Human-Centered Autonomous Resilient Space Habitats

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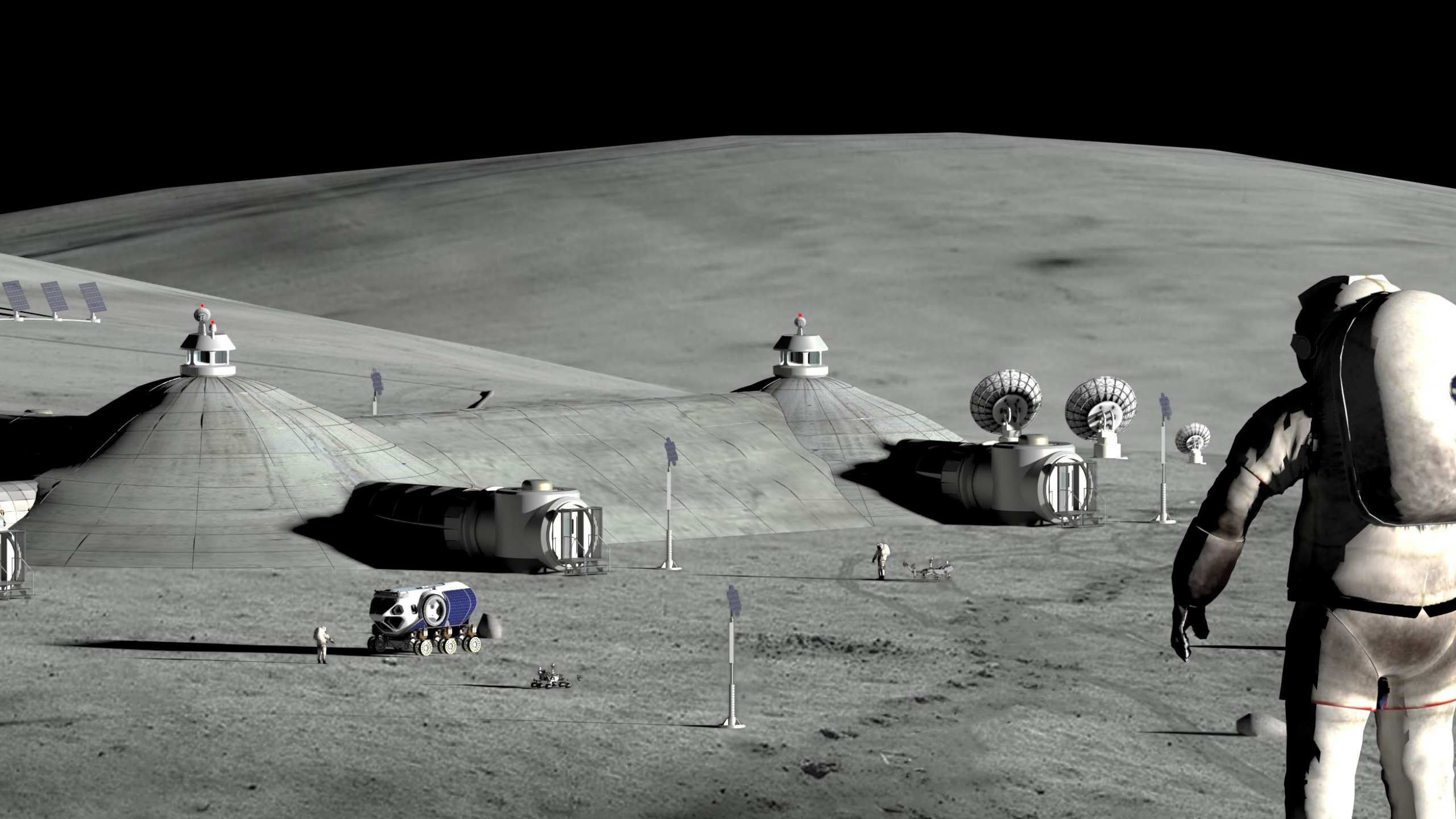
Don and Patricia Coates Professor of Innovation in

Mechanical Engineering

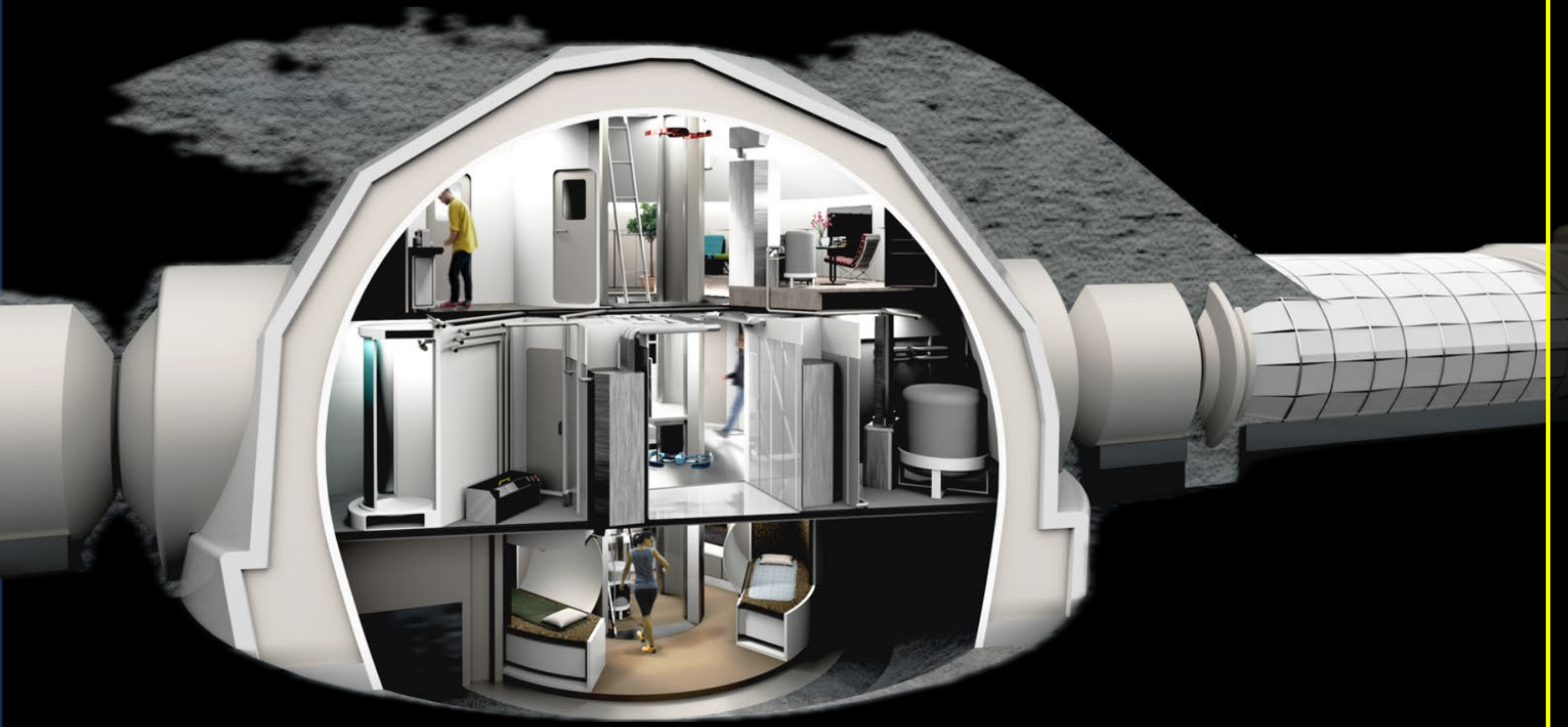
Professor of Civil Engineering

Purdue University

Supported under NASA grant 80NSSC19K1076



Hazards



- Vacuum
- Micrometeorites
- Dust
- Low Gravity
- Radiation
- Thermal extremes
- Long nights
- Moonquakes
- Fire
- Biohazards

