare the crew to respond quickly to any contingency
- As one of his duties, Neil Armstrong worked with engineers on both Gemini and Apollo to improve simulator fidelity
- *"…in the late '60s our computer simulations were really quite excellent. They were quite adequate to do most all the things that we were doing."*
  – Neil Armstrong

ModSim and Mars (1/2)

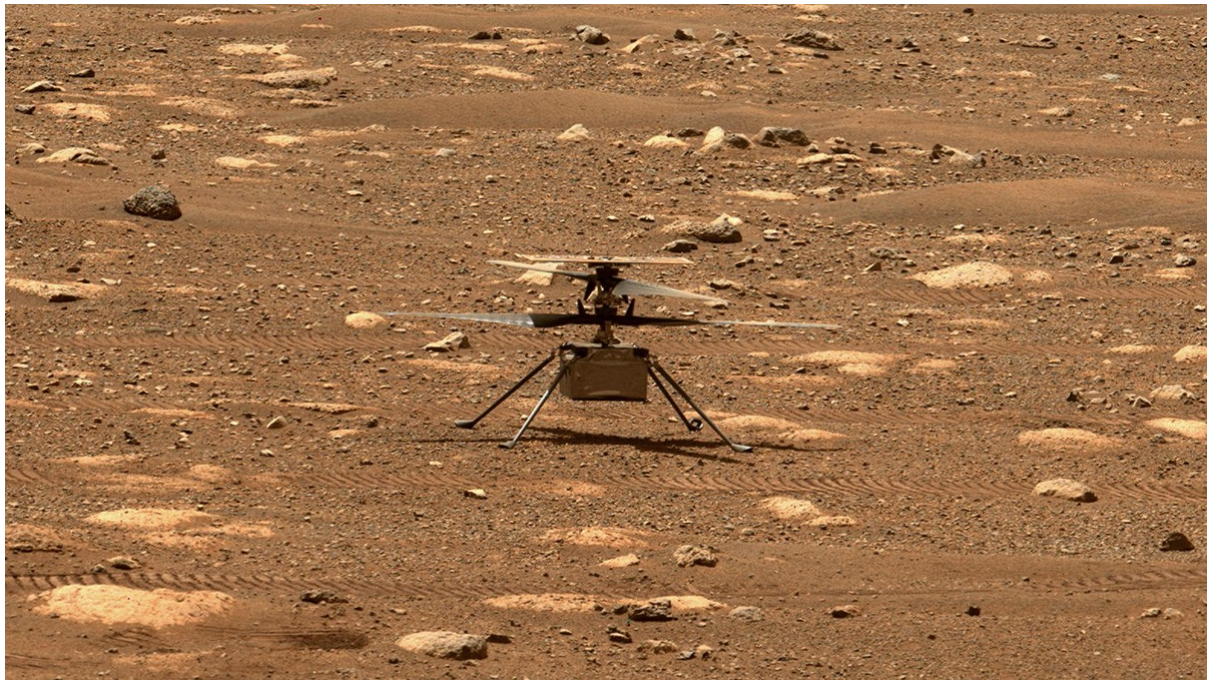
- July 20, 1976 – America became the first nation to successfully land on Mars with Viking 1
- No other nation would succeed for 45 years.
  - China became the second nation to land on Mars on May 14, 2021 with the Tianwen-1 spacecraft.
- Most missions fail during entry, descent, and landing (EDL)
- Engineers refer to Mars EDL as the “seven minutes of terror”
  - Because communication time from Mars is five or more minutes, any data sent during EDL won’t be received until the spacecraft has already landed.
- End-to-end testing of EDL can’t be done on Earth due to differences in atmosphere and gravity so NASA must simulate the end-to-end test.



Viking 1 image of Martian sunset

ModSim and Mars (2/2)

Ingenuity helicopter on Mars surface. Image taken by the Perseverance rover.

