Office of Technology, Policy, and Strategy

RESILIENCY IN FUTURE CISLUNAR SPACE ARCHITECTURES

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Report ID

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Washington, DC 20024

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Executive Summary

Office of Technology, Policy, and Strategy

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Purpose of the Study

Resiliency is an aspirational metric, and it is a common goal for complex systems – be they engineered space architectures, geopolitical networks, or the human immune system. However, despite the ubiquitous desire for resiliency, the concept is surprisingly difficult to define and apply to future planning efforts. The objective of this work is to introduce and explore the concept of resiliency as it relates to future cislunar space architectures by 1) citing examples of its growing demand across government; 2) describing potential characteristics of resilient systems; 3) introducing a framework for evaluating the linkages between resilient capabilities and visions for future cislunar architectures; and 4) exercising the framework to identify and evaluate resiliency-enabling technical capabilities for cislunar space architectures. We assert that resiliency can emerge from a layered approach of deliberately chosen capabilities with overlap and flexibility that, in aggregate, result in a resilient system. The challenge is to identify capabilities that contribute to resiliency and to accurately characterize their value. Resiliency is discussed through the lens of future architecture planning, outlining how the National Aeronautics and Space Administration (NASA) can benefit from a shift in approach when transitioning focus to the cislunar environment.

Key Findings

In 2021, NASA facilitated a study exploring the concept of resiliency as it relates to cislunar architectures. Two working groups were established, an architecture working group and a technology working group. In initial working group discussions, participants recognized the value in characterizing resiliency to be inclusive of, but not focused solely on, reliability and mission assurance. Although several definitions of resiliency were proposed by participants or identified from industry and government, no single definition of resiliency was agreed upon by participants. However, there was general agreement that resiliency is inclusive of robustness, flexibility, agility and responsiveness, and the ability to evolve. Discussions also captured several characteristics of resilient systems, such as those that offer redundancy, disaggregation, self-healing abilities, situational awareness, and survivability.

Rather than establishing a single definition, the working groups were able to characterize resiliency through a descriptive framework to provide a comprehensive assessment of resiliency. The framework, a matrix shown in Table 1, describes capabilities in terms of five aspects (i.e., the ways in which a system can be resilient) and four types of resiliency (i.e., the types of stressors to which a system can be resilient), detailing a tool to evaluate a technology's ability to preempt, withstand, react, recover, and evolve to known and unknown stressors including those originating within the environment, human, system, or support.

Table 1. Resiliency Framework

[Capabilities exist at the cross section of Resiliency Types and Resiliency Aspects]		**Resiliency Aspects (Verbs)** High-level goals which define functions, methods, or actions used by a resilient system				
		Preempt	Withstand	React	Recover	Evolve
Resiliency Types (Nouns) Types of stressors to which aspects of resiliency are applied to ensure continued utility	Environment	[Capability]	[Capability]	[Capability]	[Capability]	[Capability]
	Human	[Capability]	[Capability]	[Capability]	[Capability]	[Capability]
	System	[Capability]	[Capability]	[Capability]	[Capability]	[Capability]
	Support	[Capability]	[Capability]	[Capability]	[Capability]	[Capability]

Resiliency Types: Where does the stressor or disruptor originate?

- **Environment:** Inherent challenges and uncertainties from the natural environment
- **Human:** Human interaction
- **System:** System design, characteristics, or flaws internal to the system
- **Support:** Interaction with external supporting systems, infrastructure, or processes

Resiliency Aspects: Which functions, methods, or actions may be used and when?

- **Preempt:** Taking action, making choices, predictions, or allocations before a stressor
- **Withstand:** Maintaining full or partial capability during a stressor due to inherent qualities
- **React:** Taking action to avoid, affect, or mitigate the cause or impact of a stressor
- **Recover:** Taking action after a stressor to return to an original operating state
- **Evolve:** Changing a nominal state after a stressor to improve future performance

Once the framework was complete, the technology working group exercised the creativity matrix by identifying technical capabilities at the intersections of the Resiliency Aspects and Types. The brainstormed capabilities, such as 1) fast, efficient, and cheap dexterous robotics and 2) built in soft and hard stops, were compiled into a database of 52 resiliency-enabling technical capabilities. The listing and characterization of the technical capabilities in the database demonstrate preliminary utility of the Framework as a rubric to evaluate and aggregate resiliency. By further using the framework to identify and evaluate resilient technical capabilities in connection to cislunar mission functions - building blocks of a functional architecture – the value of the framework may be fully realized. While we provide the key elements and outline the approach, additional work is necessary to further apply the Resiliency Framework and connect the Technical Capabilities Database to cislunar architectures.

About OTPS

The Office of Technology, Policy, and Strategy (OTPS) is an independent office providing NASA leadership with data- and evidence-driven advice on technology, policy, and strategy. Established when the Office of Strategic Engagements and Assessments and the Office of the Chief Technologist combined in 2021, OTPS's trusted advice informs Agency-level decision making about NASA's activities across its six mission directorates. In this role, OTPS undertakes independent analyses and studies, such as the one described in this report, to provide leadership with a set of objective recommendations. For more information on the NASA Office of Technology, Policy, and Strategy to view publicly available reports visit https://www.nasa.gov/offices/otps/home/index.html.

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Introduction

This work introduces and explores the concept of resiliency as it relates to future cislunar space architectures by 1) citing examples of its growing demand across government; 2) describing potential characteristics of resilient systems; 3) introducing a framework for evaluating the linkages between resilient capabilities and visions for future cislunar architectures; and 4) exercising the framework to identify and evaluate resiliency-enabling technical capabilities for cislunar space architectures. We assert that resiliency can emerge from a layered approach of deliberately chosen capabilities with overlap and flexibility that, in aggerate, result in a resilient system. The challenge is to identify capabilities that contribute to resiliency and to accurately characterize their value. Resiliency is discussed through the lens of future architecture planning, outlining how the National Aeronautics and Space Administration (NASA) can benefit from a shift in approach when transitioning focus to the cislunar environment.

Resiliency

Quality metrics of spacecraft and space architectures are often reliability, robustness, or even mission assurance. However, these metrics are bounded by definitive values calculated from engineered characteristics and only apply when operating within known limits. Resiliency is the ability for a component, subsystem, system, or architecture (a system-of-systems) to provide needed utility both within and outside anticipated limits.

Resiliency is an aspirational metric, and it is a common goal for complex systems – be they engineered space architectures, geopolitical networks, or the human immune system. However, despite the ubiquitous desire for resiliency, the concept is surprisingly difficult to define and apply to future planning efforts. The National Academies of Sciences, Engineering, and Medicine defines resiliency as "the ability to plan and prepare for, absorb, recover from, and more successfully adapt to adverse events."[1] In a different view, the Department of Defense's (DoD) definition of resiliency is focused more on straightforward utility to a wide range of applications and known and detectible failure modes that gracefully degrade with some continued utility.[2] Both approaches to the term recognize resiliency as a dynamic concept that adapts or evolves, but neither provides a clear yardstick by which to measure resiliency. Another noteworthy definition of resiliency derives from the study of complex ecological

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[1] Committee on Increasing National Resilience to Hazards and Disasters; Committee on Science, Engineering, and Public Policy (COSEPUP); Policy and Global Affairs (PGA); The National Academies. Disaster Resilience: A National Imperative. The National Academies Press: http://www.nap.edu/catalog.php?record_id=13457 (2012)

[2] Goerger, Simon & Madni, Azad & Eslinger, Owen. (2014). Engineered Resilient Systems: A DoD Perspective. Procedia Computer Science. 28. 865-872. 10.1016/j.procs.2014.03.103.

systems in which resiliency is an emergent behavior of complex systems enabling continued system propagation in the face of new and unanticipated threats. For example, the human immune system builds resiliency by investing resources in randomly mutated lymphocytes that produce antibodies to protect against proteins that the body has never seen (and may never see) but could be present on future microbiological invaders. This "inefficiency" results in a greater overall system resiliency.