Challenges

Disruptions are inevitable

Cascading consequences

Limited foresight

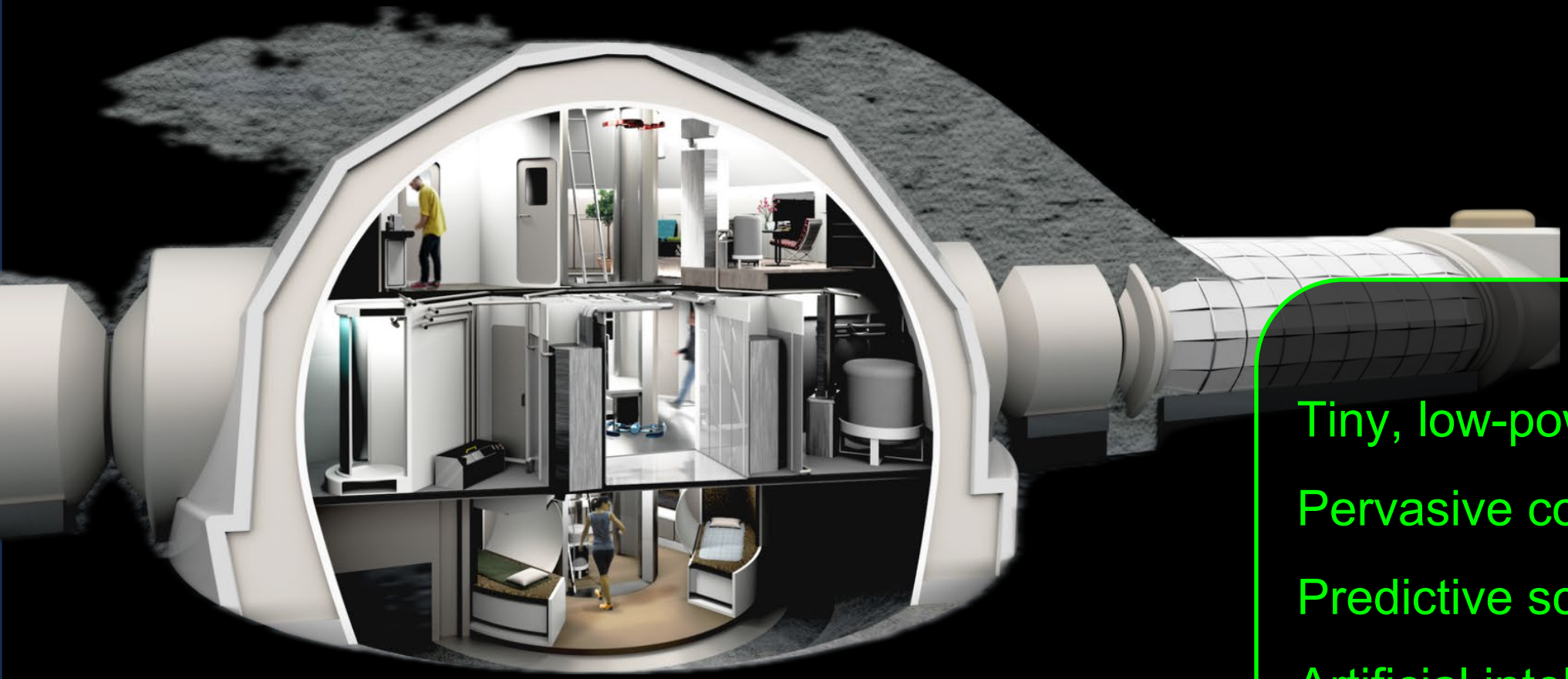
Constrained resources

Degradation, repairs

Uncrewed periods

Communication delays & blackouts

Bandwidth limitations



Opportunities

Tiny, low-power sensors

Pervasive computing

Predictive science

Artificial intelligence

Resilient ExtraTerrestrial Habitats Institute

Mission: To facilitate the realization of resilient and autonomous habitats

Resilience Thrust: Architecture

- Choose the right design features and tools to be resilient

***Awareness Thrust*: Detection+Diagnosis+Decisions**

- Detect damage and disruptions, diagnose, support decision-making

***Robotics Thrust*: Enable Action**

- Increase scope of interventions that can be carried out autonomously

PURDUE UNIVERSITY · HARVARD UNIVERSITY · UTSA The University of Texas at San Antonio · MISSISSIPPI STATE UNIVERSITY · UCONN UNIVERSITY OF CONNECTICUT

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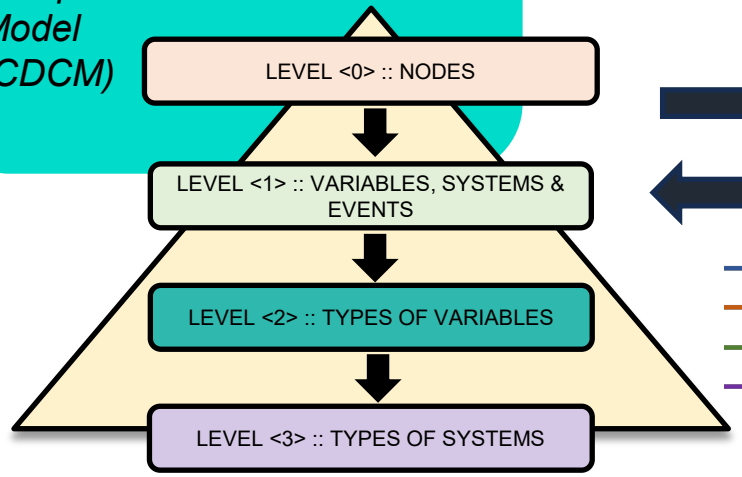
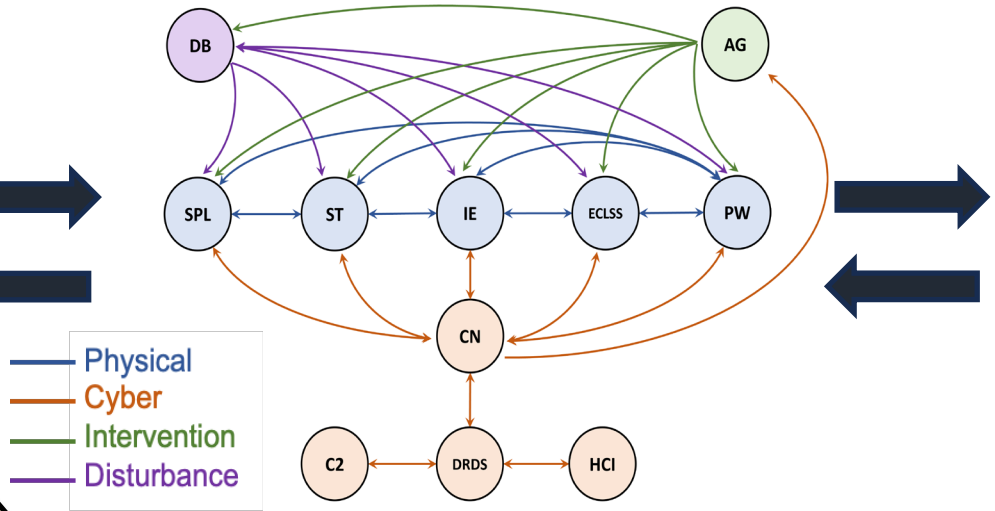
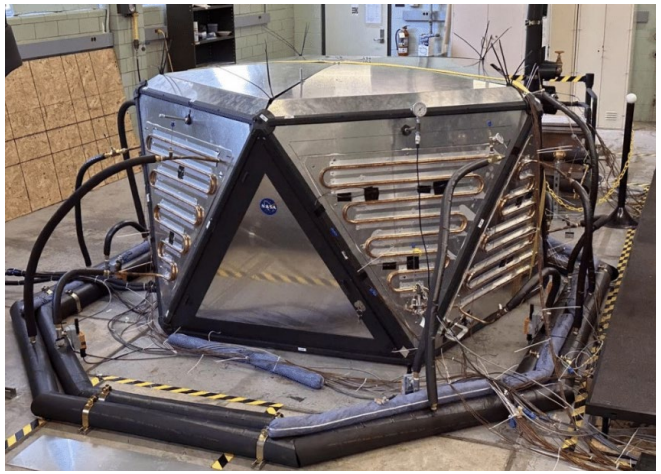
Three complementary testbeds developed to conduct the research

Diagnostics/Autonomy & Early Design
Control-oriented Dynamic Computational Model (CDCM)



HARSH a Shared Use Cyber-Physical Testbed for Testing, Validation, Digital Twins, etc





Cyber: *HabSim*

Physical Components

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Resilient ExtraTerrestrial Habitats Institute

Resilient
has the ability to react to, survive and recover from a wide range of disruptions

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Resilient ExtraTerrestrial Habitats Institute

Resilient
has the ability to react to, survive and recover from a wide range of disruptions

Autonomous
has the ability to achieve goals while operating independently of external control

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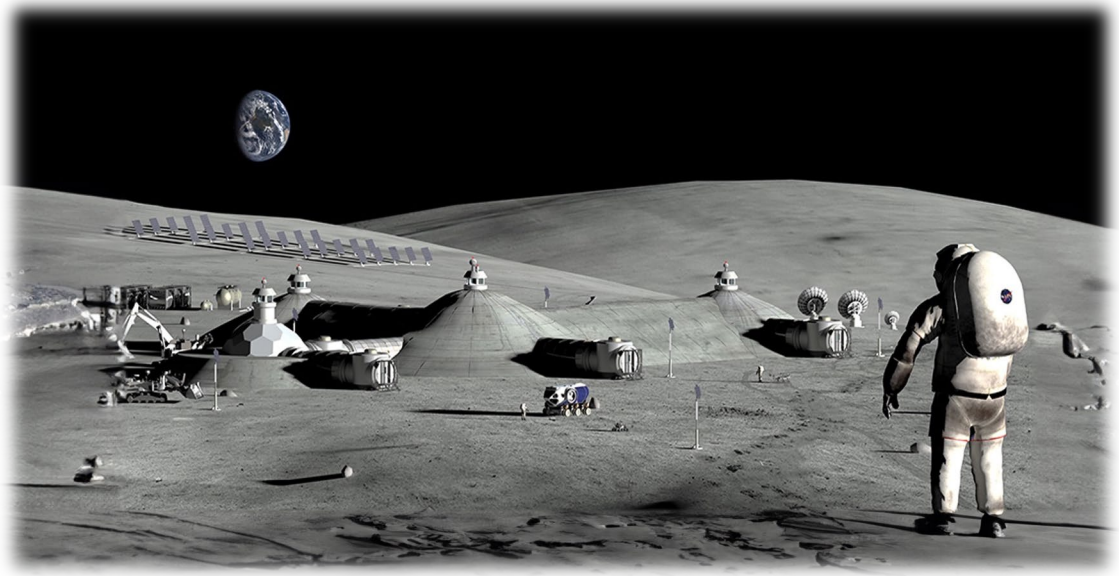
Resilience-based Design

Design, evaluate, and select safety controls for foreseen and unforeseen disruptions using a resilience framework

Create a framework to design a habitat for resilience.

How can we evaluate and select safety controls to maximize resilience?



