

The Artemis Challenge: Another Revolution in Structural Dynamics

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ABSTRACT

The National Aeronautics and Space Administration (NASA) is embarking on an exciting evolution in human exploration and spaceflight. Space Policy Directive (SPD) 1 provides the overarching narrative for returning humans to the Moon and then to Mars. We are challenged to “Lead an innovative and sustainable program with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities. Beginning with missions beyond low Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations...” Here we explore some of the key technical challenges that this new era of human exploration brings with a focus on the challenges and opportunities in the structural dynamics discipline.

Keywords: Structural Dynamics, Artemis, Moon, Mars, challenge

THE ARTEMIS MISSION

The exploration journey is encapsulated by the Artemis mission architecture. The Artemis mission architecture is maturing in a phase 1 effort with mission and systems necessary to achieve landing humans on the surface of the Moon in 2024, Figure 1. It will evolve into a phase 2 effort to establish a sustainable systems for a long-term presence on and around the Moon by 2028, Figure 2. On the moon and in the vicinity of the moon we will prove technologies, mature and operate systems necessary to live and work in the harsh environment of another world only a few days from earth (home) before embarking on multiyear missions to Mars. The launch vehicles, spacecraft, and systems developments necessary for such a bold endeavor are well underway. The designs of the new Space Launch System (SLS), the Orion spacecraft and the Exploration Ground Systems (EGS) for vehicle processing and launch are essentially complete and there has been significant progress in manufacturing and assembly of specific hardware for the Artemis 1 and Artemis 2 missions. Equally as important, the program level and integrated system level testing and analyses are also well underway to support integrated verification and validation and certificate of flight readiness (CoFR) that will be conducted on mission-by-mission basis for each Artemis mission.