Resiliency and Space

The concept of resiliency is being incorporated into the lexicon of our national leadership as well as U.S. space agencies. The United States Space Priorities Framework released by the White House highlights the need for "[enhancing] the security and resilience of space systems that provide or support U.S. critical infrastructure from malicious activities and natural hazards."[3] In the commercial sector, resiliency is approached differently but is equally critical. Several low-Earth orbit (LEO) constellation companies are building in modularity, spiral upgrades, planned obsolescence, and low-cost constellation refreshes to achieve a systems-of-systems resiliency that supersedes individual satellite brittleness or fragility. This drive toward resiliency is due in part to increased complexity of space architectures (including LEO constellations), increased autonomy, and—at least for government systems—budgetary pressures driving the need to do more with less resources.

For cislunar architectures—including, but not limited to, areas such as space domain awareness, mobility and logistics, communications, and position, navigation, and timing[4] —we are concerned about continued utility in the face of known and unknown stressors. Put simply, a resilient system works as intended and continues to work (at least to some degree) when used as it is not intended. This is a critical property for deep space systems that require a significant investment in time and money, cannot be easily replaced, and must remain operational for decades. Such systems must also be designed with imperfect knowledge about the environment, needs of future users, and evolving stressors that can impact the designed utility. As it is impossible to know every potential challenge, interface, or future application for a cislunar capability, designing or testing for resilient behavior requires a deviation from the traditional system engineering tools. We assert that resiliency can emerge from a layered approach of deliberately chosen capabilities with overlap and flexibility that, in aggregate, result in a resilient system. The challenge is to identify capabilities that contribute to resiliency and to accurately characterize their value.

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[3] https://www.whitehouse.gov/wp-content/uploads/2021/12/United-States-Space-Priorities-Framework-_-December-1-2021.pdf
[4] Drew, A. (2020). Background Paper on Cislunar. 2020 DAF-NASA-NRO Summit.

Characterizing Resiliency

In 2021, NASA facilitated a study, including a technology working group (TWG) and architecture working group (AWG), to explore the concept of resiliency as it relates to cislunar architectures. The agency recognizes the value in planning for resilient systems and the challenges of defining and characterizing resiliency through standard engineering tools. Through a working group approach, NASA looked at future plans such as NASA's Artemis architecture and potential pathways for resilient cislunar capabilities to improve our future resiliency posture. In initial working group discussions, participants recognized the value in characterizing resiliency to be inclusive of, but not focused solely on, reliability and mission assurance. Although several definitions of resiliency were proposed by participants or identified from industry (see Table 2), no single definition of resiliency was agreed upon by participants. However, there was general agreement that resiliency was inclusive of robustness, flexibility, agility and responsiveness, and the ability to evolve. Discussions also captured several characteristics of resilient systems, such as those that offer redundancy, disaggregation, self-healing abilities, situational awareness, and survivability. While the working groups did not finalize a common definition of resiliency due to the complexity and variation of perspectives, they were able to characterize resiliency through a descriptive framework. We suggest the use of this framework in place of a single definition to provide a comprehensive assessment of resiliency.

Table 2. Resiliency References

1	***Resiliency** is the ability of a system architecture to continue providing required capabilities in the face of system failures, environmental challenges, or adversary actions* Resiliency and Disaggregated Space Architectures, Air Force Space Command, 2016[5]
2	***Resilience** is defined as the ability to deliver the mission in the face of manmade or natural interference* Resiliency of Space Systems, The Aerospace Corporation, 2017[6]
3	***Resilience** is the ability of an architecture to support the functions necessary for mission success in spite of hostile action or adverse conditions. An architecture is "***more resilient***" if it can provide these functions with higher probability, shorter periods of reduced capability, and across a wider range of scenarios, conditions and threats. **Resilience** may leverage cross-domain or alternative government, commercial, or international capabilities* Department of Defense (DoD) Fact Sheet, 2011
4	**Resilience:** *The ability of an architecture to support the functions necessary for mission success with higher probability, shorter periods of reduced capability, and across a wider range of scenarios, conditions, and threats, in spite of hostile action or adverse conditions* **Resilience:** *An internally-focused characteristic of an architecture that is extremely difficult to characterize in a closed form analysis… [developed into] the fewest categories into which resiliency could be sufficiently organized. We arrived at six discrete characteristics to describe resilience approaches: disaggregation, distribution, diversification, protection, proliferation, and deception* Space Domain Mission Assurance Resilience Taxonomy, Office of the Assistant Secretary of Defense for Homeland Defense & Global Security (2015)[7]
5	**Resilience**: *The ability to adapt to changing conditions and withstand and rapidly recover from disruption due to emergencies* Presidential Policy Directive 8: National Preparedness, Obama White House, 2011[8]
6	*The characteristic or capability to maintain functionality and structure (or degrade gracefully) in the face of internal and external change* Mission Assurance Policy for the Defense Intelligence Enterprise, DoD, 2015[9]
7	*System **resilience** is defined as the ability of the system to withstand a major disruption within acceptable degradation parameters and to recover within an acceptable time and composite costs and risks* On the Definition of Resilient Systems, Haimes, et al., 2008; Haimes, 2009[10]
8	***Resilience** is designed to have systems self-heal with no intervention from humans. In the cyber context, a resilient cyber system must continue to operate as intended, even if compromised (for example, if unauthorized access is achieved)* Understanding Today's Cyber Challenges, TASC, 2011
9	*The ability to quickly adapt and recover from any known or unknown changes to the environment. **Resiliency** is not a process, but rather an end-state for organizations. The goal of a resilient organization is to continue mission essential functions at all times during any type of disruption. **Resilient** organizations continually work to adapt to changes and risks that can affect their ability to continue critical functions* Contingency Planning Guide for Federal Information Systems, National Institute for Standards and Technology (NIST), 2010[11]

The blue verbs inspired and informed the Resiliency Aspects of the Resiliency Framework. The green nouns inspired and informed the Resiliency Types of the Resiliency Framework.

Resiliency Framework

With the assistance of the facilitation and analysis team, the working groups quickly acknowledged that some systems will be more or less resilient to different types of adverse events, or "stressors," and respond in different ways. Rather than a binary quality, resiliency may vary in degree and with respect to various stressors. In turn, an agency may make different design choices based on various aspects and types of resiliency. Expanding on previous resiliency taxonomy by MITRE and the Aerospace Corporation, the team established a Resiliency Framework (see Table 3) consisting of Resiliency Aspects (i.e., the ways in which a system can be resilient) and Resiliency Types (i.e., the types of stressors to which a system can be resilient). The Resiliency Aspects are inspired by the action verbs and descriptors of resilient systems mentioned in the resiliency references in Table 1. On the other hand, the Resiliency Types, are derived from the nouns and domains in which resiliency is applied. By dissecting the various resiliency definitions and references along these two axes, the framework emerged.

Table 3. Resiliency Framework

[Capabilities exist at the cross section of Resiliency Types and Resiliency Aspects]		**Resiliency Aspects (Verbs)** High-level goals which define functions, methods, or actions used by a resilient system				
		Preempt	Withstand	React	Recover	Evolve
Resiliency Types (Nouns) Types of stressors to which aspects of resiliency are applied to ensure continued utility	Environment	[Capability]	[Capability]	[Capability]	[Capability]	[Capability]
	Human	[Capability]	[Capability]	[Capability]	[Capability]	[Capability]
	System	[Capability]	[Capability]	[Capability]	[Capability]	[Capability]
	Support	[Capability]	[Capability]	[Capability]	[Capability]	[Capability]

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[5] https://www.afspc.af.mil/Portals/3/documents/AFD-130821-034.pdf?ver=2016-04-14-154819-347

[6] https://aerospace.org/research/resilience-space-systems-white-paper#:~:text=Resilience%20is%20defined%20as%20the,ability%20to%20meet%20mission%20requirements.