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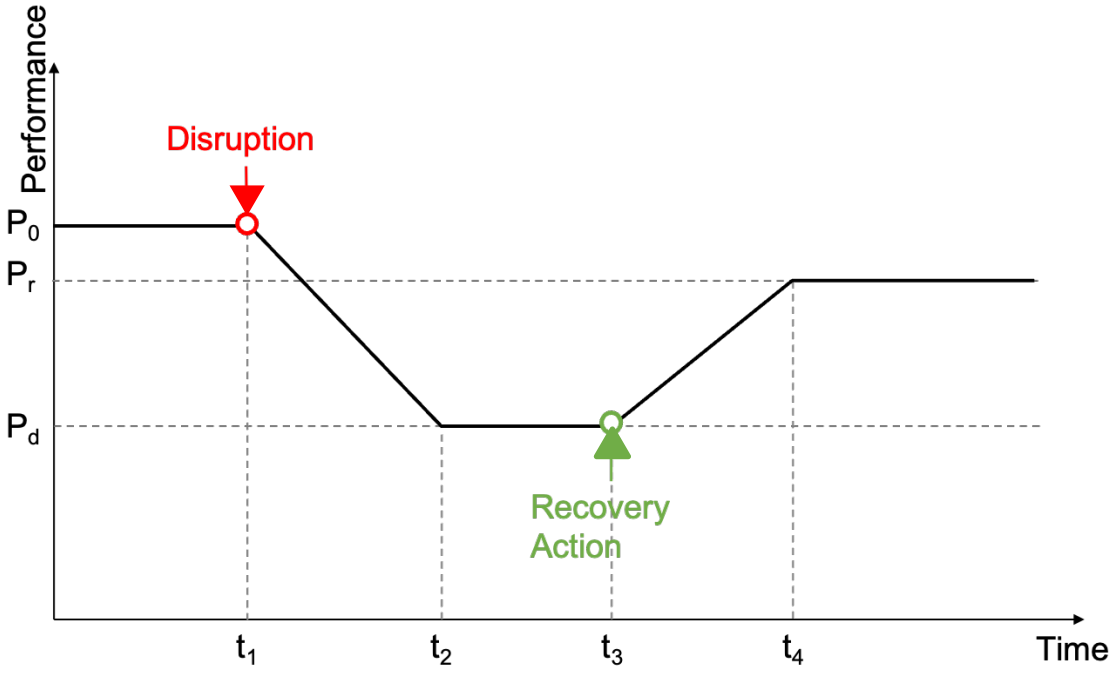

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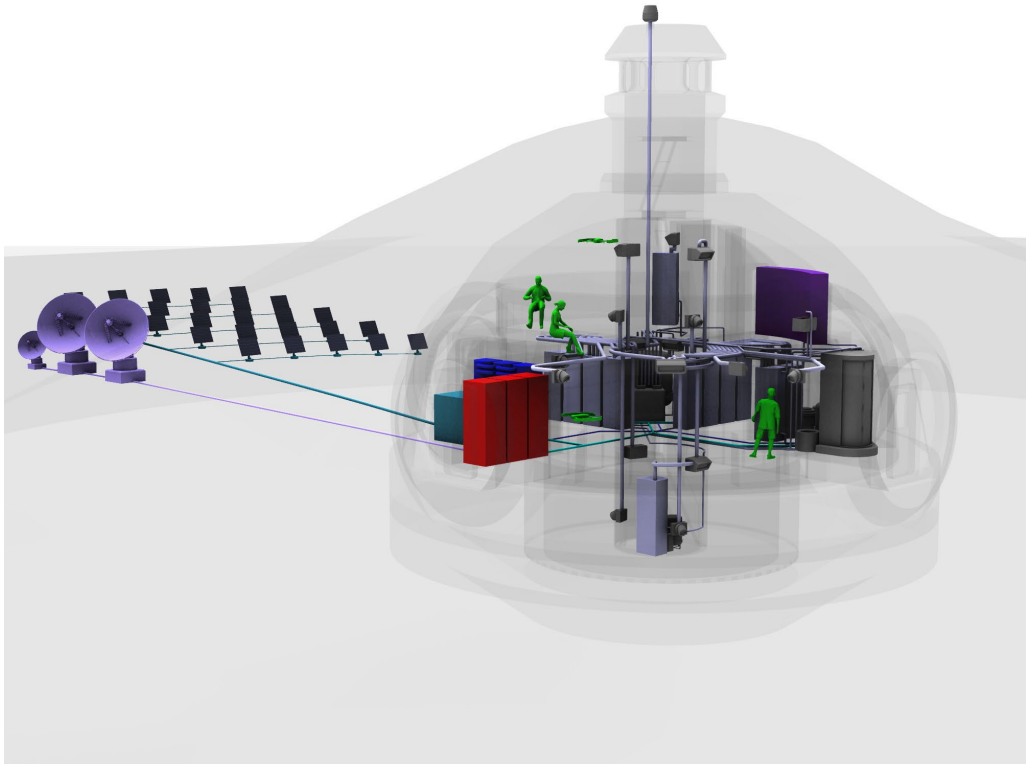

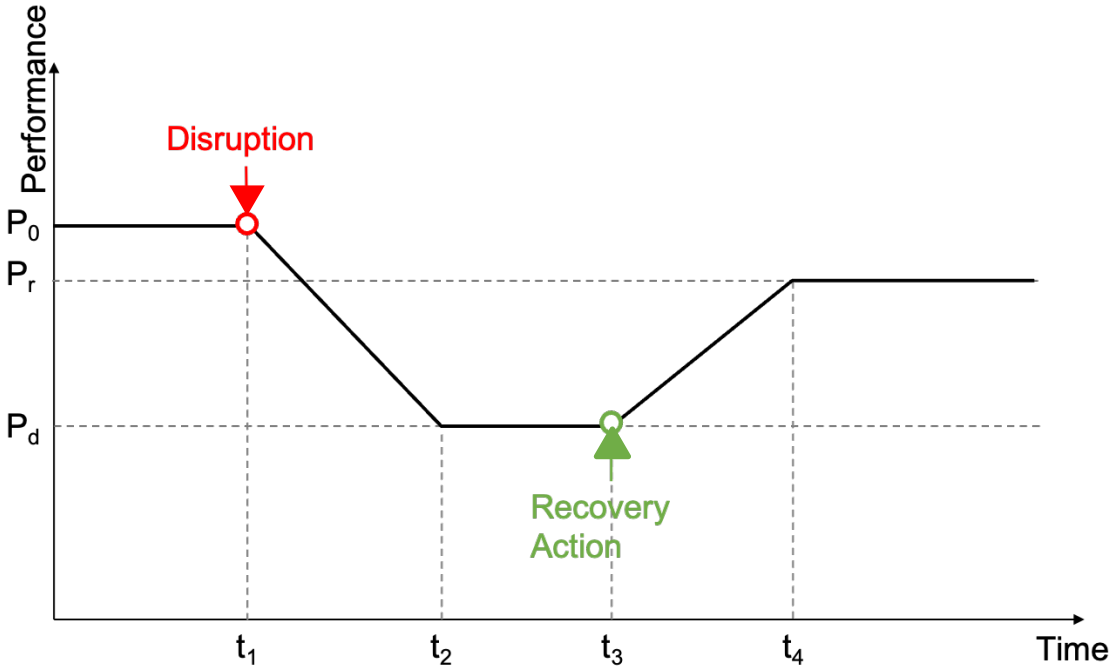

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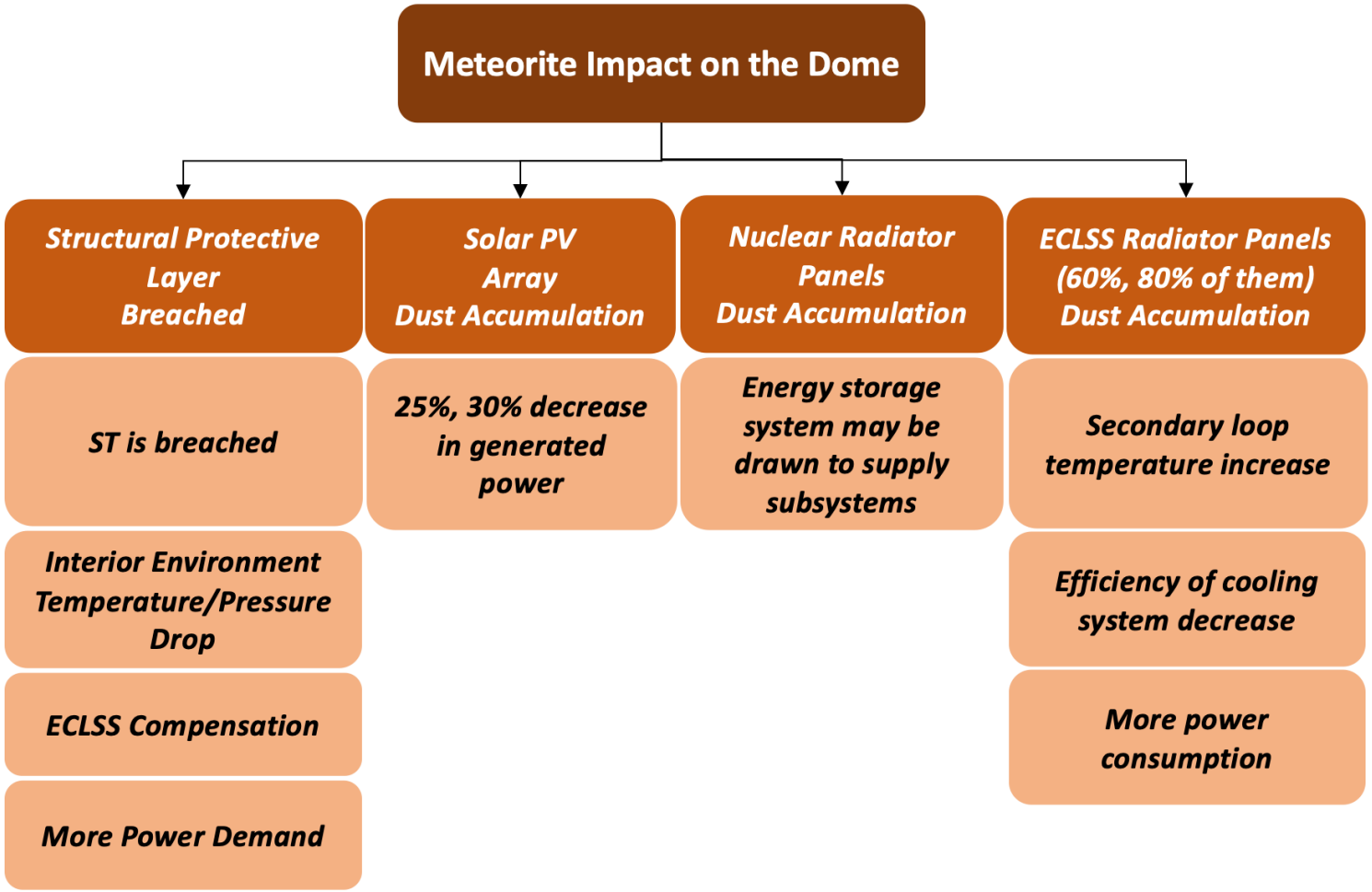
Resilience-based Design