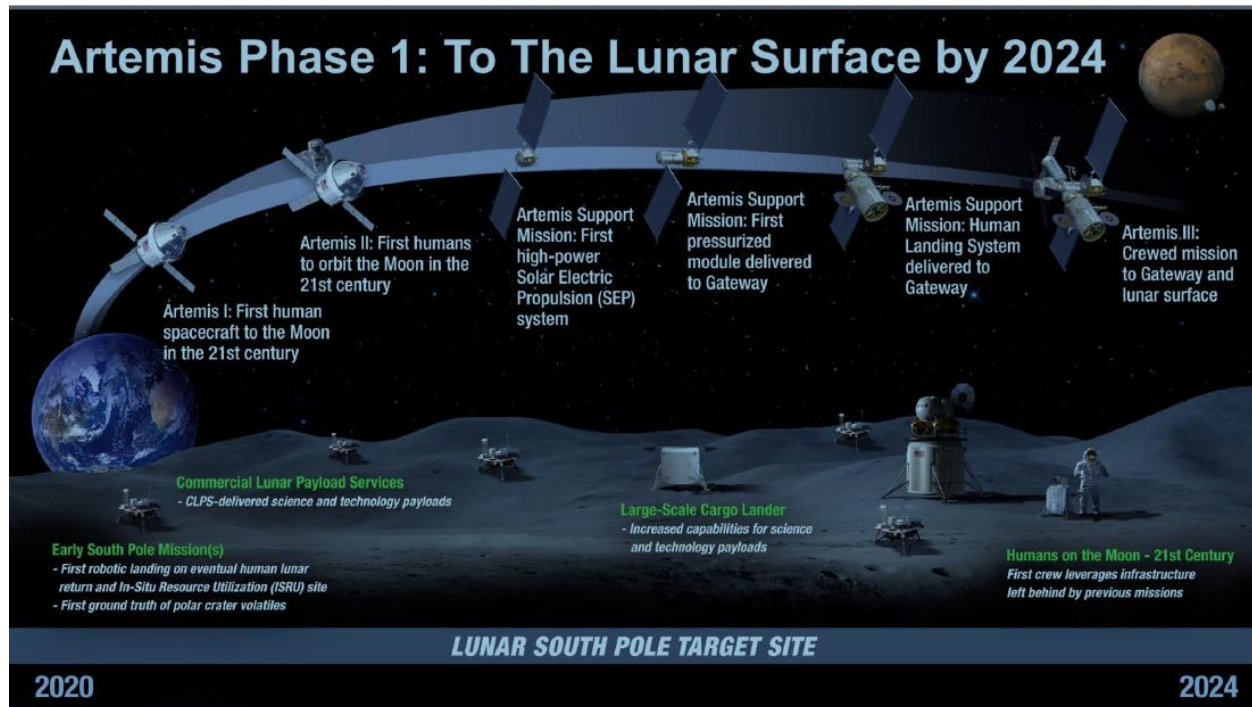


Figure 1. Artemis Phase 1: Lunar Surface by 2024

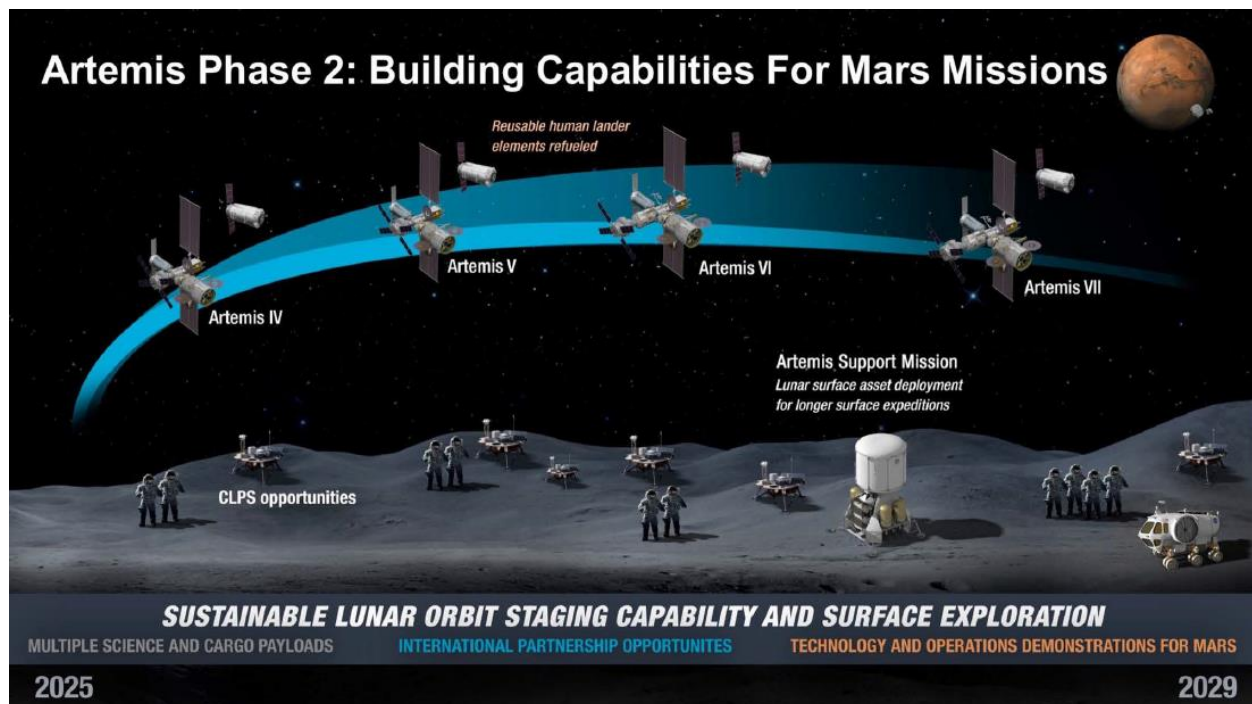


Figure 2. Artemis Phase 2: Lunar Sustainability

To achieve a human presence on the Moon in 2024, the Agency will be moving in a parallel path to achieve the Artemis mission architecture Phase 1 objectives, Figure 3. This will see a partnership between government and commercial systems to deliver crew, develop and deliver elements of the lunar orbiting Gateway system, and develop and deliver elements of the human landing system. Formulation efforts are maturing for the overall architecture, mission concept of operations, and conceptual designs of these elements. A number of hardware

development contracts are underway for some of these elements while other solicitations are in preparation for the remaining elements of the architecture.

