Evolutionary Digital Twins for Design and Manufacturing in Space

A vision by:

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Outline

This presentation will explore:

- The Challenges of Space Exploration
- What's a Digital Twin (DT)?
- Evolutionary Digital Twins (EDTs): The New Paradigm
- What Makes EDTs Transformative?
- Integration of Advanced Technologies
- Transformative Impact on Manufacturing
- From Vision To Reality: A Roadmap

The Challenges of Space Exploration

Space exploration presents unique challenges that require innovative manufacturing solutions.

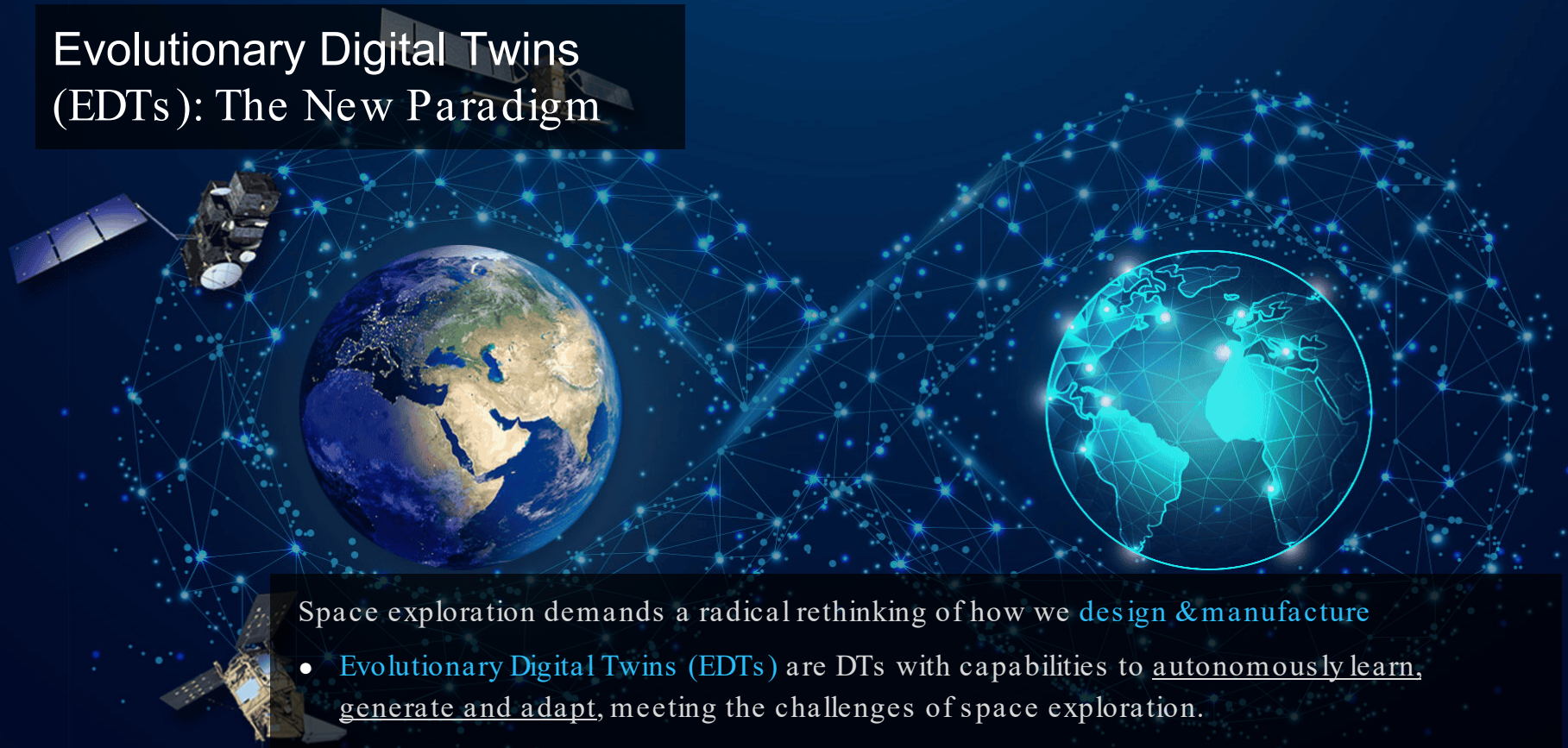
- Extreme Environments: Spacecraft, systems and infrastructures must endure harsh conditions, including radiation, vacuum, and extreme temperatures.
- Limited or Insufficient Knowledge of Resources: There is a need to adapt to locally available materials and minimize reliance on Earth-based supplies.
- Long-Duration Missions: Adaptability is essential for missions that last months or years, where traditional manufacturing methods may fall short.