[7] https://man.fas.org/eprint/resilience.pdf

[8] https://www.dhs.gov/presidential-policy-directive-8-national-preparedness

[9] https://www.esd.whs.mil/Portals/54/Documents/DD/issuances/dodi/302039p.pdf?ver=JPHOUDssXNNUJ_zp15tWcw%3D%3D

[10] https://www.researchgate.net/publication/24247494_On_the_Definition_of_Resilient_Systems

[11] https://nvlpubs.nist.gov/nistpubs/Legacy/SP/nistspecialpublication800-34r1.pdf

Resiliency Aspects

Resiliency Aspects can be defined as high-level goals which define functions, methods, or actions used by a resilient system. The working groups identified that systems could provide resiliency through multiple methods. Several actions were proposed with significant degrees of overlap and a loose temporal structure to describe actions taken before, during, or after a given stressor, as illustrated in Figure 1. For the purpose of the study, five resiliency aspects were identified and agreed to by working group participants: Preempt, Withstand, React, Recover, and Evolve.

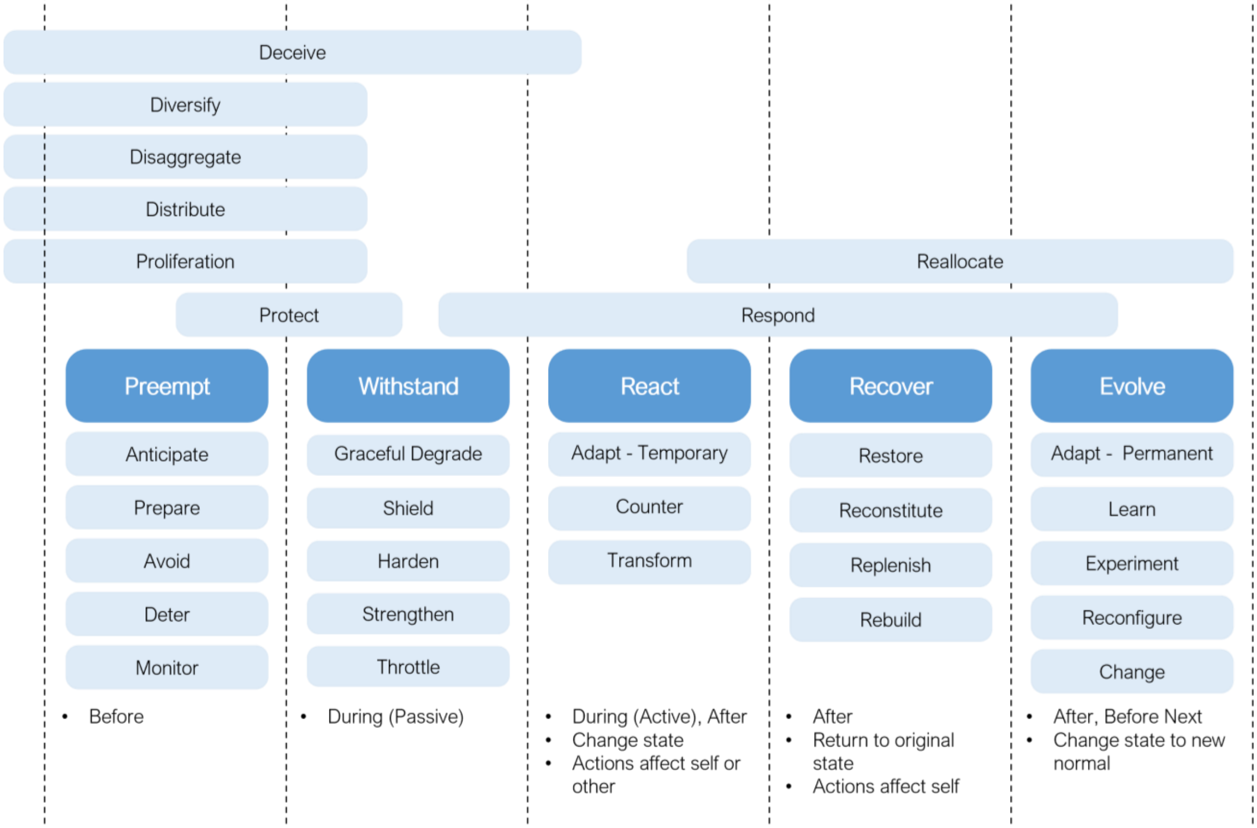

Figure 1. Resiliency Aspects

Preempt: Actions taken, choices made, predictions made, or allocations made before a stressor begins. Preempt includes terms such as anticipate, prepare, avoid, deter, monitor, protect; however, it is not simply engineering to account for expected variances or reactive decisions. An example of Preempt in a resilient cislunar system is the ability to track and forecast micrometeoroid and orbital debris (MMOD) to ensure systems operate in orbits with the least risk of impact.

Withstand: Maintaining full or partial capability during a stressing event due to inherent qualities of the system. Withstand includes terms such as shield, harden, strengthen, throttle, hibernate, and graceful degradation. Withstand does not include actions taken by the system to change its state in response to a stressor. An example of Withstand in a resilient cislunar system is inclusion of additional MMOD shielding to provide additional protection for spacecraft.

React: An action taken to avoid, affect, or mitigate the cause or impact of a stressing event. React includes temporary state changes, counters, responses, reallocation of resources, and system transformations. It can occur during or immediately after an event but is not inclusive of repair or recover actions. An example of React in a resilient cislunar system is the ability to maneuver around detected debris or orientate the spacecraft to effectively utilize the additional MMOD shielding available.

Recover: Self correction or external actions that return the system to an original operating state. Recover includes terms such as restore, reconstitute, replenish, and rebuild. Recover, in the case of resiliency, is not replacement of an entire system or architecture, but could include expendable components that can be rapidly replenished. An example of Recover in a resilient cislunar system is self-healing materials that repair MMOD damage.

Evolve: Changes to a system's nominal state in response to a stressor to improve future performance. Evolve includes terms such as adaption, learning, experimentation, reconfigure, change, and redistribution. Evolve is not a temporary response such as an avoidance maneuver or upgrades to a spacecraft. An example of Evolve is a redesign of a constellation deployment to remove critical systems from congested orbital planes where MMOD risk is high.

Resiliency Types

Resiliency Types can be defined as types of stressors to which aspects of resiliency are applied to ensure continued utility. There is a wide variety of stressors that can disrupt cislunar systems and architectures. As illustrated in Figure 2 these stressors may originate in the **system** itself, in the **environment** (in which the system exists), in a **human** (either co-located with the system or in a different environment), or in a **support** system (either co-located with the primary system or in a different environment). Brainstormed examples ranged from manufacturing flaws to supply-chain failures to natural events. For this study, four Resiliency Types were identified: Environment, Human, System, and Support.

