Uncertainty Quantification (UQ) for Modeling and Simulation at NASA

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NASA Langley Research Center

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UQ: *Enabling **Credible** Modeling and Simulation (M&S) at NASA*

Motivation and Challenge

- Accelerating reliance on M&S
- ***All models are wrong*** *(but some are useful)**

Solution

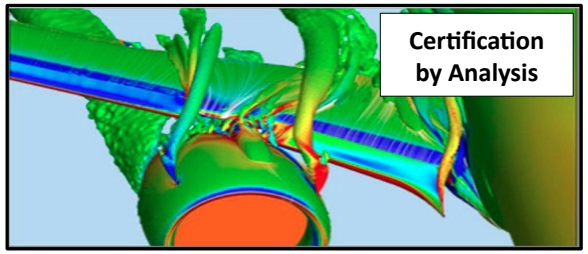
- Integrate uncertainty quantification (UQ) into M&S for *credibility*
  - UQ answers: how ***wrong*** might the model be? When is it ***useful***?

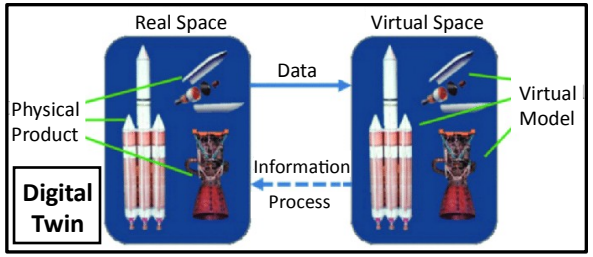
Approach

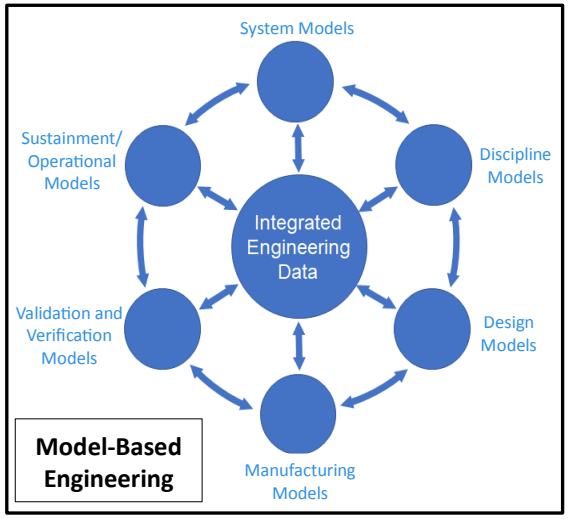
1. Perform research and development of new state-of-the-art UQ methods
2. Transition advanced UQ methods from research to engineering practice

*George Box, Journal of American Statistical Association, 1976.