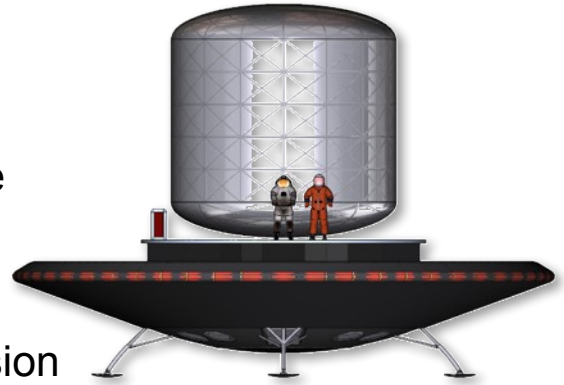


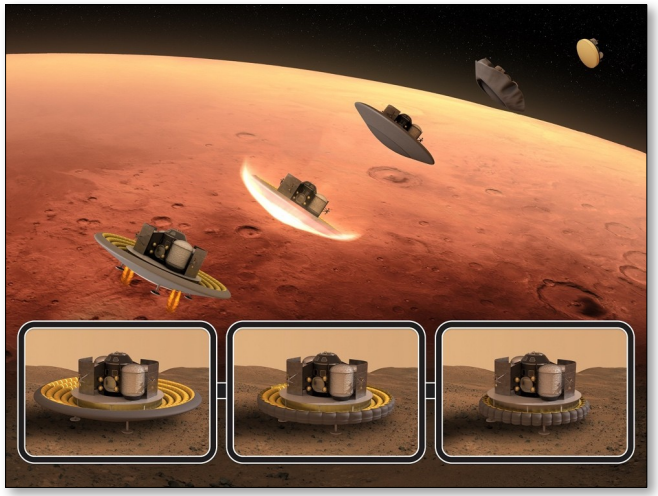
- April 19, 2021, NASA's Ingenuity helicopter performs the first flight on another planet, Mars.
- NASA relied on modeling and simulation to design the rotors and the flight control algorithms.

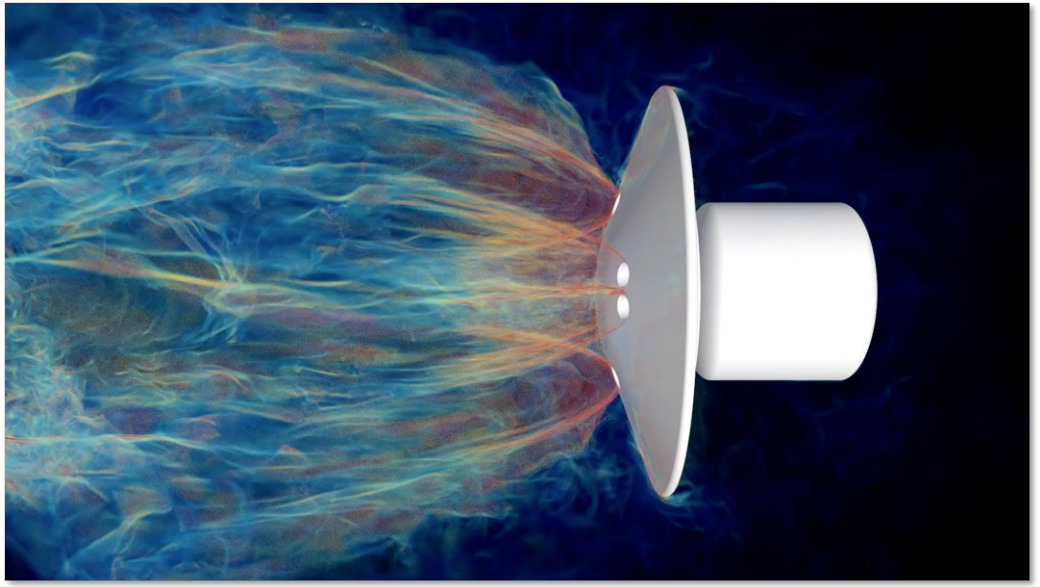
ModSim and Mars: Next Generation Capability

Human-scale Mars landers will require entirely new approaches to safely reach the planet surface

- Previous Mars landers have been a few meters in size, delivering approximately 1 ton of mass to the Martian surface
- Human missions will require landers up to 20 meters in size, capable of landing a 20-ton payload
- Decelerating such a vehicle will require powerful retropropulsion systems, for which we currently have little experience
- NASA is using its FUN3D fluid dynamics solver on Summit to simulate highly complex aero-propulsive phenomena
  - Summit is currently the world's most powerful supercomputer using a hybrid architecture of Intel Central Processing Units (CPU) and Nvidia Graphics Processing Units (GPU)
- Conventional computing requires several months to obtain a single result; Summit is able to provide several solutions in a single workweek