These challenges highlight the critical need for Evolutive Digital Twins (EDTs)

What's a Digital Twin?

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.

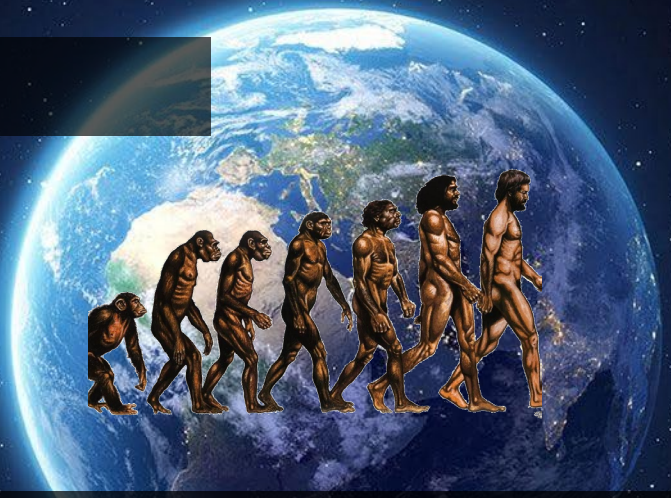
Evolutionary Digital Twins (EDTs): The New Paradigm



Space exploration demands a radical rethinking of how we design &manufacture

- Evolutionary Digital Twins (EDTs) are DTs with capabilities to autonomously learn, generate and adapt, meeting the challenges of space exploration.
- Goal: Autonomous (re)design and (re)manufacturing for Moon, Mars, and beyond.

What Makes EDTs Transformative?