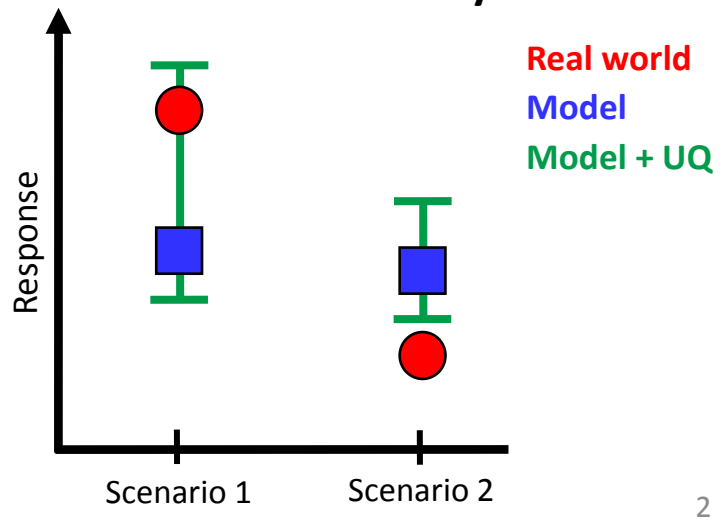
M&S-Enabled Paradigms at NASA







Models vs. Reality



Multifidelity UQ Research and Development

Motivation and Challenge

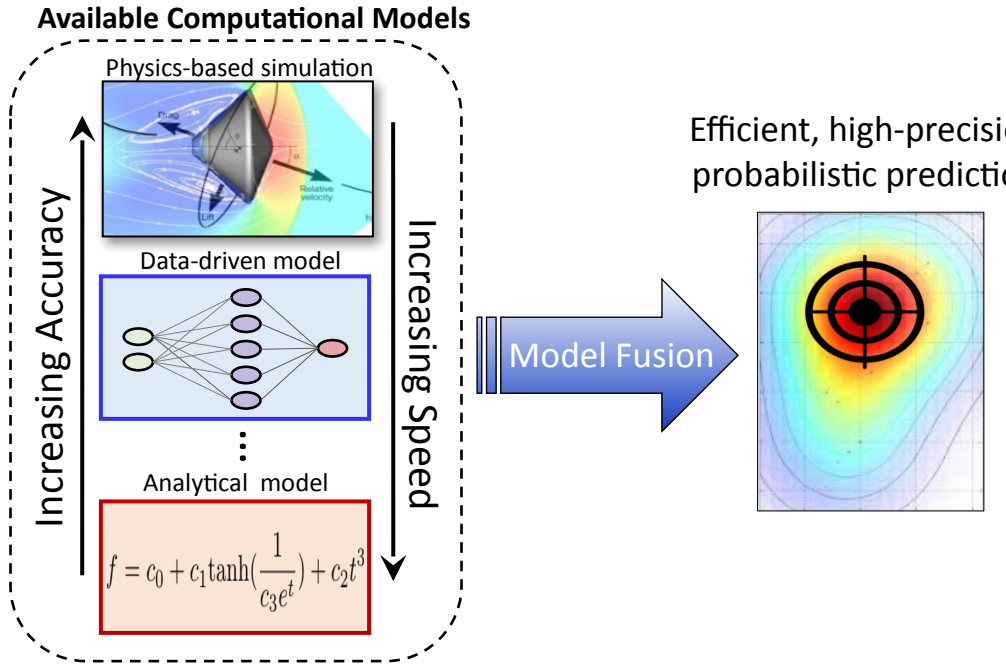
- UQ is computationally demanding
- Multiple models often exist for predicting the same phenomena

Solution

- Multifidelity UQ fuses predictions from:
  - High-fidelity model for ***accuracy guarantees***
  - Low-fidelity models for ***speedup***

Approach

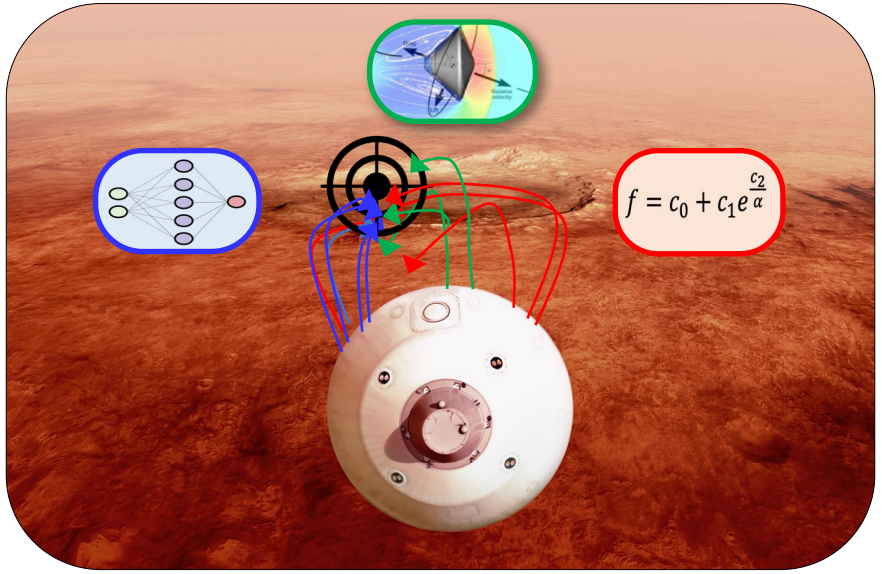
- Development of in-house and open-source software packages
- Cutting-edge research with external partners from govt. and academia