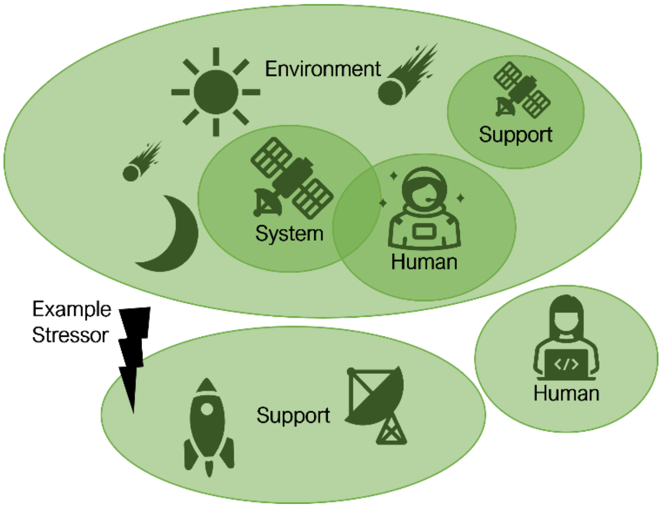

Figure 2. Resiliency Types

Environment: Stressor or disrupter resulting from inherent challenges and uncertainties from the natural environment. This includes space radiation, MMOD, and thermal challenges (note: space debris is part of the "natural" environment). Cislunar examples include a solar particle event that disrupts or damages electronics, a rocket body collision that places a new debris field in a system's path, or orbital alignment that results in a longer than typical period of darkness.

Human: Stressor or disrupter due to human interaction. This includes operator errors such as incorrect commands, misdiagnosed anomalies, processing and response delays, and incorrect software uploads. Cislunar examples include a mission operator sending an erroneous command to a spacecraft causing it to slew in an unexpected way or the crew making a mistake when following emergency protocols resulting in a system shutdown.

System: Stressor or disrupter resulting from system design, characteristics, or flaws internal to the system. This includes software bugs, unexpected performance characteristics, manufacturing flaws and system fatigue. Cislunar examples include large deployable structures failing to deploy due to a mechanical flaw or a tool failing due to inadequate knowledge of the performance requirements.

Support: Stressor or disrupter resulting from the interaction with external supporting systems, infrastructure, or processes. This includes communication network failures, supply-chain disruptions, or insufficient space domain awareness. Cislunar examples include lost position, navigation, and timing (PNT) or space situational awareness data during complex maneuvers or disruption of ground-based computing resources necessary to process spacecraft instrument data.

Resiliency-Enabling Technical Capabilities

To date, the study team has developed the Resiliency Framework and applied the creativity matrix of Resiliency Aspects and Types by creating a list of desired technical capabilities for enhancing mission resiliency in cislunar space. The brainstorming occurred over several sessions with the technology working group and the analysis team. From these meetings, we obtained 177 capabilities covering all combinations of Resiliency Aspects and Resiliency Types, according the to the developed Framework. The Analysis Team then went through and grouped similar items by their broader category, e.g., capabilities referring to cybersecurity and encryption were grouped together. Additionally, since many capabilities overlapped with functions given in the 2021 On-orbit Servicing, Assembly, and Manufacturing (OSAM) State of Play[12], we replaced these with the 11 OSAM areas for better coordination with other cross-agency efforts. The final result is a list of 52 capabilities, provided in Appendix A.

In Figure 3, we provide two examples of resiliency-enabling technical capabilities in our database: 1) Fast, efficient, and cheap dexterous robotics which were considered to be enabling in terms of preempting, recovering from, and evolving to stressors across the four Resiliency Types, and 2) Built in soft and hard stops which were considered to be enabling in terms of withstanding and reacting to disruptions in the human and support systems. These technical capabilities are further described in terms of cislunar benefits and considerations and NASA primary and secondary taxonomy[13] in Appendix A. As a demonstration of one utility that the framework offers, we show in Figure 3 how you may consider adding the two technical capabilities and their accompanying resiliency to better understand the ability of a total system to cover all aspects and types of resiliency.

This Resiliency Framework of aspects and types provides a matrix for discussing capabilities and their potential contribution to a system or architecture's aggregate resiliency. It is not a map for establishing requirements for resiliency, but instead assists with thinking creatively to understand potentially unexpected contributions or limitations and dependencies that are not expressed in traditional systems engineering. For example, a communication system that provides a sensing modality and a secondary PNT capability would address more aspect-type pairings than a higher-bandwidth but less-flexible alternative, thus increasing the system's overall resiliency. This analysis tool may also help identify when two seemingly unrelated capabilities are affected by the same stressors, potentially advocating for an overlapping Resiliency Aspect that supports both capabilities.

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[12] On-Orbit Servicing, Assembly, and Manufacturing 2021 edition: https://ntrs.nasa.gov/api/citations/20210022660/downloads/osam_state_of_play%20(1).pdf

[13] 2020 edition: https://www.nasa.gov/offices/oct/taxonomy/index.html

<table>
<tr><td colspan="7">Example Tech Capability A: Fast, efficient, and cheap dexterous robotics</td></tr>
<tr><td colspan="7">Description: Ability to perform regular, external spacecraft inspections by remotely operated or autonomous robotics. For example, consider the robotic implementation of all astronaut EVAs on ISS.</td></tr>
<tr><td colspan="2" rowspan="2">Resiliency</td><td colspan="5">Resiliency Aspects (Verbs)</td></tr>
<tr><td>Preempt</td><td>Withstand</td><td>React</td><td>Recover</td><td>Evolve</td></tr>
<tr><td rowspan="4">Resiliency Types (Nouns)</td><td>Environment</td><td>X</td><td></td><td></td><td>X</td><td>X</td></tr>
<tr><td>Human</td><td>X</td><td></td><td></td><td>X</td><td></td></tr>
<tr><td>System</td><td>X</td><td></td><td></td><td>X</td><td>X</td></tr>
<tr><td>Support</td><td></td><td></td><td></td><td></td><td>X</td></tr>
</table>

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<table>
<tr><td colspan="7">Example Tech Capability B: Built in soft and hard stops</td></tr>
<tr><td colspan="7">Description: The capability to prevent/inhibit/avoid catastrophic system damage through embedded hardware and software stops within the interfaces and subsystems for real-time and safety-critical systems.</td></tr>
<tr><td colspan="2" rowspan="2">Resiliency</td><td colspan="5">Resiliency Aspects (Verbs)</td></tr>
<tr><td>Preempt</td><td>Withstand</td><td>React</td><td>Recover</td><td>Evolve</td></tr>
<tr><td rowspan="4">Resiliency Types (Nouns)</td><td>Environment</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Human</td><td></td><td>X</td><td>X</td><td></td><td></td></tr>
<tr><td>System</td><td></td><td>X</td><td>X</td><td></td><td></td></tr>
<tr><td>Support</td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

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<table>
<tr><td colspan="7">Example Total Tech Capability: Tech Capability A + Tech Capability B</td></tr>
<tr><td colspan="7">Description: This example system includes both example technical capabilities, 1) fast, efficient, and cheap dexterous robotics and 2) built in soft and hard stops.</td></tr>
<tr><td colspan="2" rowspan="2">Resiliency</td><td colspan="5">Resiliency Aspects (Verbs)</td></tr>
<tr><td>Preempt</td><td>Withstand</td><td>React</td><td>Recover</td><td>Evolve</td></tr>
<tr><td rowspan="4">Resiliency Types (Nouns)</td><td>Environment</td><td>X</td><td></td><td></td><td>X</td><td>X</td></tr>
<tr><td>Human</td><td>X</td><td>X</td><td>X</td><td>X</td><td></td></tr>
<tr><td>System</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>Support</td><td></td><td></td><td></td><td></td><td>X</td></tr>
</table>

Figure 3. Example Resiliency-Enabling Technical Capabilities

Conclusion

Additional work is necessary to further demonstrate the value of the Resiliency Framework tool and apply it to architectures. Through this study process, we have characterized the need to think about resiliency along with mission objectives and system requirements. We note that while resiliency is challenging to define, it should be an aspirational goal for any design, particularly those with the potential for long-duration operations. Although there is not a clear-cut approach to guarantee resiliency, there are characteristics that are indicative of resilient systems and architectures. Thinking proactively about how these characteristics, that are enabled or enhanced by technical capabilities, can be applied to mitigate or neutralize potential stressors can assist in solidifying the role and utility of resiliency. The Resiliency Framework can thus be used as an analysis (or assessment) tool to identify gaps and dependencies in technical capabilities that must be considered (or addressed) to mature a system’s resiliency for envisioned future cislunar space architectures.