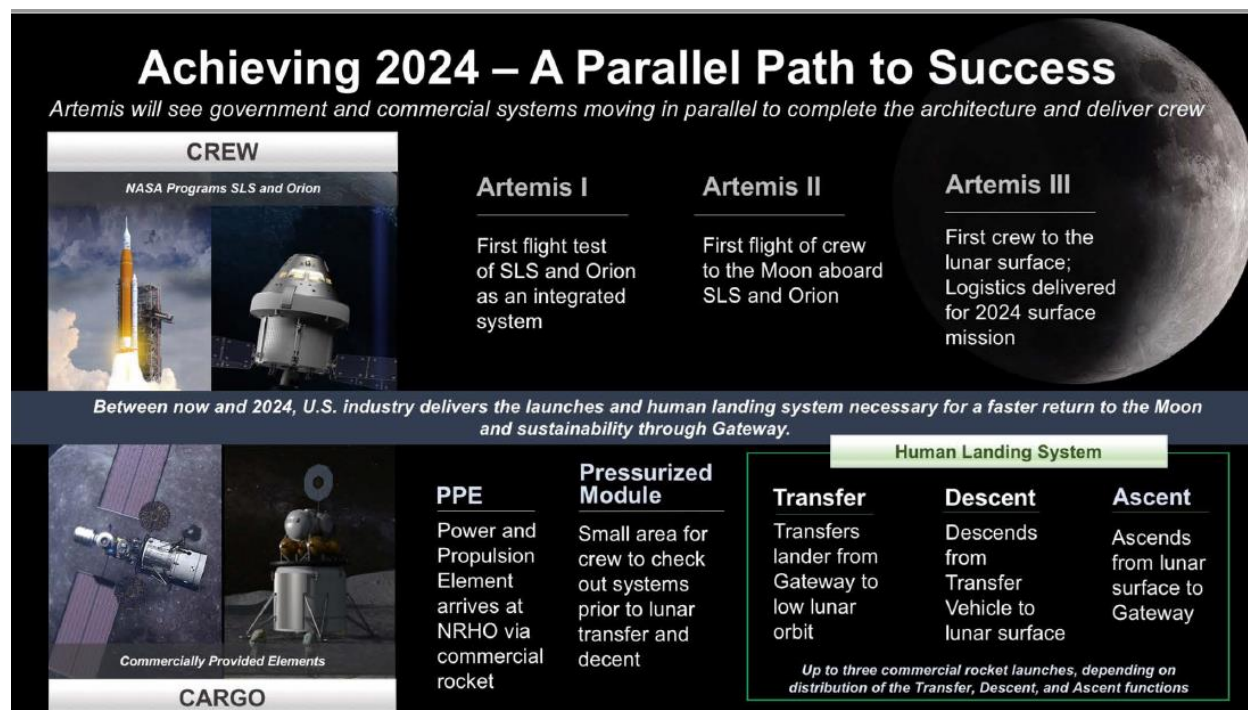


Figure 3. Parallel Paths to Achieving a Human Presence on the Moon in 2024

THE ARTEMIS MISSION ARCHITECTURE CHALLENGE

The Artemis mission architecture presents unprecedented and competing technical and programmatic challenges ahead that include: shortened development timelines, mission complexities (e.g., lunar orbit operations, multiple docking events, multiple elements, multiple launch vehicles, etc.), unprecedented mass constraints, and budgetary/schedule constraints. The combination of all of these interrelated factors presents a large technical challenge that inherently increased mission risk compared to low Earth orbit (LEO) mission. The distance from Earth, especially in a Mars class missions presents a challenge for safe haven capability. This is partially offset in the lunar architecture with some flexibility offered by the combination of Gateway, Orion and the human landing system ascent vehicles all providing crew habitable capabilities for a safe haven. The mass of spacecraft and systems intended to go beyond LEO as part of the architecture can significantly drive launch vehicle performance requirements, or conversely, realistic launch vehicle performance capabilities will significantly constrain spacecraft mass, given the large lunar and Mars gear ratios (rocket mass/delivered payload mass). In order to compensate for the inherent increased risk of deep space exploration mission, there is a need for high reliability in systems and in processes, and a need to better understand and reduce uncertainties while increasing margins, to deal with unknowns in order to achieve the necessary robustness for this bold endeavor.

Key technologies for reaching the Moon and Mars are shown in Figure 3.