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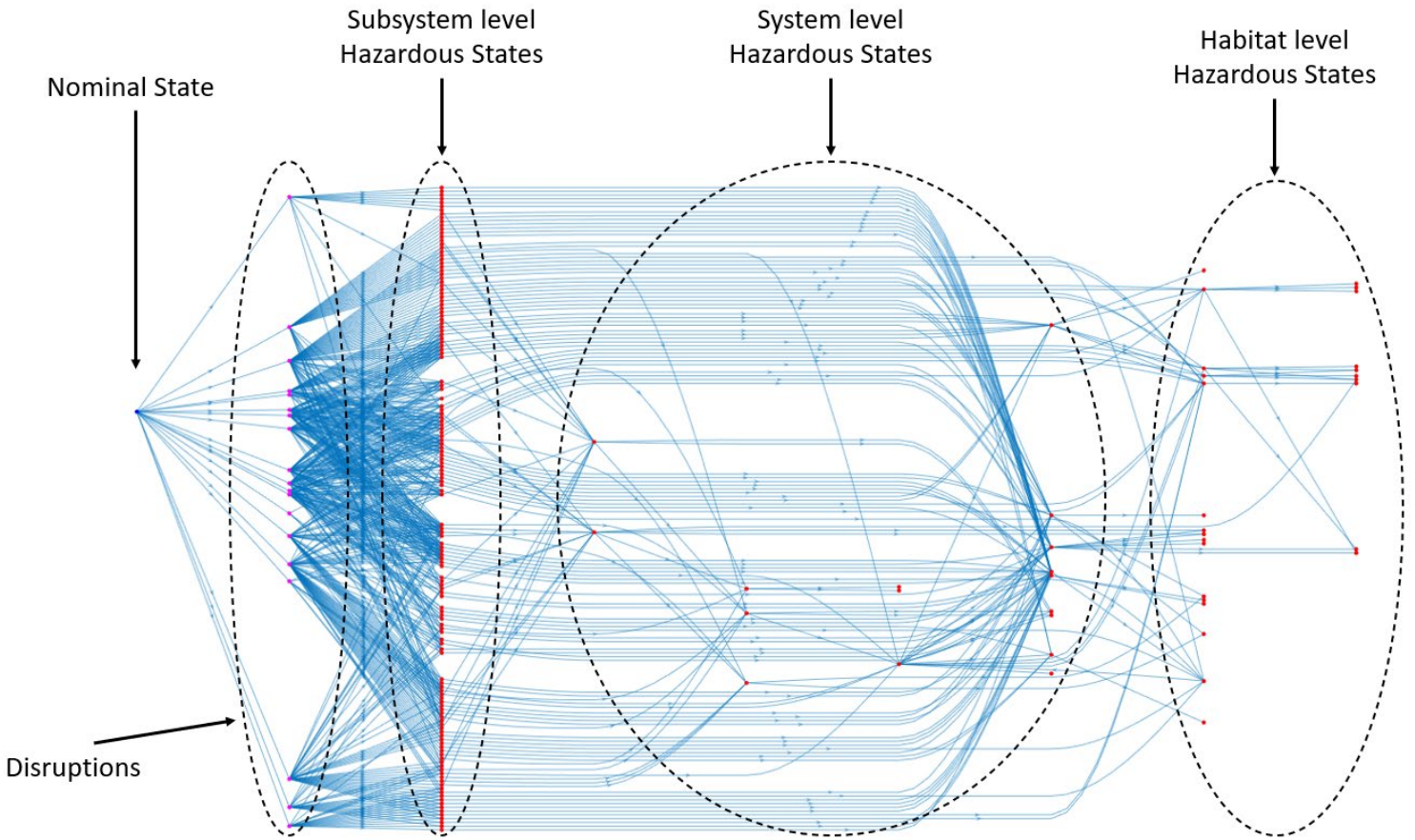
Resilience-based Design

7 disruptions, 19 triggers,
217 hazardous states, and 786 safety controls



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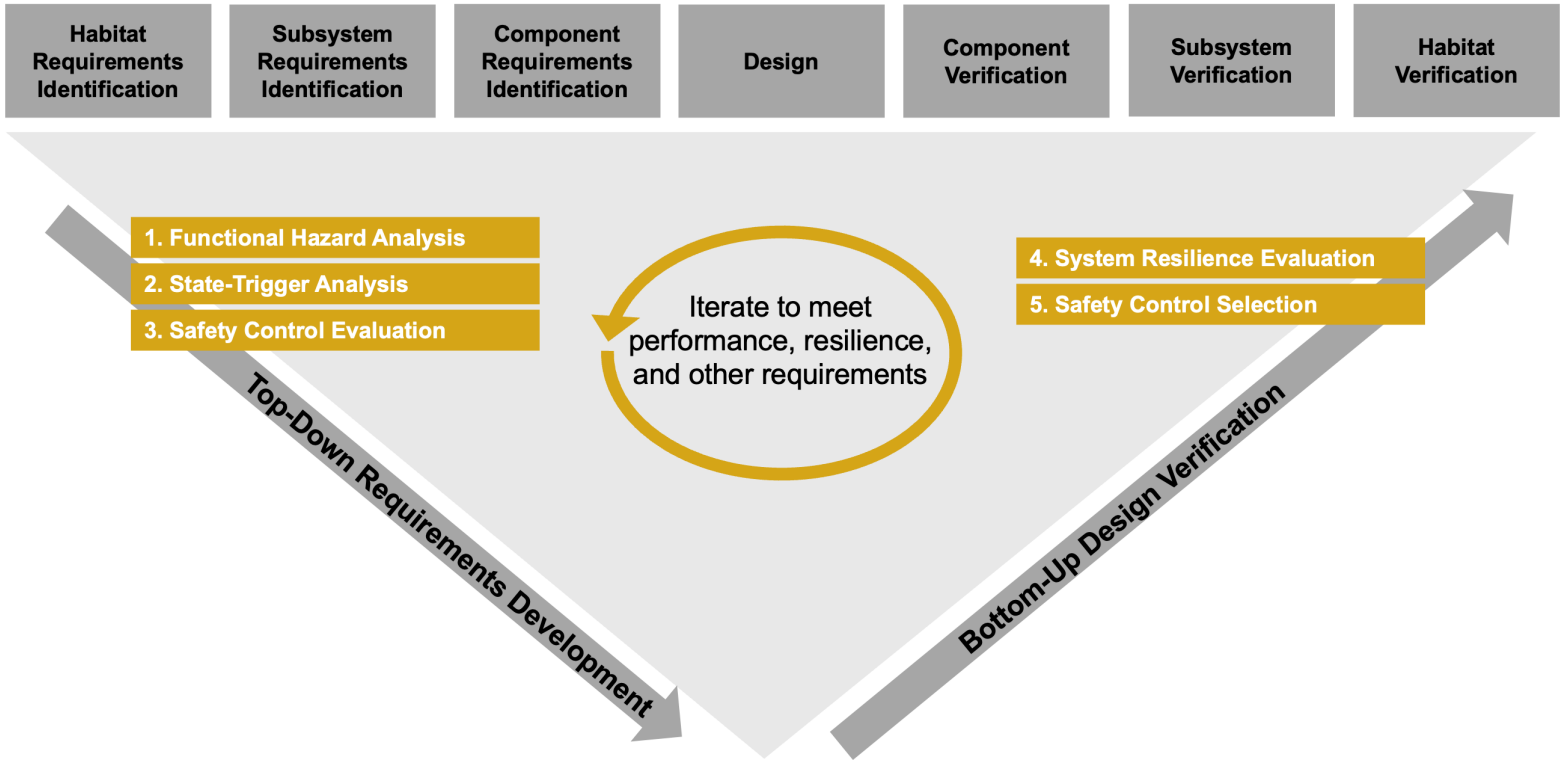
Resilience-based Design



Control Effectiveness measures the effectiveness of a safety control implementation strategy to mitigate its target hazard