Acronyms

AWG	Architecture Working Group
DoD	Department of Defense
LEO	Low-Earth Orbit
MMOD	micrometeoroid and orbital debris
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
OSAM	On-orbit Servicing, Assembly, and Manufacturing
OTPS	Office of Technology, Policy, and Strategy
PNT	Position, Navigation, and Timing
TWG	Technology Working Group

Appendix A - Resiliency-Enabling Technical Capabilities Database

For each item in the Resiliency-Enabling Technical Capabilities Database, the *Title* and *Description* give a quick overview of each capability. We were specifically interested in cislunar applications, referring to the region outside geostationary orbit where bodies are gravitationally affected by both the Earth and the Moon. *Cislunar considerations* refer to any potential difficulties or issues that apply in cislunar space, but not geostationary orbit. *Cislunar benefits* refer to technological abilities that specifically enable missions in cislunar space that would not otherwise be possible. *Primary/Secondary Taxonomy* gives the most relevant NASA technology taxonomy area(s)[14] for enabling this capability. Finally, the bottom of each box denotes the most relevant resiliency aspect/type combinations for the given resiliency.

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[14] 2020 edition: https://www.nasa.gov/offices/oct/taxonomy/index.html

Table 4. Resiliency-Enabling Technical Capabilities Database Summary

		Environment					Human					System					Support				
Capability Title	Page #	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
Advanced Encryption for Space Applications	17						x					x									
Fail-safe systems on a chip	17			x	x				x	x											
Fast, efficient and cheap dexterous robotics	18	x			x	x	x			x		x			x	x					x
Cross vehicle comm links that are independent and redundant for re-routing of comm to ground	18			x	x	x			x	x	x			x	x	x			x	x	x
RF/optical power beaming	19		x	x																	
Ability to deorbit, repurpose, or re-use end of life satellites.	19	x																			
Computer vision-based learning	20					x					x					x					x
Open data platform to monitor who is active in the cis-lunar orbital domain	20	x																			
Improved visualization/interface tools (XR)	21	x					x					x					x				
Digital threads identifying design/coding choices and impacted systems	21									x	x				x	x					
Reprogrammable or reconfigurable hardware	22					x					x					x					x
Lunar surface -- navigation systems that provide location/orientation information	22						x														
Built in soft and hard stops within interfaces/subsystems that prevent catastrophic system damage	23							x	x				x	x							
Adaptive propulsion system to transition to a new orbit, at varying time scales, in order to avoid impending damage from radiation or MMOD event	23			x	x				x	x				x	x				x	x	
Self Aware and autonomously reconfigurable Avionics	24			x	x	x			x	x	x				x	x			x	x	x
Rad-hardened computer processors (or FPGAs/GPUs) (includes error checking)	24		x		x			x		x			x		x						
Training protocols for quick and efficient recovery of optimal operator cognitive state	25							x	x	x	x										

Characterization of lunar dust clouds prior to meteor (or spacecraft) impact; model for bolide-like impact	25	x																			
Sensors that can dynamically control aperture or provide other protective measure	26			x					x												
Hibernation/Safe-Mode	26		x	x				x		x								x			
Automated check for spacecraft logic/operation consistency	27						x	x													
RF communications robustness against environmental overload	27		x	x				x	x												
Shielding against externally-caused damage (permanent or temporary deployment)	28		x	x				x	x												
Psychophysiological monitoring of crew state (using biometrics and machine learning to predict operator cognitive workload) and interaction with autonomous operation	28						x	x	x	x	x										
Solar radiation weather monitoring and modelling	29	x				x	x														
Failsafe or operational safe boot capability	29				x					x					x					x	
MMOD detection and tracking (sensors and algorithms)	30	x		x	x	x	x		x	x	x	x		x	x	x	x		x	x	x
Dynamic Space Communications Network	30	x	x	x	x	x	x		x	x	x	x			x	x					
Spacecraft command queuing system that monitors and predicts system state after a command is issued	31		x	x	x			x	x	x			x	x	x			x	x	x	
Embedded health system monitoring sensors	31	x			x		x			x		x			x						
Predictive Models for Event Impact on Systems Health	32	x			x	x	x			x	x	x			x	x	x			x	x
Propulsion and GNC algorithms that are responsive to structural health monitoring	32	x		x	x	x	x		x	x	x				x	x					
Proactive Cyber System Modeling	33						x		x												
GNC algorithms to determine optimal safe transition orbit that avoids new or emergent MMOD or radiation event	33			x		x			x												
Supply chain logistics and control	34																x	x	x		x
GPS-free navigation	34		x		x																
Ability to quarantine cyber systems and reallocate functionality	35							x	x	x											
Cislunar Depots for OSAM Capabilities	35				x	x				x	x				x	x					x
OSAM: Robotic Manipulation	36				x	x				x	x				x	x					x

OSAM: Rendezvous & Proximity Operations, Capture, Docking, Mating	36				x	x				x	x				x	x					x
OSAM: Relocation	37				x	x				x	x				x	x					x
OSAM: Planned Repair, Upgrade, Maintenance, Installation	37				x	x				x	x				x	x					x
OSAM: Unplanned or Legacy Repair	38				x	x				x	x				x	x					x
OSAM: Refueling and Fluid Transfer	38				x	x				x	x				x	x					x
OSAM: Structural Manufacturing and Assembly	39				x	x				x	x				x	x					x
OSAM: Recycling, Reuse, Repurposing	39				x	x				x	x				x	x					x
OSAM: Parts and Goods Manufacturing	40				x	x				x	x				x	x					x
OSAM: Surface Construction	40				x	x				x	x				x	x					x
OSAM: Inspection and Metrology	41				x	x				x	x				x	x					x
Distributed, Collaborative Spacecraft Systems (Multi-sensor network fusion, interoperability and capability redistribution on node failure)	41	x	x	x	x	x	x	x	x	x	x	x		x	x	x			x	x	x
Materials (hull) resistant against damage (dust, MMOD impact, lasing, radiation)	42	x	x		x																
Verification and Validation Tools, including Digital twin modeling and simulation capability	43	x			x							x			x		x			x	

Title: **Advanced Encryption for Space Applications**

Description: **Next-generation encryption will be a critical capability for ensuring the safety and security of systems in all space domains. This includes novel encryption techniques, decentralized encryption, blockchain-dependent encryption, and any form of randomized or evolving encryption technologies that exceed the current (2021) state of the art.**	*Cislunar considerations:* **Distance between assets or from the GEO or LEO sphere may add additional challenges for cislunar applications.**
	Cislunar benefits: **(no anticipated unique benefits for cislunar)**
Primary Taxonomy (NASA): Software, Modeling, Simulation, and Information Processing	*Secondary Txnmy:* Autonomous Systems

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
					X					**X**									

Title: **Fail-safe systems on a chip**

Description: **Integrated systems on a chip with built-in fail-safe mechanisms to detect errors, automatically save processes if an error is detected, and potentially recover automatically.**	*Cislunar considerations:* **(no special considerations beyond GEO)**
	Cislunar benefits: **Higher reliability/longer lifetime for deep-space mission assets without access to repair**
Primary Taxonomy (NASA): Flight Computing and Avionics	*Secondary Txnmy:* (none)