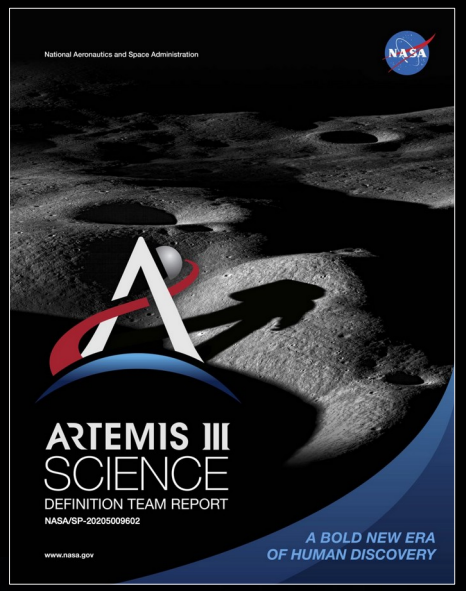




Slide courtesy of Eric Nielsen, NASA Langley Research Center

The Artemis Program

- Key Objectives: Returning to the Moon to Stay
  - Setting Humanity on a Sustainable Course to the Moon
  - Landing Human on the Moon in 2024
  - Extending Lunar Missions and Preparing for Mars
- Key Artemis Documents:
  - The Plan: https://www.nasa.gov/sites/default/files/atoms/files/artemis_plan-20200921.pdf
  - The Science: https://www.nasa.gov/sites/default/files/atoms/files/artemis-iii-science-definition-report-12042020c.pdf
  - The Accords: https://www.nasa.gov/specials/artemis-accords/index.html



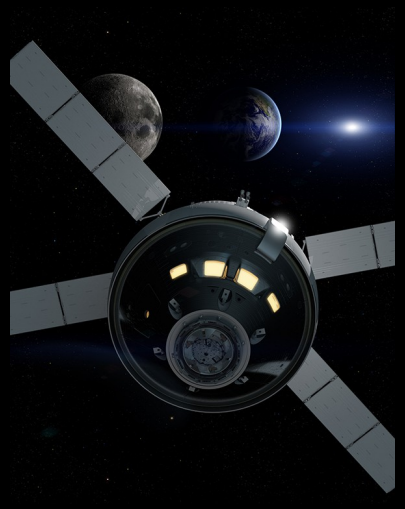
The Artemis Program: Elements

Ground Systems

The structures on the ground necessary to support launch and recovery of returning astronauts.

Space Launch System

The only rocket that can send Orion, astronauts, and cargo to the Moon on a single mission. Upon launch, the SLS will be the most powerful rocket in the world.



Orion Spacecraft

The NASA spacecraft that will carry astronauts from Earth to lunar orbit and back.

Gateway

The spaceship in lunar orbit where astronauts will transfer between Orion and the lander on regular Artemis missions. Gateway will remain in orbit for more than a decade, providing a place to live and work, and supporting long-term science and human exploration on and around the Moon.

Human Landing System

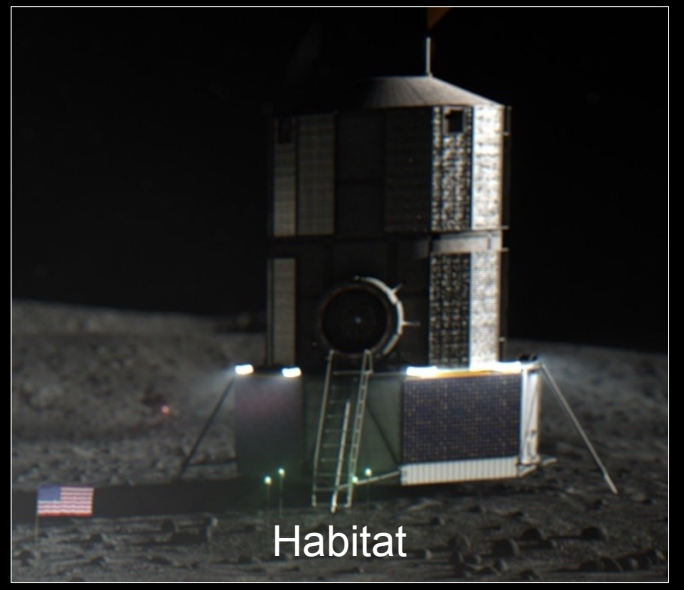
Built by American companies, human landing systems are the final mode of transportation that will take astronauts from lunar orbit to the surface and back to orbit.

Artemis Base Camp

To give astronauts a place to live and work on the moon, the Artemis Base Camp concept includes a modern lunar cabin, a rover, and a mobile home.