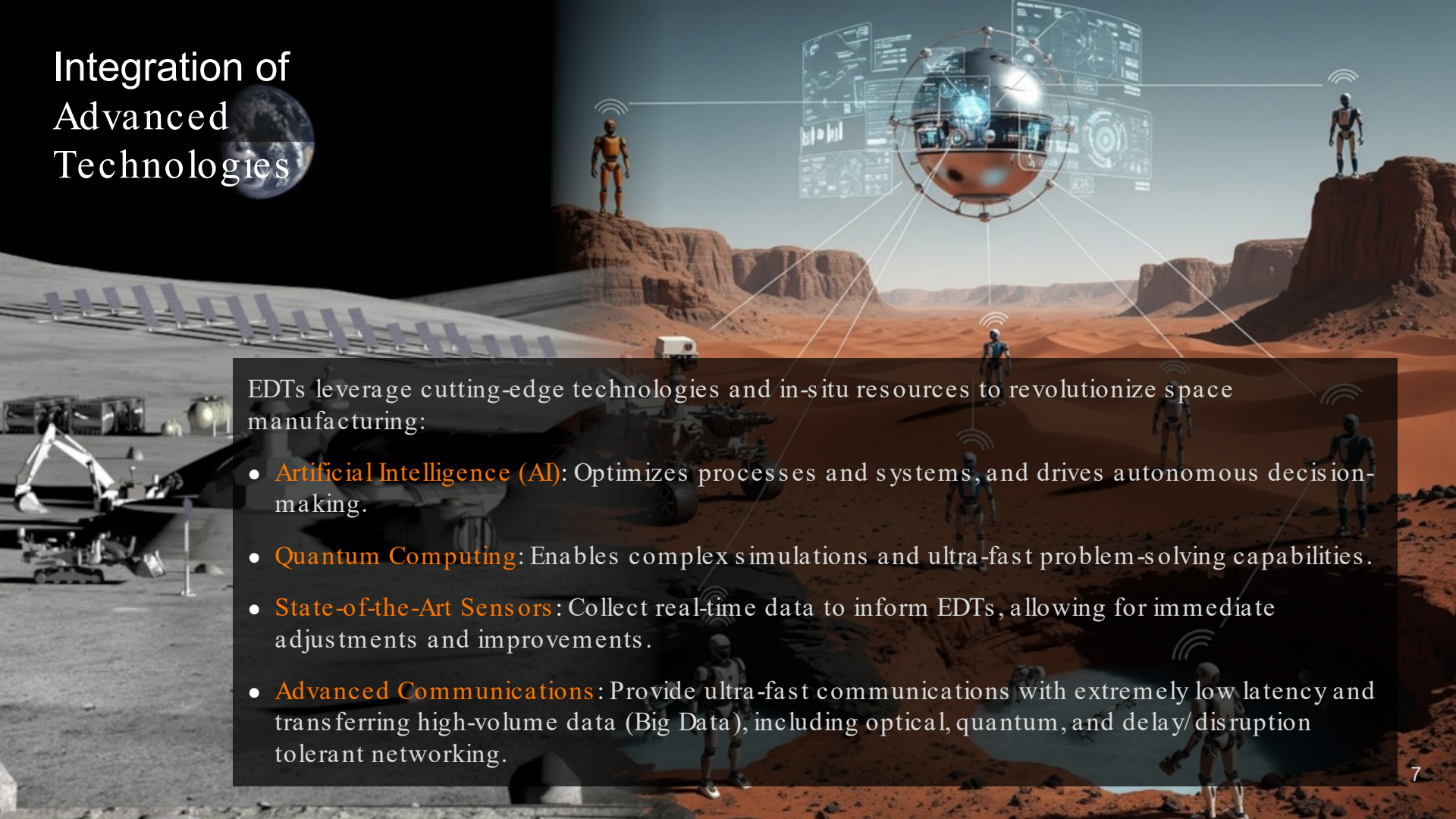


EDTs go beyond traditional DTs, by integrating an S-LGA approach:

- Self-Learning: EDTs can continuously acquire knowledge from in-situ resource utilization (ISRU) systems, real-time data, and mission performance.
- Self-Generative: EDTs can autonomously create new designs and manufacturing solutions.
- Self-Adaptive: EDTs enable real-time adaptation to resources, harsh, and dynamic space environments, ensuring optimal performance.

EDTs support self-repair, reconfiguration, and zero-waste production, crucial for space mission exploration.