Resilience Potential is a measure of effectiveness of a safety control implementation strategy in mitigating multiple hazards or hazards for which it is not designed

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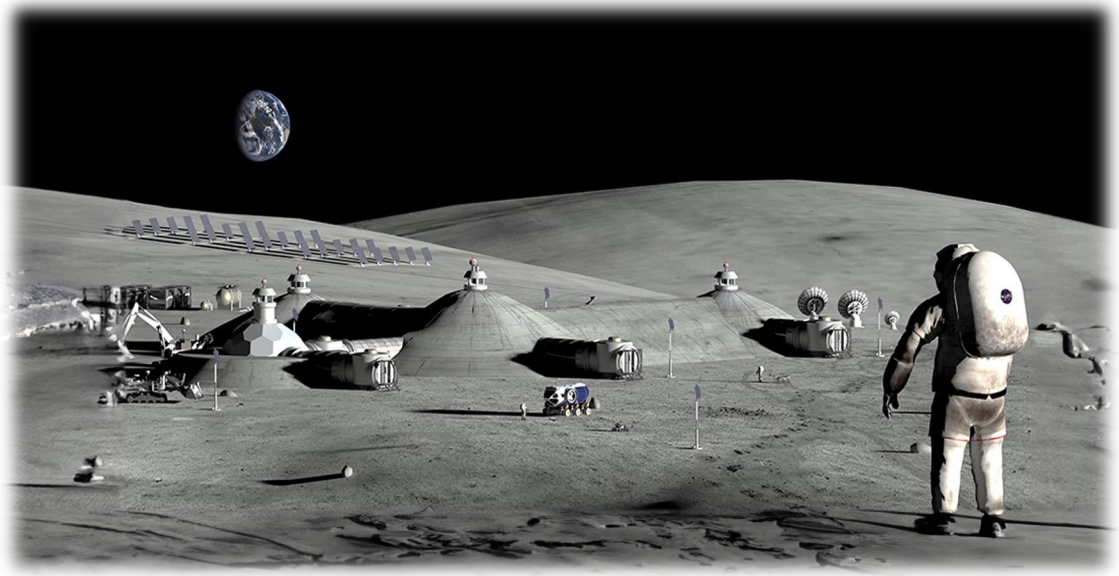
Autonomous Operation & Situational Awareness

Assess onboard monitoring, diagnostic reasoning, and task execution to recover from foreseen and unforeseen disruptions

What is the effect of delays on the resilience of deep space habitats?

How to provide onboard monitoring and reasoning to make decisions?



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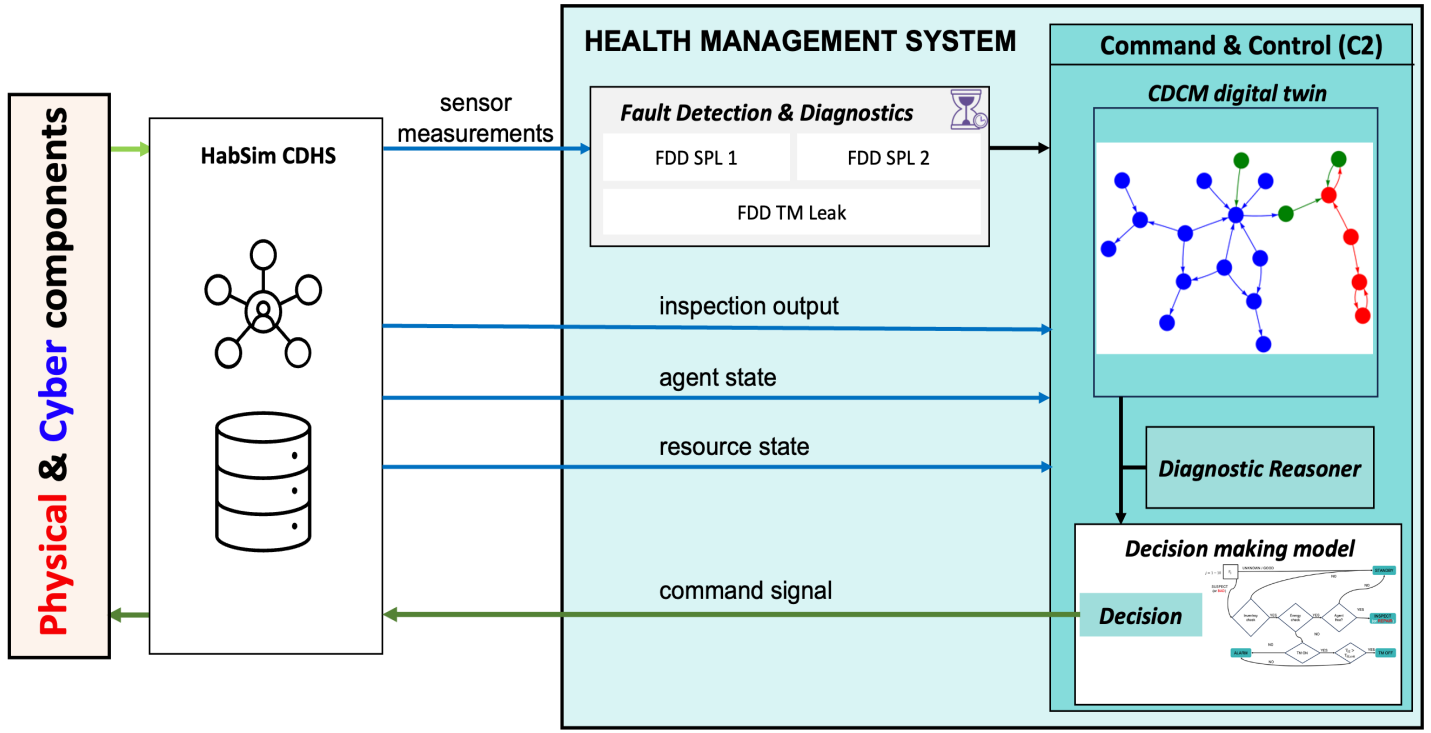

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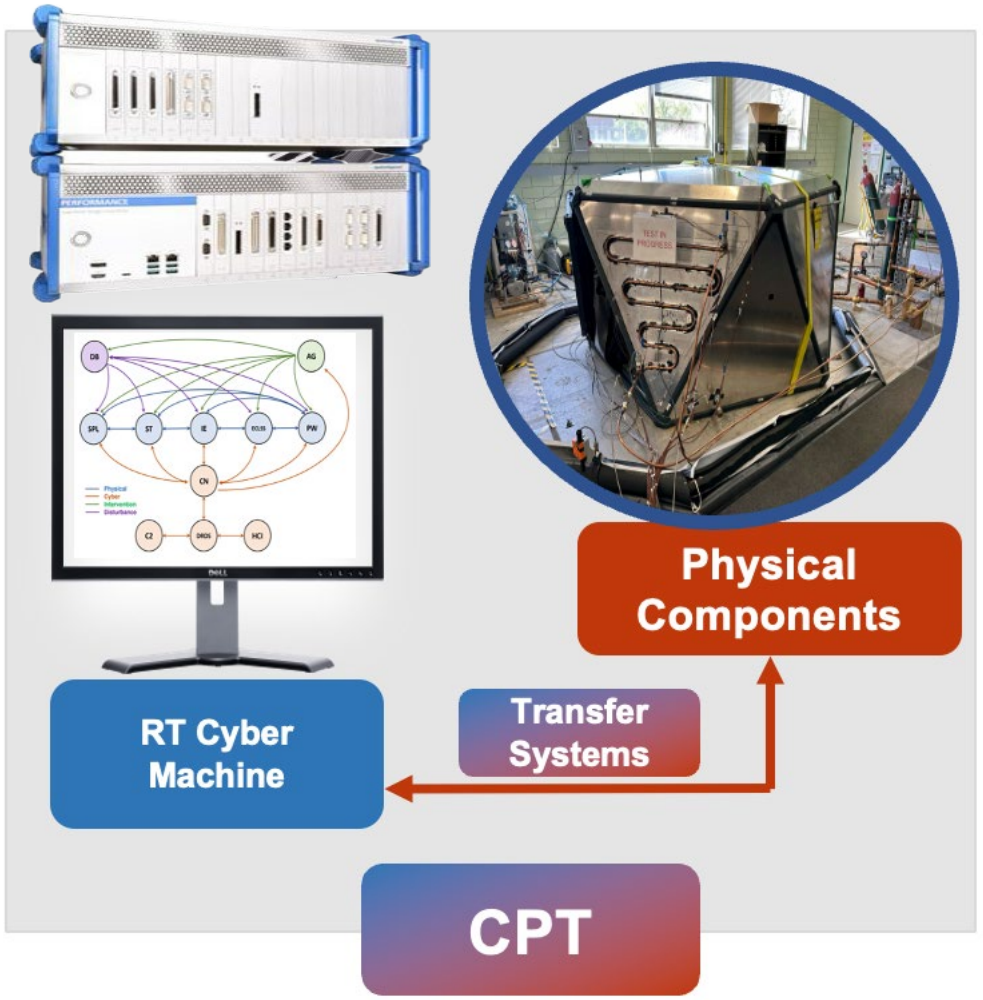