Multi-model Monte Carlo with Python; Open source via NASA Github

Transitioning UQ Research to NASA Engineering

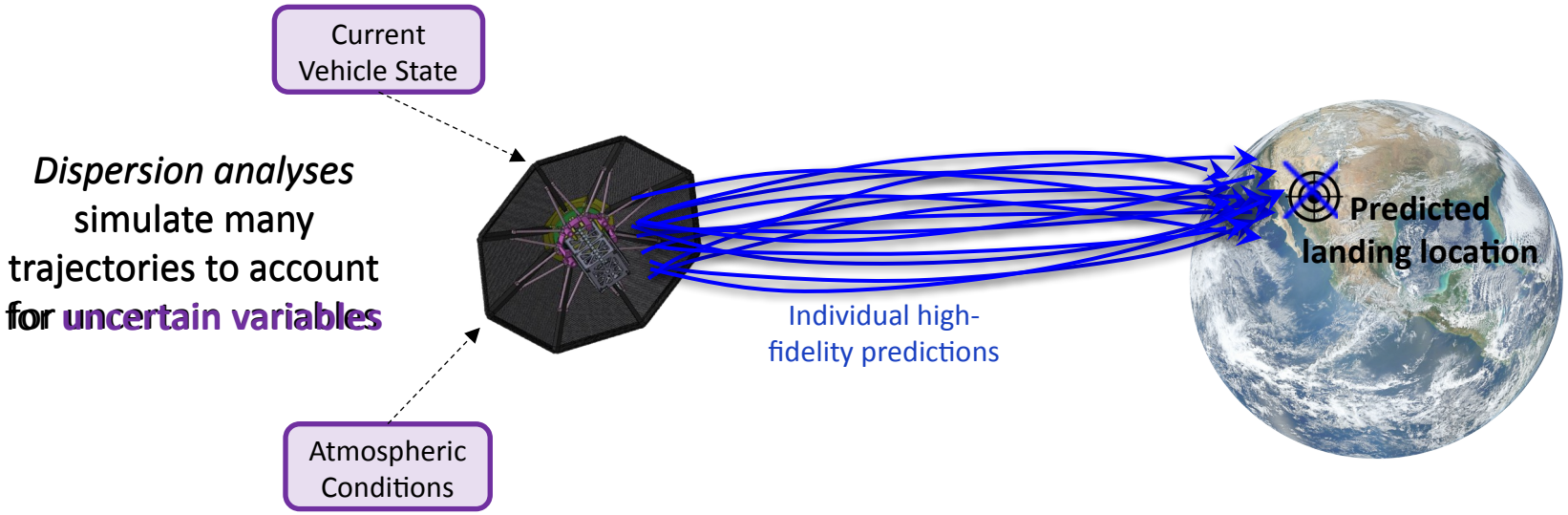
1. Trajectory Simulation for Entry, Descent, and Landing (EDL)
   - Leveraged state-of-the-art multifidelity UQ to substantially improve upon traditional UQ approaches



2. Reliability Analysis for the Exploration Extravehicular Mobility Unit (xEMU) Spacesuit
   - Introduced UQ where it traditionally is not used and demonstrated its benefits

Trajectory Simulation for EDL

- **Challenge**: Traditional UQ methods used for EDL cannot achieve target landing precision required for future Moon and Mars missions