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
		X	**X**				**X**	**X**											

Title: **Fast, efficient and cheap dexterous robotics**

Description: **Ability to perform regular, external spacecraft inspections by remotely operated or autonomous robotics. For example, consider the robotic implementation of all astronaut EVAs on ISS.**	*Cislunar considerations:* **Must be autonomous; remote operation may be impacted by time lag**
	Cislunar benefits: **Ability to inspect/repair spacecraft autonomously; reduction or elimination of human presence at remote locations**
Primary Taxonomy (NASA): Robotic Systems	*Secondary Txnmy:* (none)

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
X			**X**	**X**	**X**			**X**		**X**			**X**	**X**					**X**

Title: **Cross vehicle comm links that are independent and redundant for re-routing of comm to ground**

Description: **Ability to dynamically route communications through diverse or alternate networks; Multi-band or multi-technology communication (i.e. both Ka-band AND laser comm).**	*Cislunar considerations:* **"Ground" may be on lunar surface/orbit instead of Earth; requires infrastructure**
	Cislunar benefits: **(no anticipated unique benefits for cislunar)**
Primary Taxonomy (NASA): Communications, Navigation, and Orbital Debris Tracking and Characterization Systems	*Secondary Txnmy:* (none)

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
		X	**X**	**X**			**X**	**X**	**X**			**X**	**X**	**X**			**X**	**X**	**X**

Title: **RF/optical power beaming**

Description: **Technologies to transmit energy on demand (akin to wireless recharging) from on-orbit energy generator/supplier to other platforms (on-orbit or surface). Useful when solar power is unavailable due to eclipse or location (dark side of moon).**	*Cislunar considerations:* **"Ground" may be on lunar surface/orbit instead of Earth; requires infrastructure; range may be too limited for cislunar** *Cislunar benefits:* **(no anticipated unique benefits for cislunar)**
Primary Taxonomy (NASA): Communications, Navigation, and Orbital Debris Tracking and Characterization Systems	*Secondary Txnmy:* (none)

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
	X	**X**																	

Title: **Ability to deorbit, repurpose, or re-use end of life satellites**

Description: **If not managed properly, the gradual proliferation of space debris due to end-of-life satellites will pose an increased hazard to future space system resiliency. This capability refers to all technologies which mitigate this issue in the cislunar domain. It is inclusive of technologies that enable removal, remediation, repurposing and re-use of end-of-life satellites.**	*Cislunar considerations:* **(no special considerations beyond GEO)** *Cislunar benefits:* **(no anticipated unique benefits for cislunar)**
Primary Taxonomy (NASA): Entry, Descent, and Landing	*Secondary Txnmy:* Ground, Test, and Surface Systems

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
X																			

Title: Computer vision-based learning

Description: **Autonomous systems may be trained to interpret and understand the visual world, including anomalies and abnormalities visible: in an environment, from a human operator (facial expressions, posture, etc.), or on a piece of hardware.**	*Cislunar considerations:* **May require longer range/higher resolution for perceiving cislunar targets**
	Cislunar benefits: **(no anticipated unique benefits for cislunar)**
Primary Taxonomy (NASA): Autonomous Systems	*Secondary Txnmy:* Software, Modeling, Simulation, and Information Processing

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
				X					**X**					**X**					**X**

Title: Open data platform to monitor who is active in the cis-lunar orbital domain

Description: **Public flight tracker for cislunar space; includes standardized data framework/API for data access.**	*Cislunar considerations:* **Communications/Tracking may have time-lag; harder to verify with redundant methods**
	Cislunar benefits: **(no anticipated unique benefits for cislunar)**
Primary Taxonomy (NASA): Software, Modeling, Simulation, and Information Processing	*Secondary Txnmy:* (none)

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
X																			

Title: **Improved visualization/interface tools (XR)**

Description: **Human-computer interfaces to improve situational awareness and interface throughput. Could include heads-up displays, VR or AR overlays, haptic feedback and/or other technologies to enable faster, more reliable, more intuitive human interfaces.**	*Cislunar considerations:* **(no special considerations beyond GEO)**
	Cislunar benefits: **(no anticipated unique benefits for cislunar)**
Primary Taxonomy (NASA): Software, Modeling, Simulation, and Information Processing	*Secondary Txnmy:* (Robotic Integration, Modularity, Commonality, and Interfaces)

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
X					**X**					**X**					**X**				

Title: **Digital threads identifying design/coding choices and impacted systems**

Description: **Frameworks to support engineering for autonomous and artificial intelligence systems. Includes metadata tools to trace decision spaces, identify commonalities and dependencies, and trace failure modes.**	*Cislunar considerations:* **(no special considerations beyond GEO)**
	Cislunar benefits: **(no anticipated unique benefits for cislunar)**
Primary Taxonomy (NASA): Software, Modeling, Simulation, and Information Processing	*Secondary Txnmy:* (none)

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
								X	**X**				**X**	**X**					

Title: **Reprogrammable or reconfigurable hardware**

Description: **Shift from applications specific hardware. Includes IC technologies (FPGA, GPU, TPU) but also extrapolates to systems and subsystems with the ability to reconfigure or reprogram through flexibility, modularity, or software defined interfaces.**	*Cislunar considerations:* **(no special considerations beyond GEO)**
	Cislunar benefits: **Reprogrammable satellites may increase efficiency of cislunar missions; reduce need to replace assets in space**
Primary Taxonomy (NASA): Software, Modeling, Simulation, and Information Processing	*Secondary Txnmy:* Materials, Structures, Mechanical Systems, and Manufacturing

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
				X					**X**					**X**					**X**

Title: **Lunar surface navigation systems that provide location/orientation information**

Description: **Positioning systems for lunar navigation akin to GPS.**	*Cislunar considerations:* **(no special considerations beyond GEO)**
	Cislunar benefits: **(no anticipated unique benefits for cislunar)**
Primary Taxonomy (NASA): Guidance, Navigation, and Control	*Secondary Txnmy:* (none)

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
X					**X**														

Title: **Built in soft and hard stops within interfaces/subsystems that prevent catastrophic system damage**

Description: **The capability to prevent/inhibit/avoid catastrophic system damage through embedded hardware and software stops within the interfaces and subsystems for real-time and safety-critical systems.**	*Cislunar considerations:* **(no special considerations beyond GEO)**
	Cislunar benefits: **Higher reliability/longer lifetime for deep-space mission assets without access to repair**
Primary Taxonomy (NASA): Flight Computing and Avionics	*Secondary Txnmy:* Materials, Structures, Mechanical Systems, and Manufacturing

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
						X	**X**				**X**	**X**							

Title: **Adaptive propulsion system to transition to a new orbit, at varying time scales, in order to avoid impending damage from radiation or MMOD event**

Description: **Propulsion systems that are highly efficiency, highly throttleable, and multidirectional to enable transition to new orbits to avoid new/emergent MMOD or radiation event.**	*Cislunar considerations:* **Gravity environment/orbit paths more complex in cislunar space**
	Cislunar benefits: **(no anticipated unique benefits for cislunar)**
Primary Taxonomy (NASA): Propulsion Systems	*Secondary Txnmy:* Guidance, Navigation, and Control

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
		X	**X**				**X**	**X**				**X**	**X**				**X**	**X**	

Title: **Self Aware and autonomously reconfigurable Avionics**

Description: **Avionics with built in intelligence to recognize their current state, identify an optimal state, and plot a path to the optimal state. Obvious examples exist in navigation but could also apply to internal power or resource allocations, sensor tasking, etc.**	*Cislunar considerations:* **(no special considerations beyond GEO)**
	Cislunar benefits: **Higher reliability/longer lifetime for deep-space mission assets without access to repair**
Primary Taxonomy (NASA): Flight Computing and Avionics	*Secondary Txnmy:* Autonomous Systems

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
		X	**X**	**X**			**X**	**X**	**X**				**X**	**X**			**X**	**X**	**X**