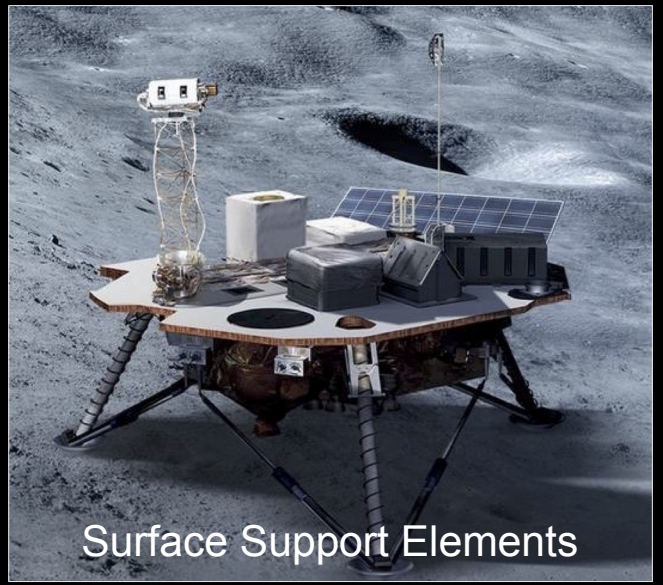
Artemis Base Camp: Elements

- A place for Astronauts to live on the Moon
  - A modern lunar cabin (Habitat)
  - A way to get around (Unpressurized Rover)
  - A mobile home (Pressurized Rover)
  - Other support elements (Power, Water, Comm, etc.)


Habitat

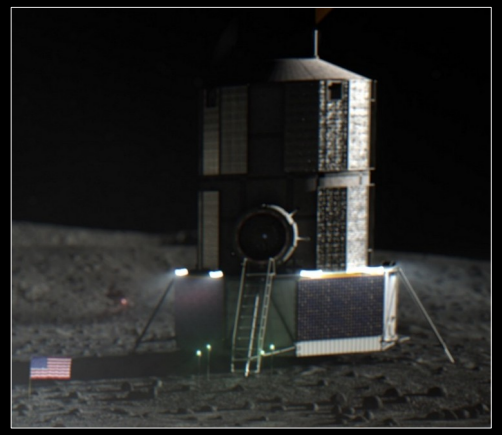
Unpressurized Rover

Pressurized Rover


Surface Support Elements

Simulation of Artemis Base Camp (ABC)

- The Artemis program has an evolving complex multi-element architecture.
- The Artemis program needs the ability to model the integrated performance of this complex system of systems.
- The elements will be developed and provided by a variety of international and commercial partners.
- These elements will need to interoperate and so will the element simulations.
- Element providers are likely to have their own, often proprietary, element simulations.



Integrated Mission Simulations

- Supports Systems Engineering and Integration (SE&I)
  - Captures coupled effects throughout the system lifecycle
  - Provides insight into design choices
  - Explores handling qualities and human-machine interaction
- Supports hardware and software testing in test-as-you-fly (or operate) scenarios
- Supports training and operations

Simulation ABC: Construction

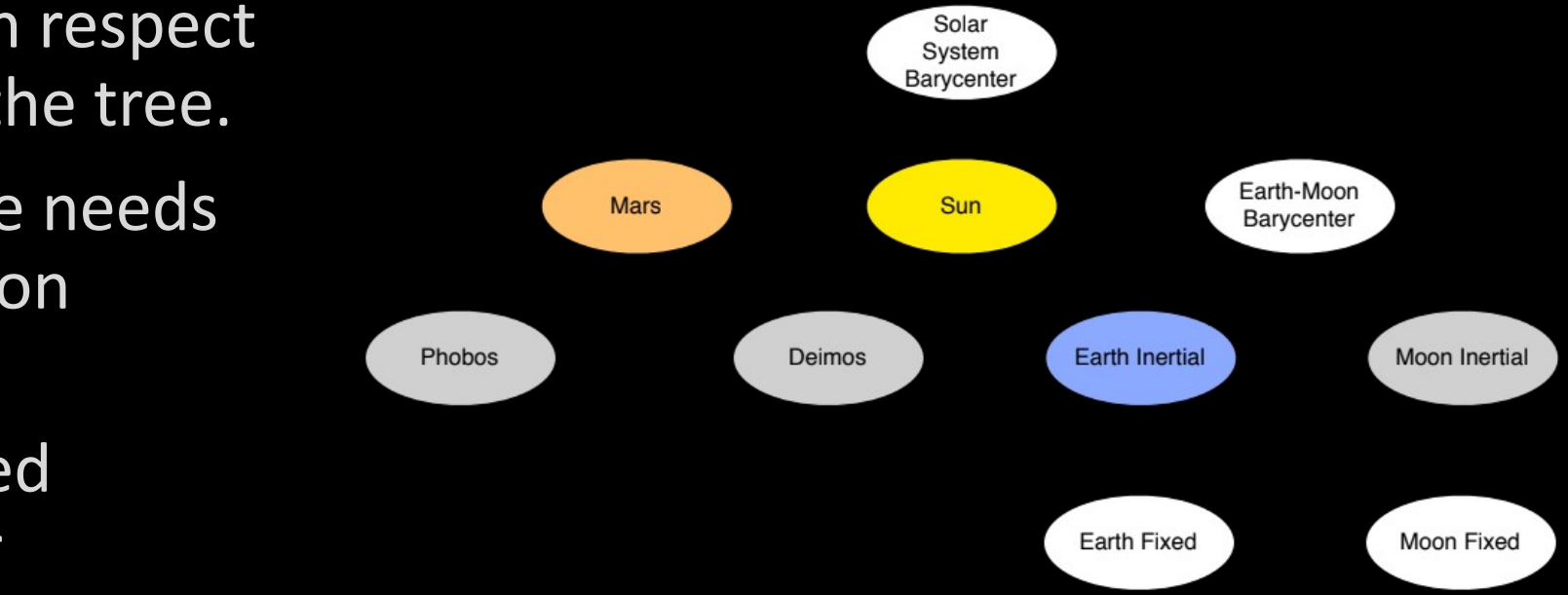
- The NASA Exploration Systems Simulations (NExSyS) Team is developing an integrated simulation of the Artemis Base Camp
- Current focus on resource flow and integrated architecture performance
- Initially using NASA simulations but will transition to partner simulations as available
- Using HLA and SpaceFOM as the simulation interoperability standards
  - IEEE 1516-2010 - High Level Architecture (HLA)
  - SISO-STD-018-2020 - Space Reference Federation Object Model (SpaceFOM)