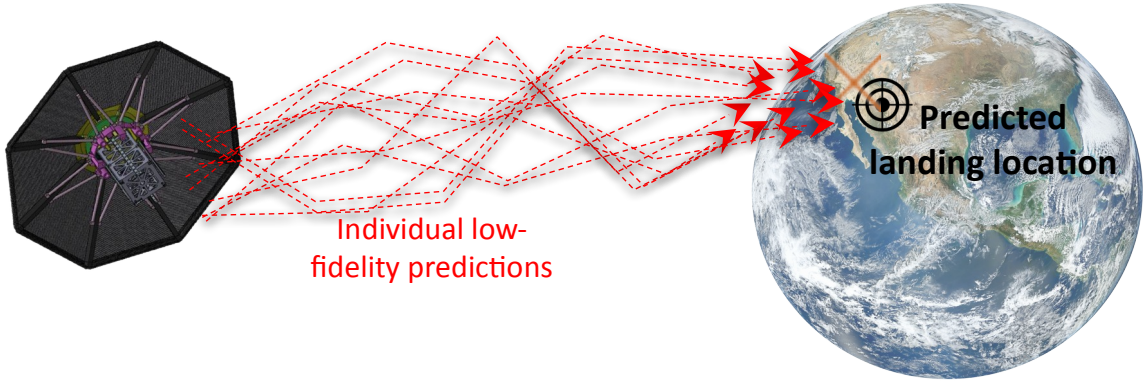


- Leveraging a high-fidelity model alone is **too time consuming**

Trajectory Simulation for EDL

- **Challenge**: Traditional UQ methods used for EDL cannot achieve target landing precision required for future Moon and Mars missions

Dispersion analyses simulate many trajectories to account for uncertain variables

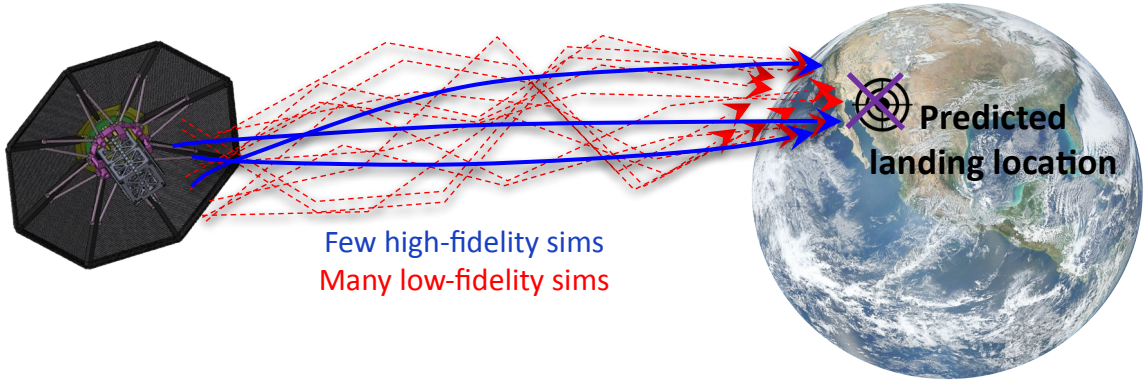


- Leveraging a low-fidelity model alone is **too inaccurate**

Trajectory Simulation for EDL

- **Challenge**: Traditional UQ methods used for EDL cannot achieve target landing precision required for future Moon and Mars missions
- **Approach**: high- and low-fidelity model fusion with multifidelity UQ

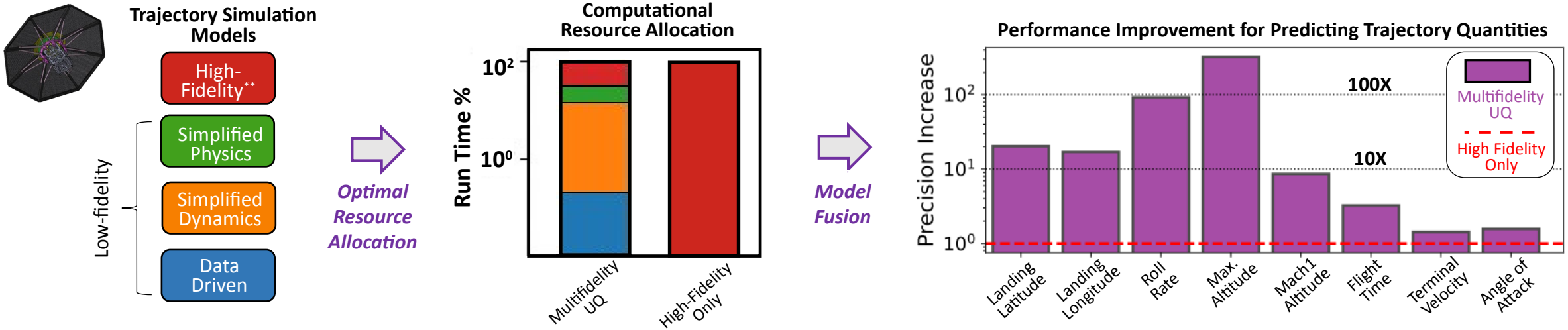
Dispersion analyses simulate many trajectories to account for uncertain variables