Title: **Rad-hardened computer processors (or FPGAs/GPUs) (includes error checking)**

Description: **Computer hardware for space operations robust against high levels of radiation or charged particles; includes error-checking or resistance to bit-flipping errors.**	*Cislunar considerations:* **Cislunar has different radiation environment; may require different tolerance levels**
	Cislunar benefits: **Higher reliability/longer lifetime for deep-space mission assets without access to repair**
Primary Taxonomy (NASA): Flight Computing and Avionics	*Secondary Txnmy:* (none)

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
	X		**X**			**X**		**X**			**X**		**X**						

Title: **Training protocols for quick and efficient recovery of optimal operator cognitive state**

Description: **Robust and comprehensive training protocols prepare human operators to respond to stressors quickly and efficiently, as if they were on auto-pilot.**	*Cislunar considerations:* **(no special considerations beyond GEO)**
	Cislunar benefits: **(no anticipated unique benefits for cislunar)**
Primary Taxonomy (NASA): Human Health, Life Support, and Habitation Systems	*Secondary Txnmy:* (none)

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
						X	**X**	**X**	**X**										

Title: **Characterization of lunar dust clouds prior to meteor (or spacecraft) impact; model for bolide-like impact**

Description: **Models for creation and evolution of lunar surface dust clouds generated from surface impacts.**	*Cislunar considerations:* **(no special considerations beyond GEO)**
	Cislunar benefits: **(no anticipated unique benefits for cislunar)**
Primary Taxonomy (NASA): Exploration Destination Systems	*Secondary Txnmy:* Sensors and Instruments

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
X																			

Title: **Sensors that can dynamically control aperture or provide other protective measure**

Description: **Built in "reflexive" responses that protect sensitive instruments or systems in the event of a potentially damaging error (e.g. telescope slews toward sun).**	*Cislunar considerations:* **(no special considerations beyond GEO)**
	Cislunar benefits: **Higher reliability/longer lifetime for deep-space mission assets without access to repair**
Primary Taxonomy (NASA): Sensors and Instruments	*Secondary Txnmy:* Autonomous Systems

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
		X					X												

Title: **Hibernation/Safe-Mode**

Description: **Ability to enter a hibernation state that dramatically reduces resource requirements (e.g. power, comm, data, etc.) while ensuring that the system remains safe and recoverable in the future. Entering hibernation may be forced by external stressors, internal malfunction, or operator planning.**	*Cislunar considerations:* **Duration of dormancy may be longer in cislunar space; Rescue/in-situ Repair may not be possible**
	Cislunar benefits: **Higher reliability/longer lifetime for deep-space mission assets without access to repair**
Primary Taxonomy (NASA): Thermal Management Systems	*Secondary Txnmy:* Aerospace Power and Energy Storage

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
	X	X				X		X								X			

Title: **Automated check for spacecraft logic/operation consistency**

Description: **Algorithms that check commands given to spacecraft for consistency with mission goals/operations.**	*Cislunar considerations:* **(no special considerations beyond GEO)**
	Cislunar benefits: **Comprehensive satellite missions achieving multiple simultaneous objectives in large volumes of space**
Primary Taxonomy (NASA): Software, Modeling, Simulation, and Information Processing	*Secondary Txnmy:* Autonomous Systems

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
					X	X													

Title: **RF communications robustness against environmental overload**

Description: **Technologies that can maintain communication/transmission functions in externally-generated RF noise.**	*Cislunar considerations:* **May require robustness against different environmental processes than in GEO**
	Cislunar benefits: **(no anticipated unique benefits for cislunar)**
Primary Taxonomy (NASA): Communications, Navigation, and Orbital Debris Tracking and Characterization Systems	*Secondary Txnmy:* (none)

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
	X	X				X	X												

Title: **Shielding against externally-caused damage (permanent or temporary deployment)**

Description: **Sacrificial systems to absorb damage that would otherwise be incurred by sensitive/important systems onboard spacecraft. May be single- or multi-use. Analogous to an airbag on a car.**	*Cislunar considerations:* **(no special considerations beyond GEO)** *Cislunar benefits:* **Higher reliability/longer lifetime for deep-space mission assets without access to repair**
Primary Taxonomy (NASA): Materials, Structures, Mechanical Systems, and Manufacturing	*Secondary Txnmy:* (none)

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
	X	**X**				**X**	**X**												

Title: **Psychophysiological monitoring of crew state (using biometrics/machine learning to predict operator cognitive workload) and interaction with automation**

Description: **A human operator's functional state may be objectively and passively monitored by tracking their behavior and/or physiology. Informing an autonomous system of a human operator's functional state would allow for appropriate, personalized, and timely support.**	*Cislunar considerations:* **(no special considerations beyond GEO)** *Cislunar benefits:* **(no anticipated unique benefits for cislunar)**
Primary Taxonomy (NASA): Human Health, Life Support, and Habitation Systems	*Secondary Txnmy:* Autonomous Systems

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
					X	**X**	**X**	**X**	**X**										

Title: **Solar radiation weather monitoring and modelling**

<table>
<tr><td colspan="10" rowspan="2"><i>Description:</i>
Monitoring solar wind/radiation/charged particles with a fleet of satellites; physical model and data assimilation to provide real-time information and forecast future conditions throughout cislunar space.</td><td colspan="10"><i>Cislunar considerations:</i>
(no special considerations beyond GEO)</td></tr>
<tr><td colspan="10"><i>Cislunar benefits:</i>
Integration of multi-asset data into comprehensive picture; Increased resolution and accuracy of environmental analysis/forecasts</td></tr>
<tr><td colspan="10"><i>Primary Taxonomy (NASA):</i> Sensors and Instruments</td><td colspan="10"><i>Secondary Txnmy:</i> Software, Modeling, Simulation, and Information Processing</td></tr>
<tr><td colspan="5"><i>Environmental</i></td><td colspan="5"><i>Human</i></td><td colspan="5"><i>System</i></td><td colspan="5"><i>Support</i></td></tr>
<tr><td>Preempt</td><td>Withstand</td><td>React</td><td>Recover</td><td>Evolve</td><td>Preempt</td><td>Withstand</td><td>React</td><td>Recover</td><td>Evolve</td><td>Preempt</td><td>Withstand</td><td>React</td><td>Recover</td><td>Evolve</td><td>Preempt</td><td>Withstand</td><td>React</td><td>Recover</td><td>Evolve</td></tr>
<tr><td>X</td><td></td><td></td><td></td><td>X</td><td>X</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Title: **Failsafe or operational safe boot capability**

<table>
<tr><td colspan="10" rowspan="2"><i>Description:</i>
Modular, highly-configurable software that can reboot from a known safe state and reconstruct itself following a cyber attack or system malfunction.</td><td colspan="10"><i>Cislunar considerations:</i>
(no special considerations beyond GEO)</td></tr>
<tr><td colspan="10"><i>Cislunar benefits:</i>
Higher reliability/longer lifetime for deep-space mission assets without access to repair</td></tr>
<tr><td colspan="10"><i>Primary Taxonomy (NASA):</i> Software, Modeling, Simulation, and Information Processing</td><td colspan="10"><i>Secondary Txnmy:</i> Autonomous Systems</td></tr>
<tr><td colspan="5"><i>Environmental</i></td><td colspan="5"><i>Human</i></td><td colspan="5"><i>System</i></td><td colspan="5"><i>Support</i></td></tr>
<tr><td>Preempt</td><td>Withstand</td><td>React</td><td>Recover</td><td>Evolve</td><td>Preempt</td><td>Withstand</td><td>React</td><td>Recover</td><td>Evolve</td><td>Preempt</td><td>Withstand</td><td>React</td><td>Recover</td><td>Evolve</td><td>Preempt</td><td>Withstand</td><td>React</td><td>Recover</td><td>Evolve</td></tr>
<tr><td></td><td></td><td></td><td>X</td><td></td><td></td><td></td><td></td><td>X</td><td></td><td></td><td></td><td></td><td>X</td><td></td><td></td><td></td><td></td><td>X</td><td></td></tr>
</table>