SpaceFOM: Extension to HLA

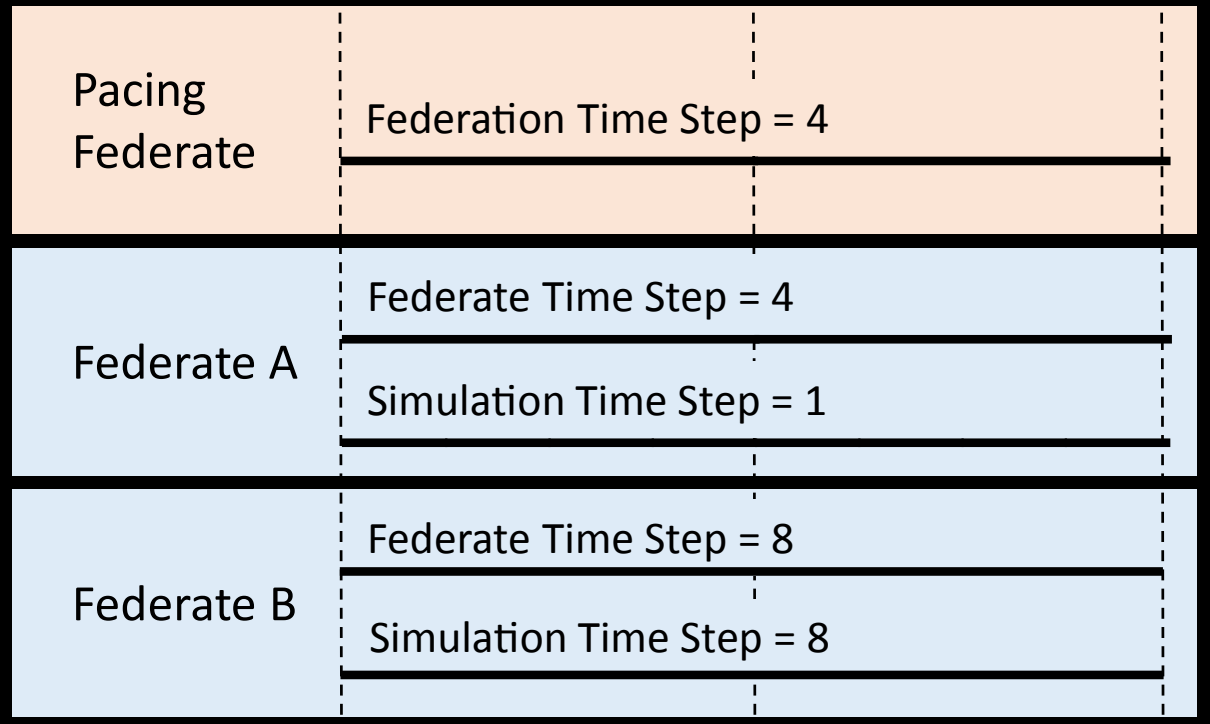
- HLA relies on a Federation Object Model (FOM) to define interoperable information exchange among simulation participants.
- Existing FOMs did not provide adequate support space systems simulations.
- The SpaceFOM provides additional specifications for space-based scenarios:
  - Roles and responsibilities;
  - Common data types;
  - Timelines and time standards;
  - Time-stepped focused time management;
  - Reference frames and references frame trees;
  - Reference frame naming convention;
  - Common base for space entities: entities and interfaces;
  - Well defined execution control definition;
  - Rules for assessing SpaceFOM compliance;
  - Base set of FOM modules.