➢ Multifidelity UQ improves **efficiency** and **precision**

Trajectory Simulation for EDL

- **Challenge**: Traditional UQ methods used for EDL cannot achieve target landing precision required for future Moon and Mars missions
- **Approach**: high- and low-fidelity model fusion with multifidelity UQ
- **Results:** Up to 100X performance improvement for trajectory simulation*



*J. E. Warner et al. *Multi-Model Monte Carlo Estimators for Trajectory Simulation*. AIAA SciTech 2021.
**Program to Optimize Simulated Trajectories II (POST2)

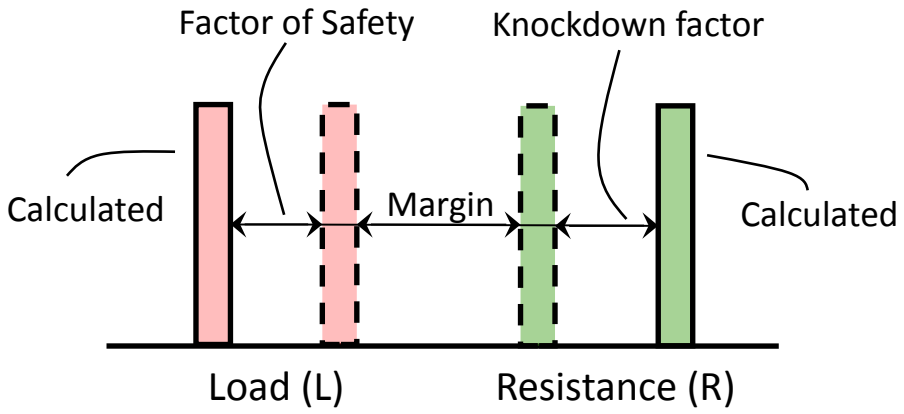
Trajectory Simulation for EDL

- **Challenge**: Traditional UQ methods used for EDL cannot achieve target landing precision required for future Moon and Mars missions
- **Approach**: high- and low-fidelity model fusion with multifidelity UQ
- **Results:** Up to 100X performance improvement for trajectory simulation
- **Impact:**
  - A breakthrough for making onboard, *real-time* guidance technology feasible
  - A *broadly applicable* multifidelity UQ capability delivered for NASA problems

Reliability Analysis for the xEMU Spacesuit

- **Challenge**: Traditional certification approaches using factor of safety (FoS) cannot satisfy both weight and robustness requirements

Traditional Design Based on FoS



➢ Certify design if *Margin 0*

FoS Shortcomings

- ***Difficulties*** specifying for new vehicles, materials, environments
- ***Inconsistencies*** observed across programs, organizations
- ***(Often) Overly conservative*** - may be sequentially applied by multiple teams
- ***(Potentially) Under conservative*** – no direct connection to design reliability/risk