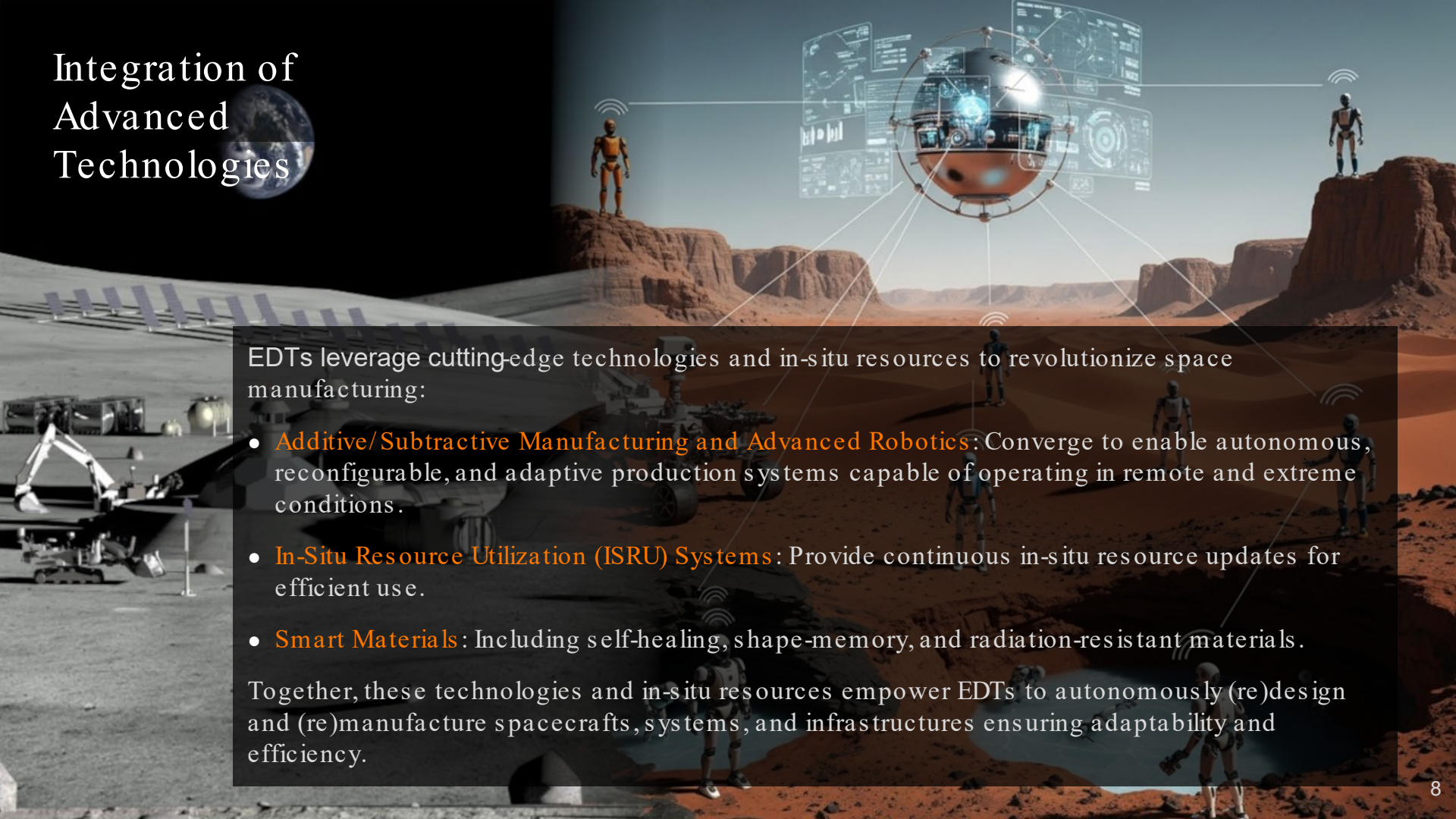
Integration of Advanced Technologies



EDTs leverage cutting-edge technologies and in-situ resources to revolutionize space manufacturing:

- Artificial Intelligence (AI): Optimizes processes and systems, and drives autonomous decision-making.
- Quantum Computing: Enables complex simulations and ultra-fast problem-solving capabilities.
- State-of-the-Art Sensors: Collect real-time data to inform EDTs, allowing for immediate adjustments and improvements.
- Advanced Communications: Provide ultra-fast communications with extremely low latency and transferring high-volume data (Big Data), including optical, quantum, and delay/disruption tolerant networking.

Integration of Advanced Technologies



EDTs leverage cutting-edge technologies and in-situ resources to revolutionize space manufacturing:

- Additive/Subtractive Manufacturing and Advanced Robotics: Converge to enable autonomous, reconfigurable, and adaptive production systems capable of operating in remote and extreme conditions.
- In-Situ Resource Utilization (ISRU) Systems: Provide continuous in-situ resource updates for efficient use.
- Smart Materials: Including self-healing, shape-memory, and radiation-resistant materials.

Together, these technologies and in-situ resources empower EDTs to autonomously (re)design and (re)manufacture spacecrafts, systems, and infrastructures ensuring adaptability and efficiency.

Transformative Impact on Manufacturing

EDTs are set to revolutionize the manufacturing landscape for space exploration:

- Sustainability: By optimizing resources and minimizing waste, EDTs contribute to more sustainable practices in space manufacturing.
- Efficiency: the ability to autonomously redesign and repair systems reduces downtime and enhances mission capabilities.

EDTs redefine manufacturing as intelligent, autonomous, and adaptive.

Transformative Impact on Manufacturing

- EDTs enables:
  - Autonomous generation of efficient designs adapted to extreme environments like the Moon or Mars.
  - Autonomous manufacturing and repair equipment in space, offering significant cost savings by minimizing launch mass from Earth, thus contributing to "Factories-In-Space" (*Ajay Malshe, 2018 Blue Sky Competition*)
  - Remote monitoring and teleoperation of in-space manufacturing systems from Earth, utilizing XR technologies and advanced spatial 3D sensors (scanners).
- EDTs can simulate, predict, optimize, monitor, and control—reducing risks, lowering costs, and making space exploration more effective.