SpaceFOM: Reference Frames and Trees

- Defines a reference frame tree.
- Supports the computation of a state in one frame with respect to any other frame in the tree.
- Is defined based on the needs of the specific federation execution.
- Proposes a standardized naming convention for reference frames.

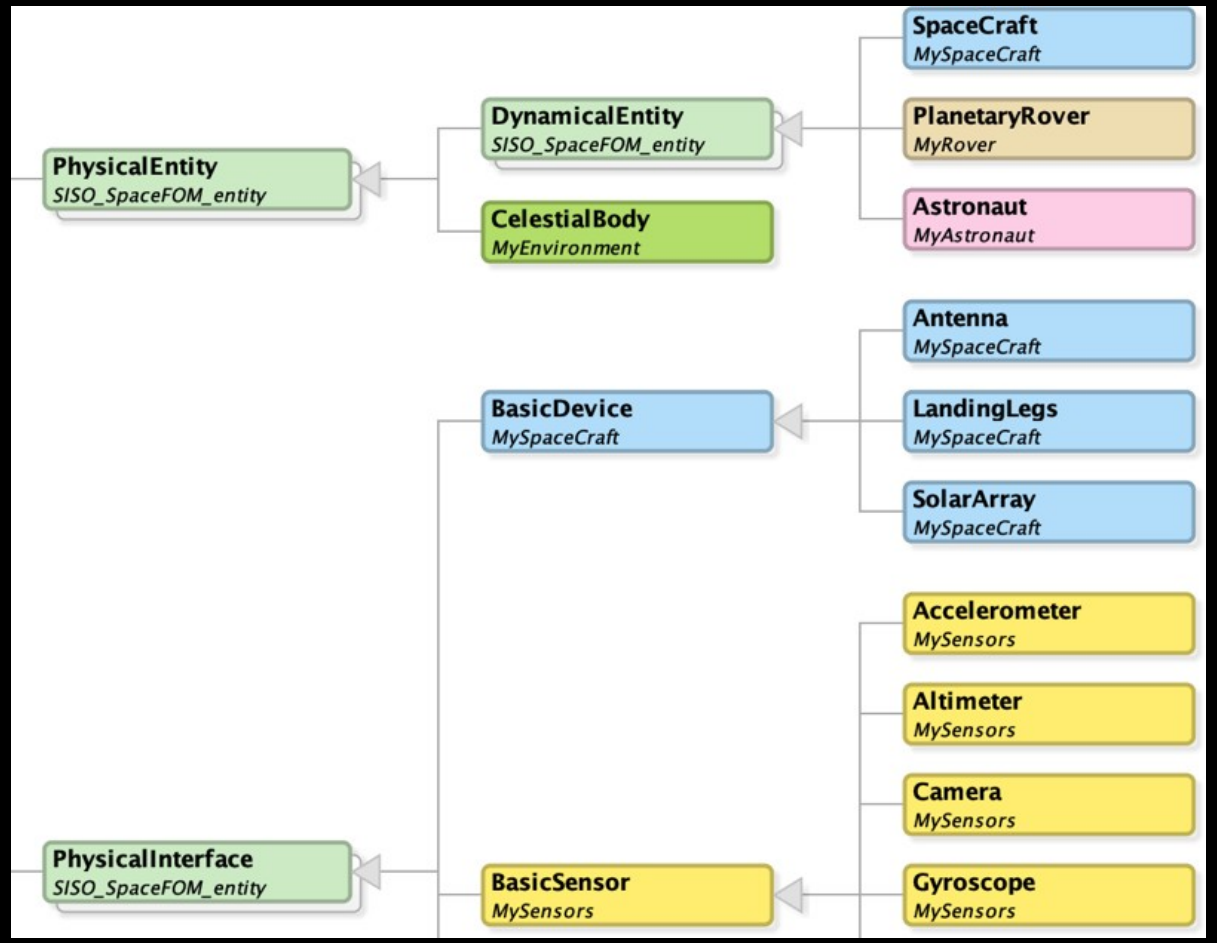


SpaceFOM: Time Standard and Timelines



- Defines Terrestrial Time (TT) as the time basis across the federation execution.
  - Defines conversions between other time standards.
- Defines 6 related timelines to support execution control:
  - Physical Time
  - Computer Clock Time
  - Simulation Elapsed Time
  - Simulation Scenario Time
  - HLA Logical Time
  - Federation Scenario Time
- Supports different simulation time steps.
- Support non-realtime and realtime execution.
- Support Central Timing Equipment (CTE).