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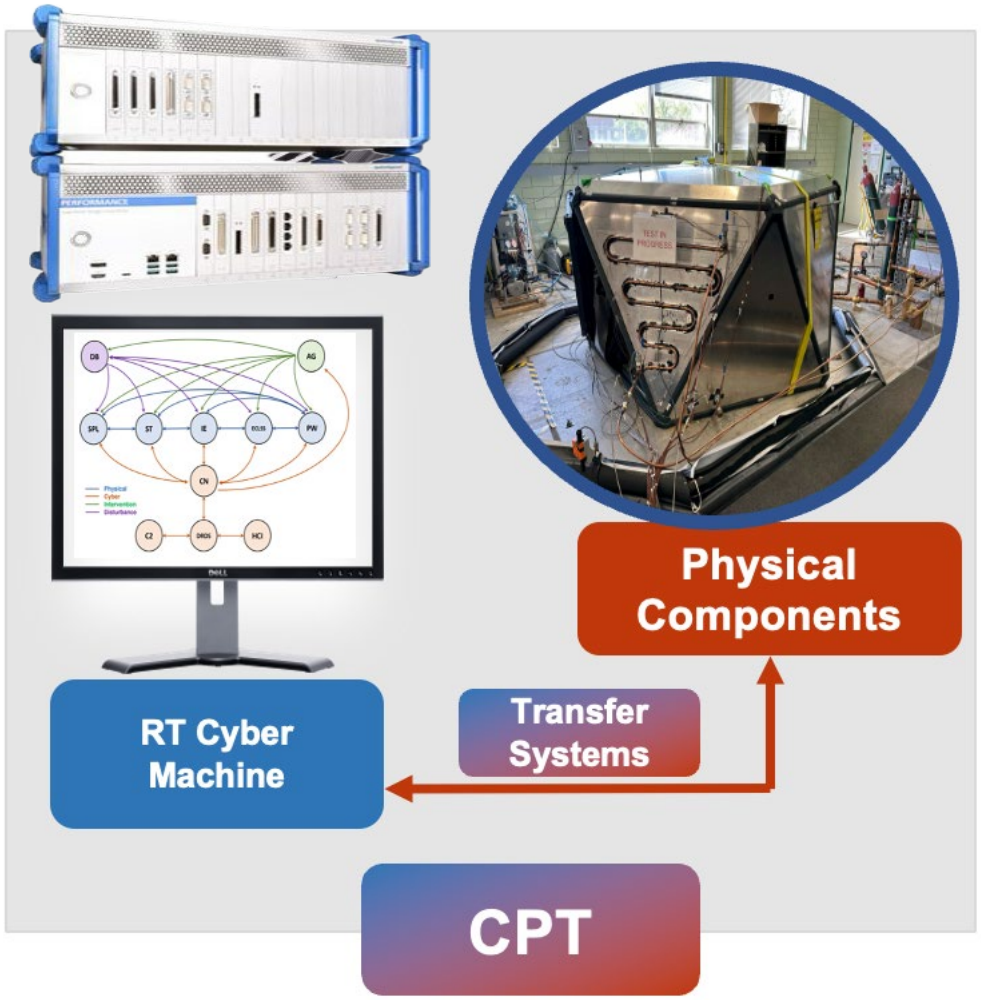

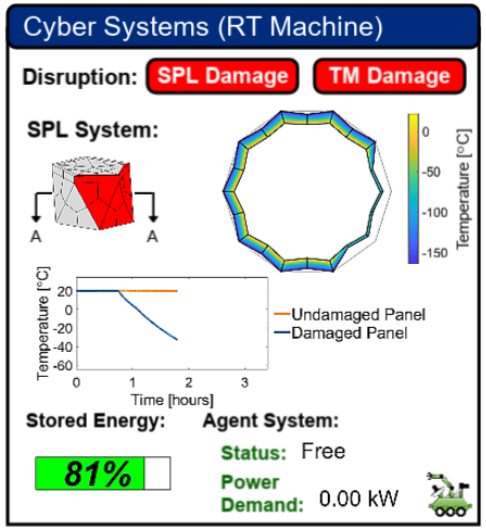

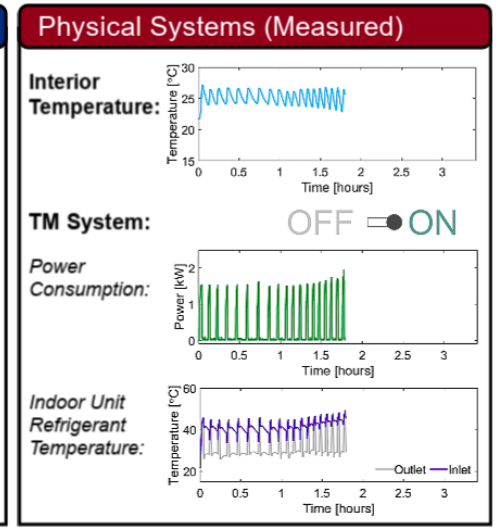

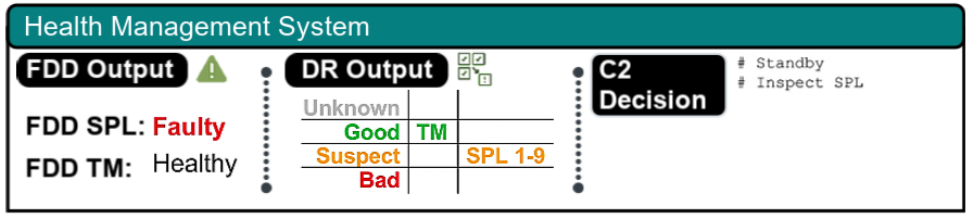

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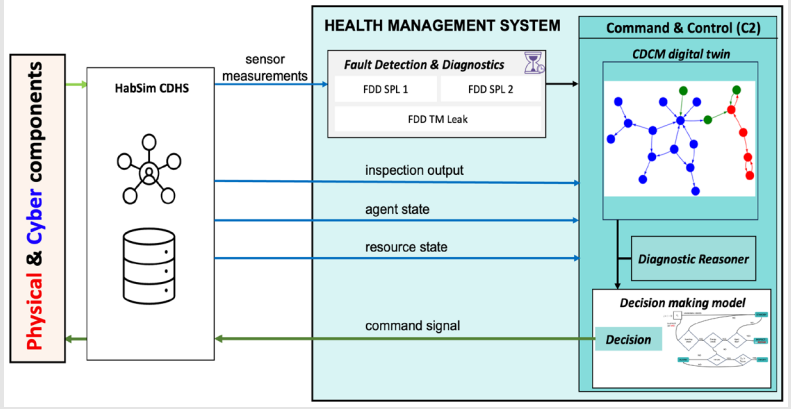
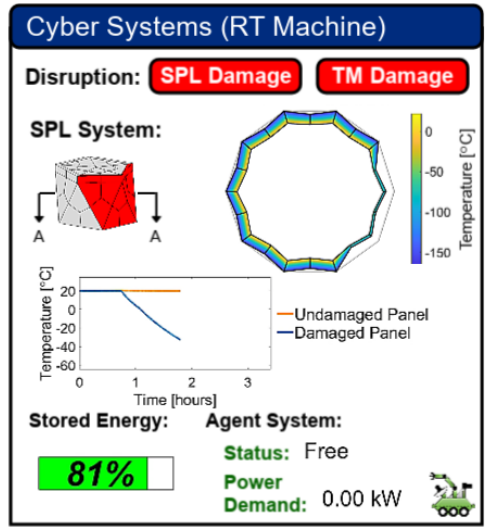
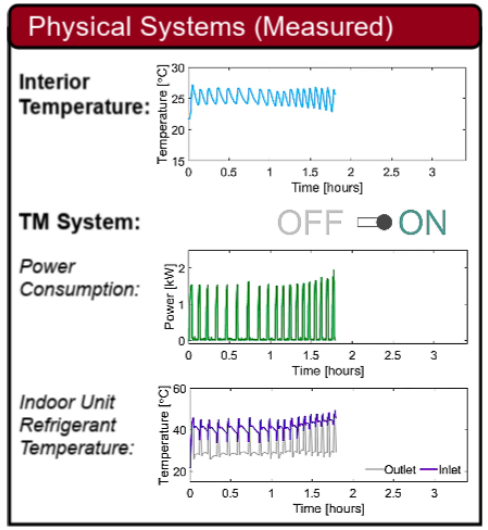
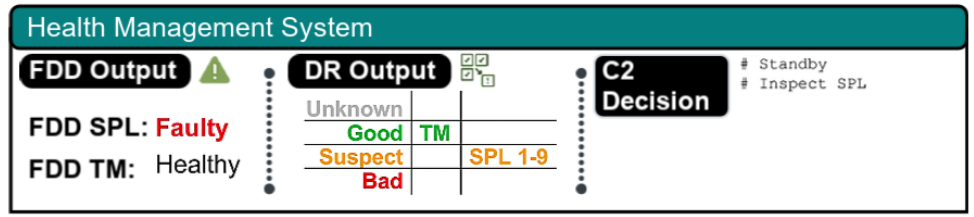