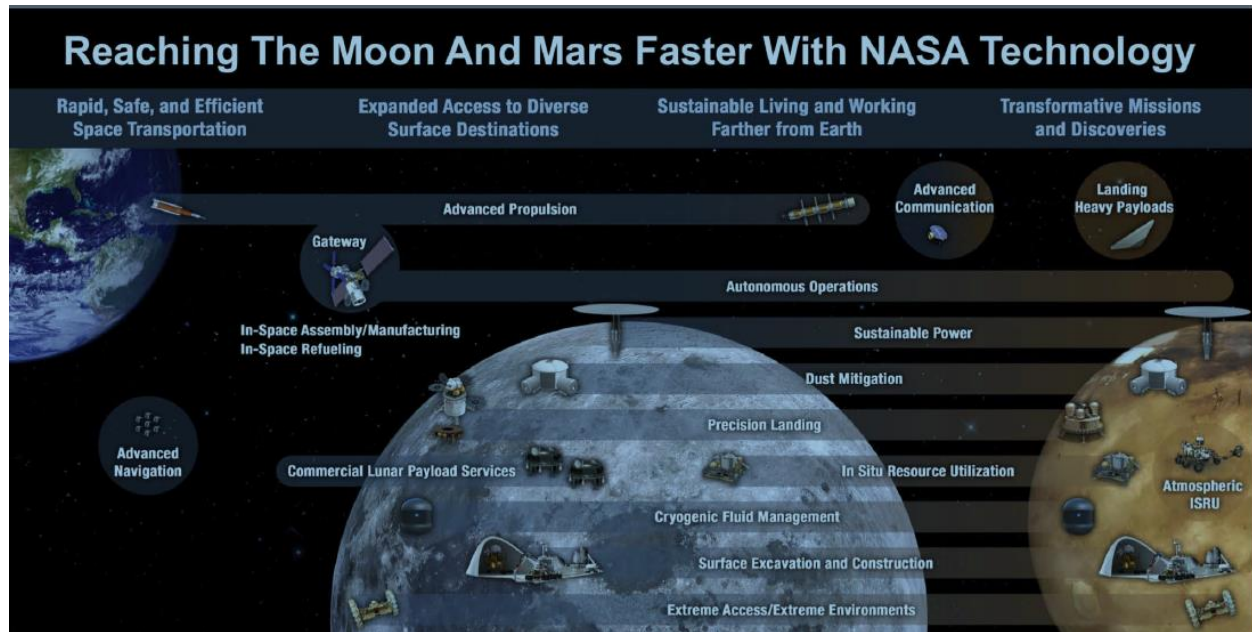


Figure 3. NASA Key Technology Drivers for Reaching the Moon and Mars

All of these challenges combined drive the need to be innovative in our development (design, analysis and test) efforts to optimize designs to exploit every ounce of reliability, system performance measure, and mass efficiency, that can be done within the time and budgets allowed. The structural dynamics discipline is key in all of these efforts.

WHAT ARE THE TECHNICAL NEEDS DRIVEN BY THE ARTEMIS MISSION?

A design philosophy of simplicity needs to be employed. One that starts with a system engineering process for top down functional allocation considering other systems to provide capabilities and control hazards before adding component or system level redundancy with associated increase in mass and complexity. To help with the reduced development timeline and take advantage demonstrated reliability, the architecture and system design should consider the use of proven heritage systems that have been qualified to the new environment. An integrated approach to development of NASA flight systems based on a reliability methodology with uncertainty quantification (UQ) could prove valuable. Current design approaches use “factors of safety” and “uncertainty factors” that may be sequentially applied by multiple teams. This approach stacks conservatism, inefficiencies and manifests itself in system cost growth. Appropriate factors for new technologies (e.g., components produces with additive manufacturing, composites, etc.) are unknown, so using existing factors may not be conservative nor appropriate. Verification and validation is expensive and has no consistent quantified metric across the Agency. Many probabilistic tools exist but best practices for their use and implementation in design and operations is lacking maturity and a standard process. Present development path relies on NASA having prior applicable experience which is dwindling with workforce attrition. NASA missions will require new technologies for which the heritage factor-of-safety structural design approaches (based on historical experience with materials like aluminum) have no technical foundation. The same is true in the development of uncertainty factors used in load, dynamic, and controls analyses as reliance on full vehicle testing diminishes and becomes heavily reliable on element testing. A reliability metric and reliability/UQ design methodology can place all structural materials/concept, and loads and dynamics on a common basis. NASA missions have cost and schedule constraints for which reliability/UQ methods would provide a rational approach to decisions by project management, system engineering, loads development, and structures engineering and provide a quantified basis for risk management.

Testing and analysis will be key to dealing with these challenges. Building block approaches are required that provide the right balance between component, system, and/or element level testing that satisfies verification and validation objectives and where, uncertainties are quantified and minimized. Given the significant cost and time required for to implement qualification test programs, we need to agree on methodologies very early in the development cycle. Consideration for investing in lower cost development testing of the more critical and complex