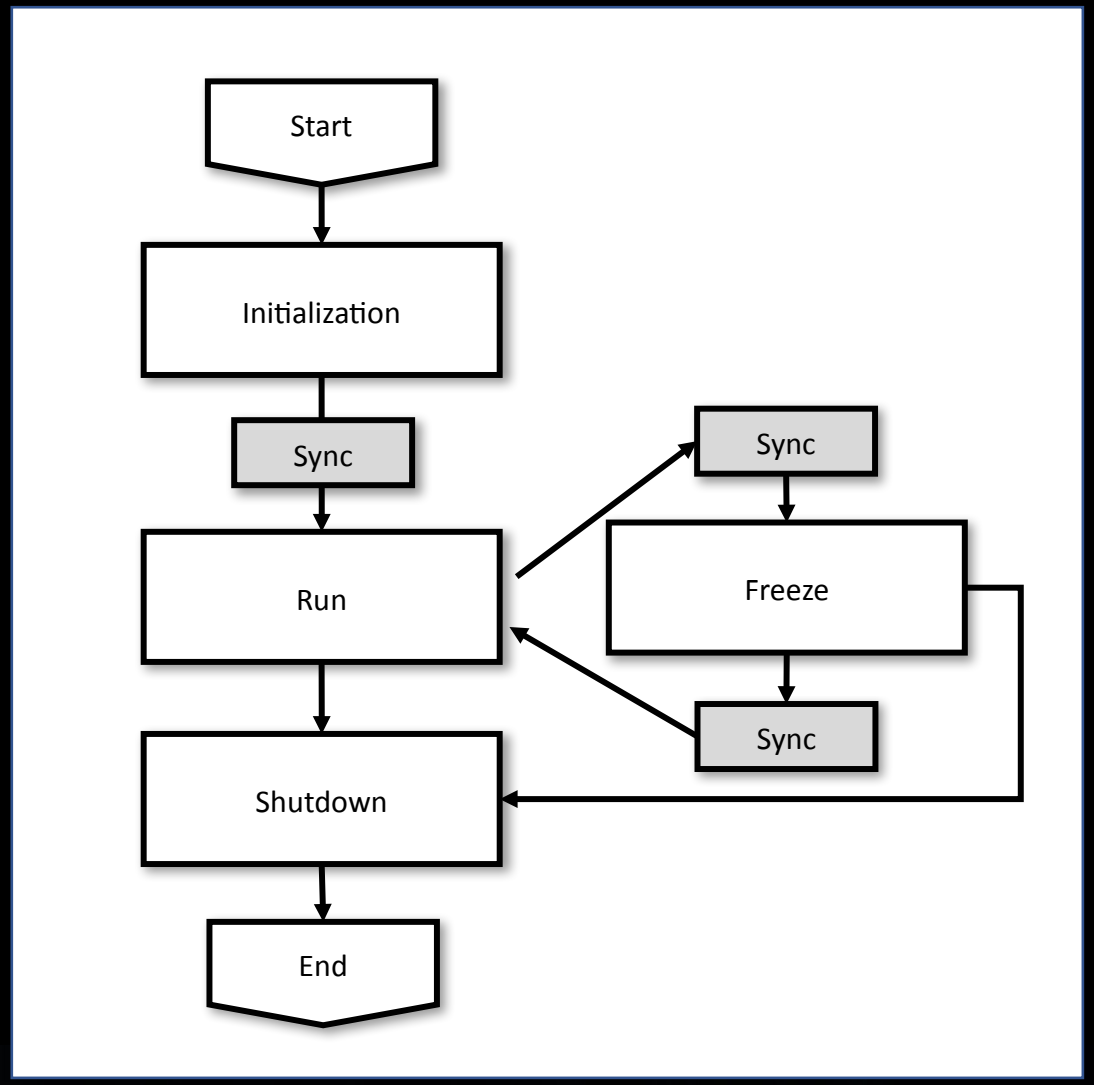
SpaceFOM: Objects and Extension



- Builds off of the HLA base objects.
- Provides a small set of common object types tailored to space system needs:
  - Physical Entity,
  - Dynamical Entity,
  - Physical Interface.
- Other space systems can extend from these.
- Provides a set of common unit definitions for object attributes.

SpaceFOM: Rules, Roles, and Execution Control

- Rules:
  - Specifies 103 rules for compliance
  - Additional guidelines
- Roles:
  - Master Federate
  - Pacing Federate
  - Root Reference Frame Publisher
- Execution Control
  - A well-defined executive cycle
  - Gated to reduce potential deadlocks
  - Supports multi-phase initialization
  - Supports controlled mode sequencing



In Summary

- Modeling and Simulation (ModSim) have been critical technologies for NASA space missions include Apollo, Mars Missions, and Artemis.
- NASA continues to invest in ModSim capabilities to support space missions, especially Moon2Mars.
  - For the engineering of human-scale Mars Landers, NASA is rewriting physics simulations for graphical processing units in next-generation, high-performance computers to predict more complex phenomena with shorter runtimes.
  - For Artemis, NASA is developing a new generation of integrated simulations that rely on distributed simulation standards including HLA and SpaceFOM.
- We are focused on realizing a new age of human space exploration!