Transformative Impact on Manufacturing

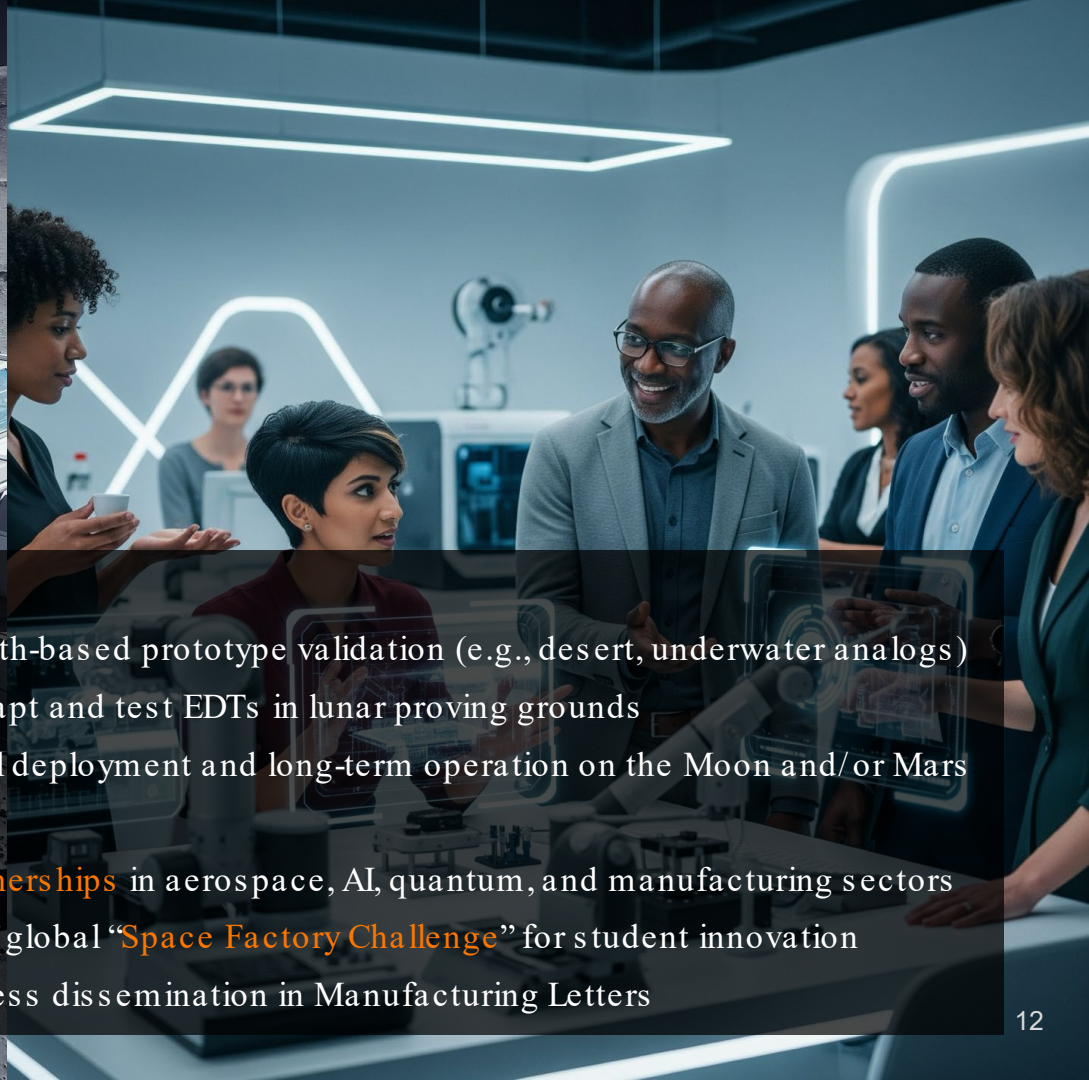
For Space Exploration:

- Critical for NASA's Artemis program.
- Enables SpaceX's Mars goals.
- Accelerates international deep-space missions.

For Earth:

- Sparks a manufacturing renaissance.
- Promises self-adaptive and sustainable production systems.
- Drives economic growth and delivers societal benefits.

From Vision to Reality: A Roadmap



Phases:

- Phase 1: Earth-based prototype validation (e.g., desert, underwater analogs)
- Phase 2: Adapt and test EDTs in lunar proving grounds
- Phase 3: Full deployment and long-term operation on the Moon and/or Mars

Call to action:

- Seek partnerships in aerospace, AI, quantum, and manufacturing sectors
- Launch of global "Space Factory Challenge" for student innovation
- Open-access dissemination in Manufacturing Letters

Summary

- Space exploration necessitates innovative manufacturing solutions due to extreme environments, limited resource knowledge, and the demands of long-duration missions.
- Evolutionary Digital Twins (EDTs) are a new paradigm: self-learning, self-generative and self-adaptive virtual systems capable of autonomous (re)design and (re)manufacturing for deep-space missions.
- EDTs integrate cutting-edge technologies like AI, quantum computing, state-of-the-art sensors, advanced communications, and robotics with in-situ resource utilization (ISRU) and smart materials.
- This approach revolutionizes manufacturing by enabling cost savings through in-space fabrication, while reducing risks and making space exploration more effective.
- EDTs are critical for programs like NASA's Artemis and SpaceX's Mars goals, simultaneously sparking a manufacturing renaissance and driving economic growth and societal benefits on Earth.

Acknowledgements

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NSF Future of Manufacturing Program

Q&A

"Exploration is in our nature. We began as wanderers, and we are wanderers still."

Carl Sagan, Cosmos