components and systems is important to gain valuable early insight into the fundamental physics, assumption and uncertainties, and will help buy down the potential for future schedule risk in more expensive qualification test programs. Sills and Allen provided a historical review of the building block approach in validation for human space flight [1] and state that “The National Aeronautics and Space Agency (NASA) manned flight programs has an enduring technical history in developing high performance flight systems, and in developing approaches to model, test and validate these complicated vehicles. The approach to understanding these systems is steeped in using a building block approach to understanding the fundamental physics of the integrated structural systems and developing test validated models for use in system analyses. From the Saturn V program to the current integrated stacked SLS system, the general premise of the building block approach was and is employed. The approach has evolved and leveraged lessons learned and observations from the past, while some challenges remain the same (i.e., joints are uncertain, people make mistakes when simplifying the models, etc...).” They further state that “Successful implementation of the building block approach requires that uniform criteria are implemented across the elements to gauge the success of the test and model correlation/correction. This includes adherence to standards and implementation of a structural verification plan that specifies consistent test and model correlation requirements for all the elements. These include mode survey test completeness and mode shape orthogonality criteria, model to test frequency and mode shape comparison criteria, and the requirement that all finite element model (FEM) changes made to improve agreement with test data must be consistent with the drawings and the hardware.”

As the Agency evolves into the Artemis phase 2 efforts for the sustainable lunar architecture and certainly for the Mars class missions, systems and structural health monitoring and long term life extension capabilities will be necessary. The Agency must design and certify to environments and life time/cycles requirements conservatively in the design phase. We will want to leverage the fact that the conservative design approach will have margins that we can take advantage of later in life extensions. Part of this involves early investments in the design for strategic flight instrumentation that can help quantify actual life usage, and even structural health monitoring as insight/control against potential catastrophic failure by indicate time for maintenance/repair or replacement.

THE ARTEMIS OPPORTUNITY

The Artemis mission architecture will challenge the structural dynamics discipline, and other disciplines, to improve current methods in both test and analysis and physics based understanding of large complex flexible structures. Given that the Artemis mission architecture requires complex systems, it provides a challenge to the community to develop analysis and testing techniques that can define nonlinear systems and provide for analysis tools to describe the system. This leads to a near term need to find innovative and affordable methods to not only enhance testing and analysis within the structural dynamics discipline, but also in ways that combine the physics of multiple interacting disciplines, a systems-of-systems methodology philosophy.

This opportunity provides for a re-focus on the merger of analysis and test. The current trend is a heavy reliance on analysis versus balanced approach of test and analysis for certification. Furthermore, there is a trend of analysis models not being an adequate representation of as-built hardware and an over-confidence in analytical model results as accurate representation. Today there are sophisticated tools and modeling capabilities in most disciplines like loads & structural dynamics, GNC, mechanical dynamics (docking system, robotics, etc...), propulsion, aero, thermal, etc. We need to leverage these analytical capabilities while ensuring they are properly anchored in real test data with uncertainties appropriately characterized and minimized. More consideration should be given for combinations of these tools to combine the physics that influence system design, performance, reliability, and mass to help optimize and exploit efficiencies. There should be more consideration for probabilistic approaches (Monte-Carlo) to quantifying system margins/safety factors rather than more conservative deterministic approaches, but at the same time one must understand the physics and distributions of individual parameters. There is a need to reconsider what can be achieved in ground testing and what requires flight testing for verification and validation considering gravity effects, vacuum effects, cryogenic effects, and combined system effects. This new paradigm will require leveraging model base system engineering (MBSE) and the use of intelligent learning algorithms as appropriate to help increase modeling efficiency and configuration management. At the end, the question that needs answering is, how do we best build confidence in systems and system-of-systems performance capabilities and margins and understand uncertainties?

Success in all of this will be measured by our collective ability to understand the new and complex systems that the mission architecture requires and by our incremental understanding of environments beyond low earth orbit and our

ability to apply this knowledge to influence efficiencies in design, performance, and reliability of the systems and architecture so that it closes on the this bold exploration mission endeavor.

CONCLUDING REMARKS ON THE ARTEMIS MISSION CHALLENGE

We are truly at the brink of another revolution in structural dynamics and interactions with other disciplines and the opportunities and challenges afforded as we return to the Moon and continue on Mars. This revolution builds on the revolutionary work from, the 1940's, 50's, and 60's that saw monumental changes in the discipline as computing power increased. The challenge is to find the appropriate balance analysis tool in terms of size, complexity, cases run, etc. to arrive at good reliable answer/solution with knowledge of product use (i.e., trade study decision making, critical system flight margin verification)-Avoid paralysis by analysis

REFERENCES

- [1] Sills, J, W, Allen, M. S, "Historical Review of "Building Block Approach" in Validation for Human Space Flight," Sensors and Instrumentation, Aircraft/Aerospace, Energy Harvesting & Dynamic Environments Testing, Volume 7, Proceedings of the 37th IMAC, A Conference and Exposition on Structural Dynamics 2019.