HMS







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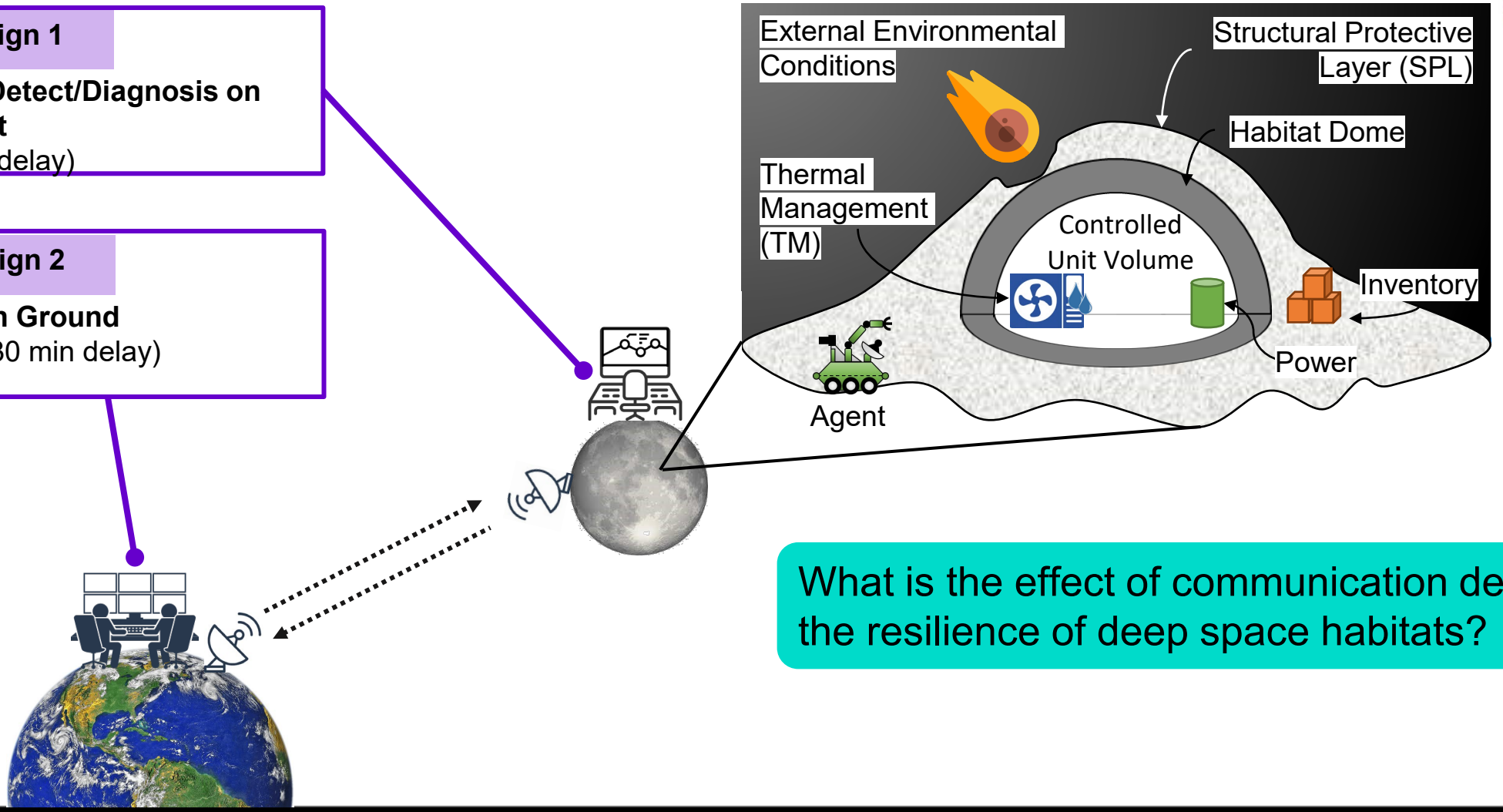
Autonomous Operation & Situational Awareness

Design 1

Fault Detect/Diagnosis on Habitat
(0 min delay)

Design 2

FDD on Ground
(15 or 30 min delay)



What is the effect of communication delays on the resilience of deep space habitats?

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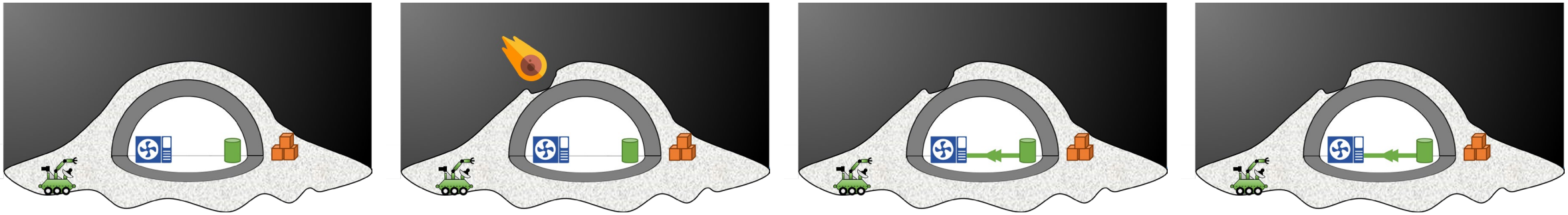
Scenario:
Episode “SPL Damage” on “FDD on Habitat” Design

1 Nominal Condition → 2 Micrometeorite Strike → 3 Increase in TM Power Consumption → 4 FDD SPL Detection

Habitat System



Perceived by C2

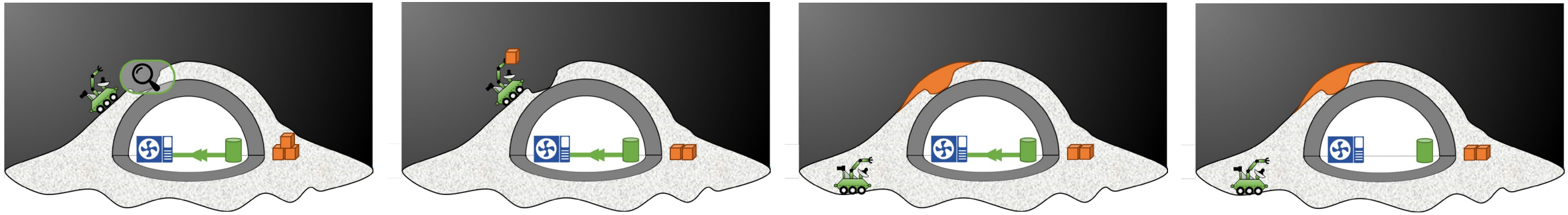
	1 Nominal Condition	2 Micrometeorite Strike	3 Increase in TM Power Consumption	4 FDD SPL Detection
HP Cycle:	ACTIVATED	ACTIVATED	ACTIVATED	ACTIVATED
Temperature:	NOMINAL	NOMINAL	NOMINAL	NOMINAL
FDD SPL:	HEALTHY	HEALTHY	HEALTHY	FAULTY
FDD TM Leak:	HEALTHY	HEALTHY	HEALTHY	HEALTHY
DR:	SPL1-9, TM	SPL1-9, TM	SPL1-9, TM	SPL1-9, TM
Agent:	FREE	FREE	FREE	FREE
Decision	**STANDBY**	**STANDBY**	**STANDBY**	**SPL INSPECTION**

Funded by the National Aeronautics and Space Administration

Scenario:
Episode “SPL Damage” on “FDD on Habitat” Design

5 SPL Inspection by Agent → 6 SPL Repair by Agent → 7 SPL Repair Completed → 8 Recovery

Habitat System



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	5 SPL Inspection by Agent	6 SPL Repair by Agent	7 SPL Repair Completed	8 Recovery
HP Cycle	ACTIVATED	ACTIVATED	ACTIVATED	ACTIVATED
Temperature	NOMINAL	NOMINAL	NOMINAL	NOMINAL
FDD SPL	FAULTY +	FAULTY +	HEALTHY	HEALTHY
FDD TM Leak	HEALTHY	HEALTHY	HEALTHY	HEALTHY
DR	SPL1-6, SPL7-9, TM	SPL1-6, SPL7-9, TM	SPL1-9, TM	SPL1-9, TM
Agent	SPL INSPECTION	SPL REPAIR	FREE	FREE
Decision	**SPL REPAIR**	**STANDBY**	**STANDBY**	**STANDBY**