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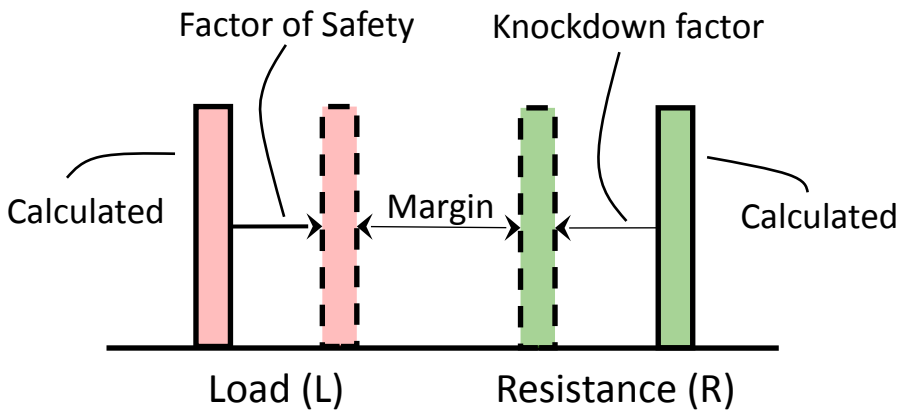
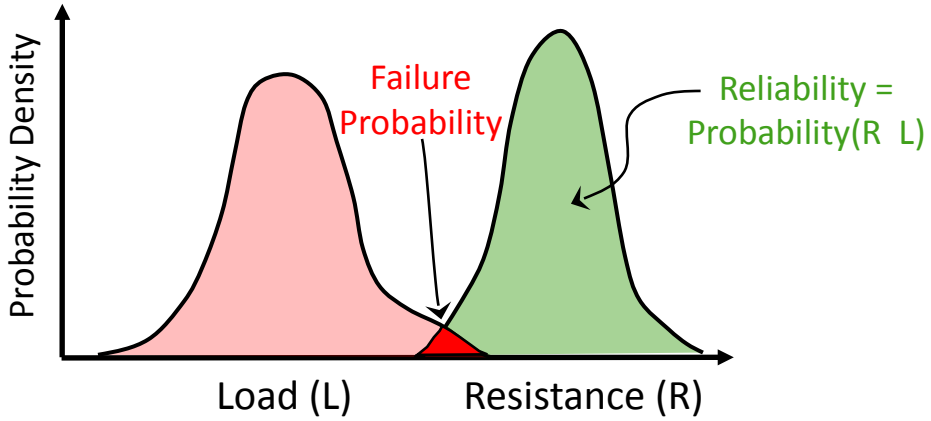


➢ Certify design if *Margin 0*

Reliability-Based Design

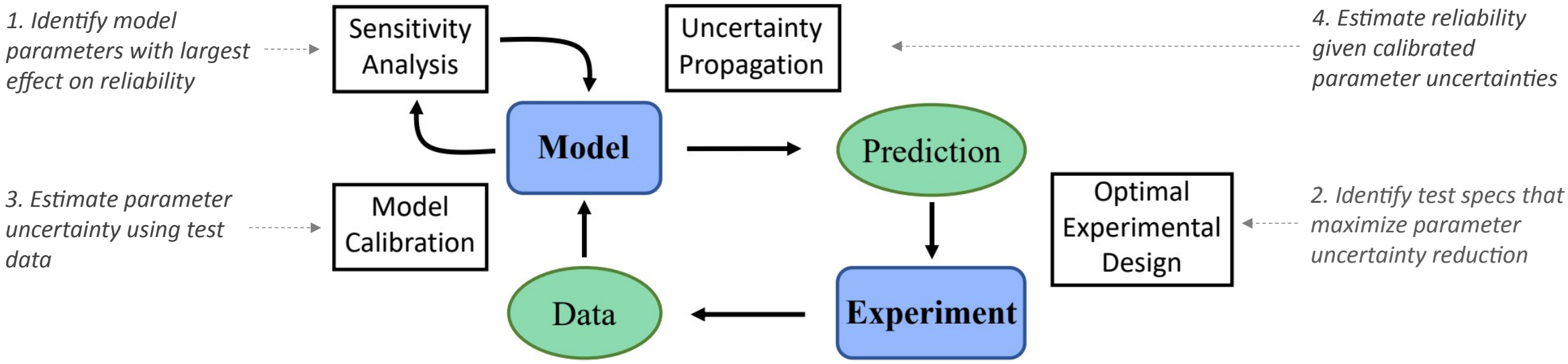


➢ Certify design if *Reliability Target Value*

xEMU Impact Dynamics Project Lead sought alternative reliability-based approach ***"to reduce conservatism where possible in order to avoid the pitfall of a heavy and overdesigned suit structure"***