Questions?

NASA Movie - Why The Moon?: https://www.youtube.com/watch?v=bmC-FwibsZg

NASA Movie – We Are Focused: https://www.youtube.com/watch?v=OsIhTw0CK8U

Michael Madden – Chief Engineer for Modeling and Simulation

- Arrived at NASA Langley Research Center in 1993
  - Software Engineer, Unisys Corp, flight simulation facility (1993-1999)
  - In 1999, hired into the Simulation Development and Analysis Branch (SDAB)
    - Develops and operates the flight simulation facility
  - 2008 to 2018 - Chief Scientist for SDAB.
  - 2018 to Present - Chief Engineer for Modeling and Simulation
- Education
  - B.S. (1990) and M.S. (1997) in Aerospace Engineering from Virginia Tech
- 41 Technical Publications on Modeling and Simulation including
  - NASA's standard check cases for vehicle simulations
  - Professional society standards for model exchange (AIAA/ANSI S-119), distributed simulation of space missions (SISO-STD-018-00-2020), and simulation use to certify aircraft (AIAA R-154)
- Current Roles
  - Member, NASA Software Architecture Review Board
  - Member, Agency Integrated Model-Based Everything Team
  - Member, Engineering Application Program Management Board
  - Member, AIAA Modeling and Simulation Technical Committee
  - Member, AIAA Digital Engineering Integration Committee

<u>Technical background/passion</u>

- Vehicle and environment modeling
- Live, virtual, and constructive (LVC) simulation
- Software engineering for real-time systems
- Model-based methods
- Advancing fidelity and validation of modeling and simulation
- Collaboration through digital engineering

Additional SpaceFOM Information

B. Möller, E. Z. Crues, D. E. Dexter, A. Garro, A. Skuratovskiy, A. Vankov. **A First Look at the Upcoming SISO Space Reference FOM**. Proceedings of the SISO 2016 Simulation Innovation Workshop (**SIW 2016**), Orlando, Florida, USA, September 11-16, 2016.

B. Möller, A. Garro, A. Falcone, E. Z. Crues, D. E. Dexter. **Promoting a-priori interoperability of HLA-based Simulations in the Space domain: the SISO Space Reference FOM initiative**. Proceedings of the 20th IEEE/ACM International Symposium on Distributed Simulation and Real Time Applications (**ACM/IEEE DS-RT 2016**), London, UK, September 21-23, 2016, ISBN: 978-150903504-5.

B. Möller, E. Z. Crues, D. E. Dexter, A. Garro, M. Madden, A. Skuratovskiy. **Design and Principles Enabling the Space Reference FOM**. Proceedings of the SISO 2017 Simulation Innovation Workshop (**SIW 2017**), Orlando, Florida, USA, September 10-15, 2017.

B. Möller, A. Garro, A. Falcone, E. Z. Crues, D. E. Dexter. **On the Execution Control of HLA Federations using the SISO Space Reference FOM**. Proceedings of the 21st IEEE/ACM International Symposium on Distributed Simulation and Real Time Applications (ACM/IEEE DS-RT 2017), Rome, Italy, October 18-20, 2017.

B. Möller, A. Falcone, A. Garro, and E. Z. Crues. **Experiences in using the SISO Space Reference FOM standard**. Proceedings of the 2019 Summer Simulation Conference, SummerSim 2019, Berlin, Germany, July 22-24, 2019, pages 1–12. The Society for Modeling and Simulation International Inc., 2019. url: https://dl.acm.org/citation.cfm?id=3374187.

B. Möller, A. Rydell, E. Z. Crues, D. Dexter, A. Falcone, and A. Garro. **SISO Space Reference FOM - Tools and Testing**. Proceedings of the 2020 Winter Simulation Innovation Workshop, SIW 2020, Orlando, FL, USA, February 10-14, 2020. Simulation Interoperability Standards Organization, 2020.

E. Z. Crues, D. Dexter, A. Falcone, A. Garro, and B. Möller. **SpaceFOM - A Robust Standard for Enabling A-Priori Interoperability of HLA-Based Space Systems Simulations**. Journal of Simulation, 2021. issn: 1747-7778. doi: 10.1080/17477778.2021.1945962. url: https://doi.org/10.1080/17477778.2021.1945962.