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Results

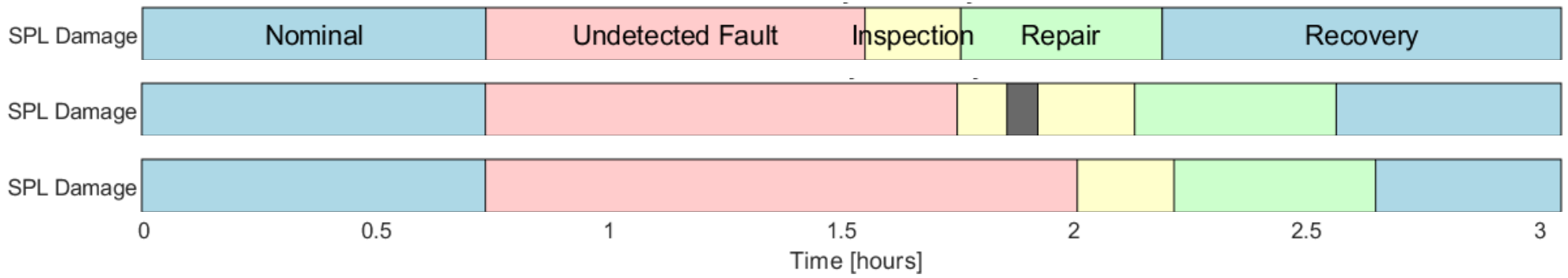
FDD Delay

Episode 1: SPL Damage

0 min

15 min

30 min



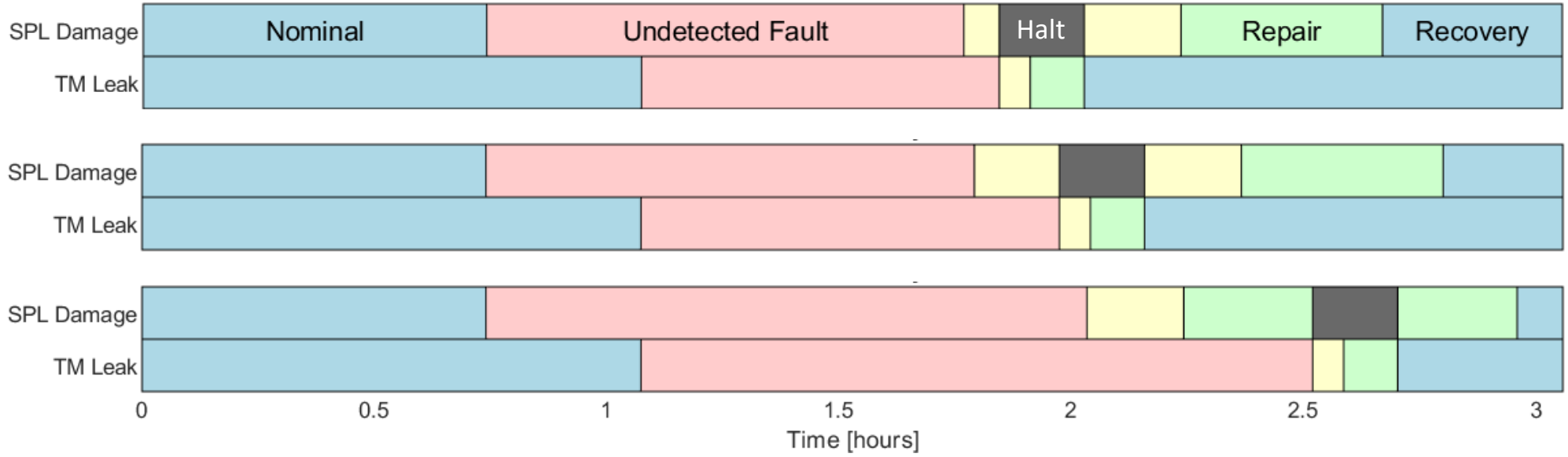
FDD Delay

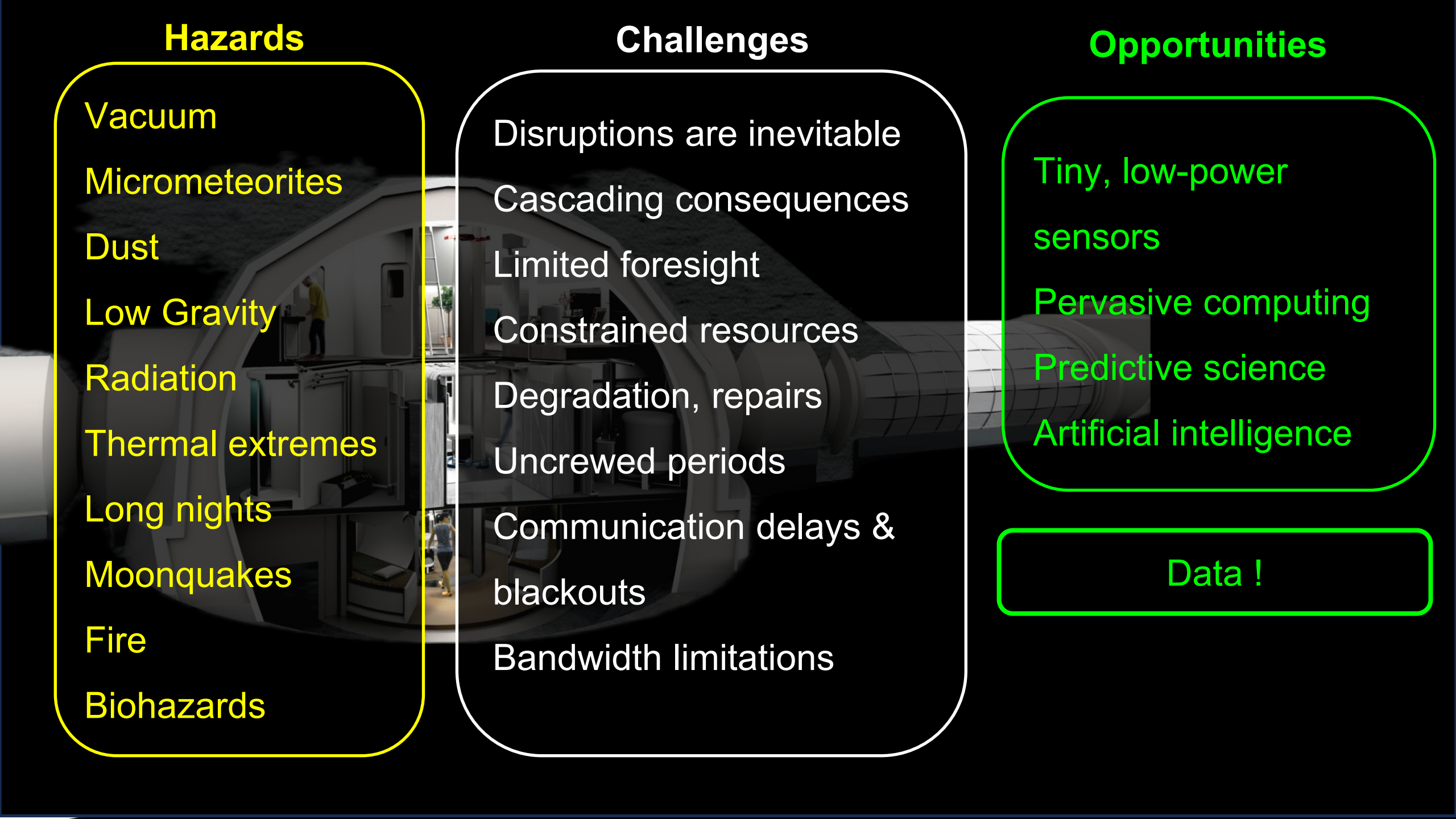
Episode 2: SPL Damage and TM Leak

0 min

15 min

30 min





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Opportunities

- Tiny, low-power sensors
- Pervasive computing
- Predictive science
- Artificial intelligence

- Data !

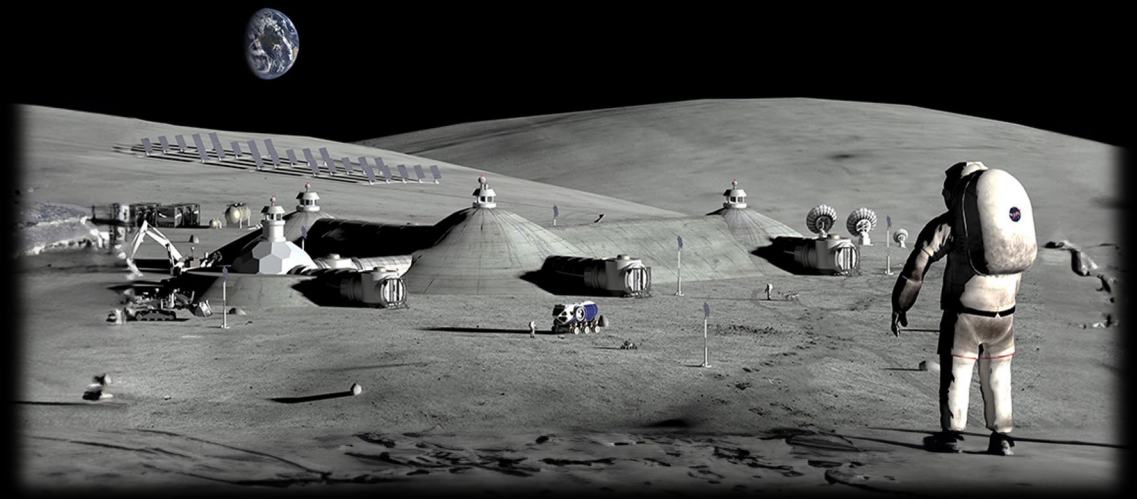
Some of the Lessons We Have Learned

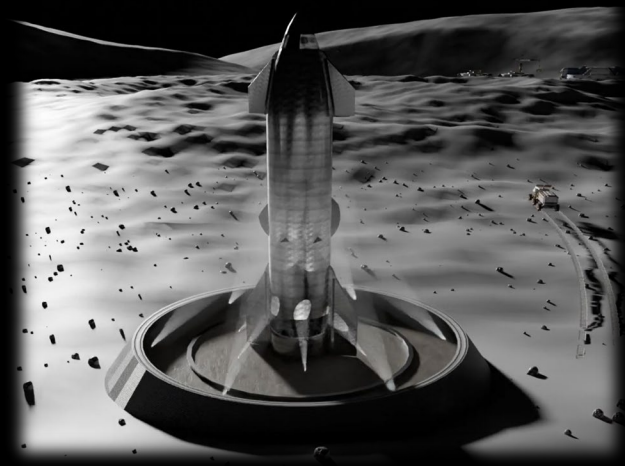
AI is going to be more and more relevant for the management of our complex systems with **deep informational dependencies**. Current safety and resilience engineering frameworks do not account for these classes.

Control effectiveness and **resilience potential** metrics help assess safety controls from early development to detailed design. Control effectiveness focuses on foreseen hazards, while resilience potential addresses unforeseen hazards.

The opportunity to work with **real hardware** – i.e., a testbed that is modular and reconfigurable – is essential to reveal the real challenges and allows for testing ideas.

Access to reliable, documented **data sets** is critical for tackling questions about modeling, fault detection, digital twins, and interconnectedness.





Acknowledgements

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Thanks to Dr. Takaharu Igarashi who generated the images of the RETH institute notional space habitat.

Website:
https://www.purdue.edu/rethi/

Resilient and Smart Extraterrestrial Habitats
Coming soon, ~May 2025

Look for RETH institute in: LinkedIn