Reliability Analysis for the xEMU Spacesuit

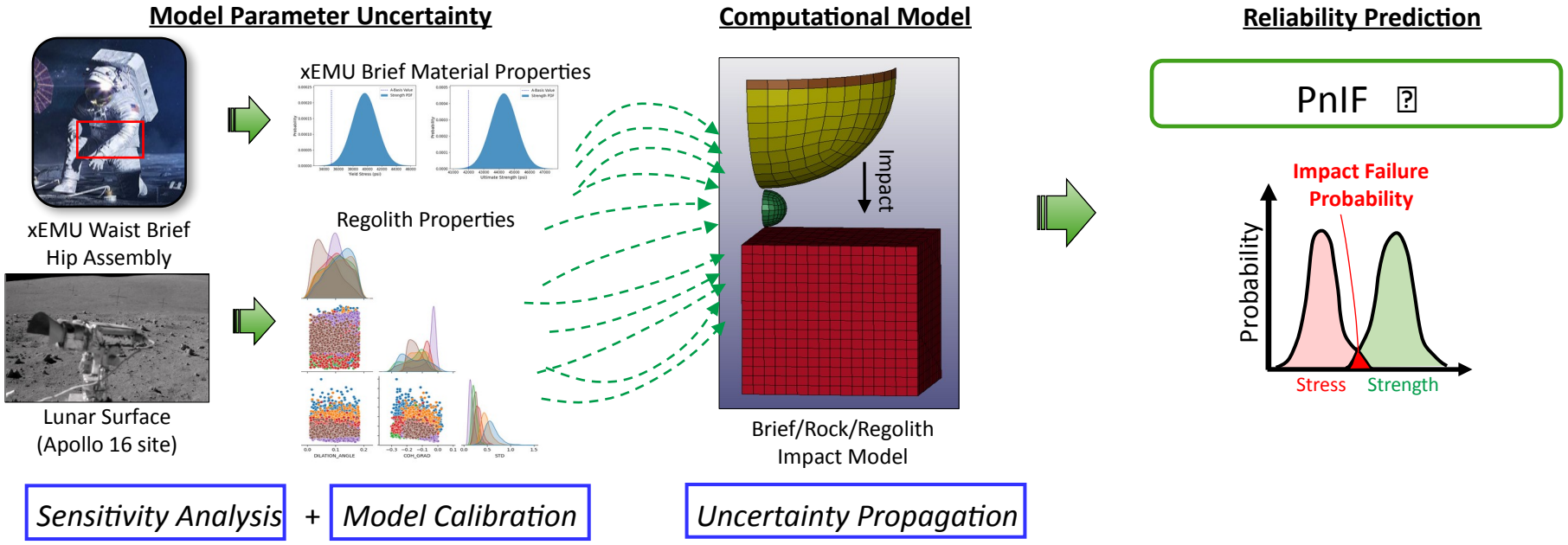
- **Challenge**: Traditional certification approaches using factor of safety (FoS) cannot satisfy both weight and robustness requirements
- **Approach**: Introduced general UQ workflow for estimating reliability*



*J. E. Warner et al. Assessing *Next-Gen Spacesuit Reliability: A Probabilistic Analysis Case Study.* NASA/TM-20210019495.

Reliability Analysis for the xEMU Spacesuit

- **Challenge**: Traditional certification approaches using factor of safety (FoS) cannot satisfy both weight and robustness requirements
- **Approach**: Introduced general UQ workflow for estimating reliability
- **Results:** applied UQ workflow to verify that the probability no impact failure (PnIF) in the xEMU brief is greater than the requirement



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- **Results:** applied UQ workflow to verify that the probability no impact failure (PnIF) in the xEMU brief is greater than the requirement
- **Impact:**
  - Viable path forward for certifying lightweight, next-generation xEMU spacesuit
  - Reliability-based design paradigm for reduced conservatism/cost/risk at NASA

Summary: UQ at NASA

- UQ is required for the credible use of M&S for all NASA missions
  - Make predictions with confidence, quantified uncertainty to inform critical decisions
  - Enable paradigms like reliability-based design, Digital Twin, certification by analysis
- Many hurdles to UQ adoption, workforce development is key
  - Learning curve for successfully applying UQ for real world problems
  - Rapidly evolving research field
  - Overwhelming number of tools, methods
- NASA UQ researchers continue to work to overcome these challenges
  - Organized UQ Seminar Series in Spring 2023 with presentations and tutorials by external speakers (most recently, Prof. Bobby Gramacy from Va. Tech. on 3/20)
  - Developing/releasing UQ software; providing tutorials on UQ approaches