Title: **MMOD detection and tracking (sensors and algorithms)**

Description: **Ability to continuously monitor, detect, track, and predict micrometeroids and orbital debris (MMOD) events in standard and non-Keplerian orbits, to include prediction of future location, as well as forecasting of debris field risk area.**	*Cislunar considerations:* **(no special considerations beyond GEO)**
	Cislunar benefits: **Higher reliability/longer lifetime for deep-space mission assets without access to repair; more comprehensive knowledge of cislunar activity (natural or artificial)**
Primary Taxonomy (NASA): Communications, Navigation, and Orbital Debris Tracking and Characterization Systems	*Secondary Txnmy:* Sensors and Instruments

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
X		**X**	**X**	**X**	**X**		**X**	**X**	**X**	**X**		**X**	**X**	**X**	**X**		**X**	**X**	**X**

Title: **Dynamic Space Communications Network**

Description: **Future space communications will need to serve a diverse userbase with wide-ranging and possibly evolving communications needs. A dynamic communications network will be capable of serving this broad set of needs, offer numerous paths for any given communication, and be reconfigurable to address both evolving needs and sudden, unplanned scenarios.**	*Cislunar considerations:* **May require asynchronous communications due to time lags; difficulties in reallocating resources over large volumes**
	Cislunar benefits: **Increase transmission of data over larger volumes**
Primary Taxonomy (NASA): Communications, Navigation, and Orbital Debris Tracking and Characterization Systems	*Secondary Txnmy:* Software, Modeling, Simulation, and Information Processing

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
X	**X**	**X**	**X**	**X**	**X**		**X**	**X**	**X**	**X**			**X**	**X**					

Title: **Spacecraft command queuing system that monitors and predicts system state after a command is issued**

Description: **Trained artificial intelligence supervising agent to confirm operator commands are within reasonable bounds and will not place the system into an unrecoverable state, including rate limiting for command sequences that alter spacecraft steady-state operations. Once an out-of-bounds condition is observed, the supervising agent can request confirmation, recommend corrections, limit operation, or direct recovery to safe state.**	*Cislunar considerations:* **(no special considerations beyond GEO)** *Cislunar benefits:* **(no anticipated unique benefits for cislunar)**
Primary Taxonomy (NASA): Software, Modeling, Simulation, and Information Processing	*Secondary Txnmy:* Autonomous Systems

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
	X	**X**	**X**			**X**	**X**	**X**			**X**	**X**	**X**			**X**	**X**	**X**	

Title: **Embedded health system monitoring sensors**

Description: **As spacecraft complexity increases, monitoring of subsystem health becomes more essential. Embedded sensors will monitor subsystems, warning about potential errors, and report observed errors to a central system.**	*Cislunar considerations:* **(no special considerations beyond GEO)** *Cislunar benefits:* **Higher reliability/longer lifetime for deep-space mission assets without access to repair**
Primary Taxonomy (NASA): Sensors and Instruments	*Secondary Txnmy:* Autonomous Systems

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
X			**X**		**X**			**X**		**X**			**X**						

Title: Predictive Models for Event Impact on Systems Health

Description: **By leveraging both historical and simulated spacecraft health data, it should be possible to develop predictive models for future system health. Such models will exploit system health monitoring to predict the future health of a system. This prediction enables mission operators to address potential system health issues before they are actually observed. Note that this high-level capability is inclusive of both single spacecraft models and network-level system of systems models.**	*Cislunar considerations:* **(no special considerations beyond GEO)** *Cislunar benefits:* **Higher reliability/longer lifetime for deep-space mission assets without access to repair**
Primary Taxonomy (NASA): Software, Modeling, Simulation, and Information Processing	*Secondary Txnmy:* (none)

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
X			**X**	**X**	**X**			**X**	**X**	**X**			**X**	**X**	**X**			**X**	**X**

Title: Propulsion and GNC algorithms that are responsive to structural health monitoring

Description: **Propulsion algorithms that account for structural damage, defects, etc. and modify propulsive maneuvers so as to not exacerbate the stressor (e.g., placing high loads on already damaged support structure).**	*Cislunar considerations:* **(no special considerations beyond GEO)** *Cislunar benefits:* **(no anticipated unique benefits for cislunar)**
Primary Taxonomy (NASA): Materials, Structures, Mechanical Systems, and Manufacturing	*Secondary Txnmy:* Propulsion Systems

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
X		**X**	**X**	**X**	**X**		**X**	**X**	**X**				**X**	**X**					

Title: **Proactive Cyber System Modeling**

Description: **This capability includes all technologies that assure a higher level of safety and security by constantly modeling software activity and system health. This includes, but is not limited to, command hash verification, AI-enhanced monitoring systems that recognize cyber-intrusions, verifiable state machines to enable trusted autonomy, decentralized monitoring, and applications of blockchain technology as a trusted command ledger.**	*Cislunar considerations:* **(no special considerations beyond GEO)**
	Cislunar benefits: **(no anticipated unique benefits for cislunar)**
Primary Taxonomy (NASA): Software, Modeling, Simulation, and Information Processing	*Secondary Txnmy:* Autonomous Systems

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
					X		**X**												

Title: **GNC algorithms to determine optimal safe transition orbit that avoids new or emergent MMOD or radiation event**

Description: **Propulsion algorithms that adjust orbit/distribution design to minimize risk to spacecraft/constellation from new or emergent MMOD or radiation event.**	*Cislunar considerations:* **Gravity environment/orbit paths more complex in cislunar space; "quick" orbit changes may not be needed**
	Cislunar benefits: **(no anticipated unique benefits for cislunar)**
Primary Taxonomy (NASA): Communications, Navigation, and Orbital Debris Tracking and Characterization Systems	*Secondary Txnmy:* Autonomous Systems

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
					X		**X**												

Title: **Supply chain logistics and control**

Description: **Algorithms to enhance efficiency and service of supply chains in cislunar space. Includes forecasting of demand, allocation of resources, and estimation of reliability/success.**	*Cislunar considerations:* **Cislunar domain much larger in volume; time scales for delivery are longer; deliveries will be less frequent**
	Cislunar benefits: **Enabling of cislunar missions with many and more complicated assets (which need more supplies)**
Primary Taxonomy (NASA): Exploration Destination Systems	*Secondary Txnmy:* Software, Modeling, Simulation, and Information Processing

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
															X	**X**	**X**		**X**

Title: **GPS-free navigation**

Description: **Abilities to navigate in-situ within the cislunar domain. Uses position of Earth/Moon/stars.**	*Cislunar considerations:* **Stars may be in slightly different positions relative to position of cislunar observer; may depend on precision (or lack thereof) of measurement**
	Cislunar benefits: **Allow for navigation without underlying infrastructure**
Primary Taxonomy (NASA): Guidance, Navigation, and Control	*Secondary Txnmy:* (none)

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
	X		**X**																

Title: Ability to quarantine cyber systems and reallocate functionality

Description: **Future space architectures are expected to have a large number of networks, spacecraft, and support infrastructure. This capability encompasses technologies that enable rapid isolating of off-nominal or compromised systems and enable the functionality of quarantined systems to be offloaded or distributed to remaining, unaffected systems.**	*Cislunar considerations:* **(no special considerations beyond GEO)**
	Cislunar benefits: **(no anticipated unique benefits for cislunar)**
Primary Taxonomy (NASA): Software, Modeling, Simulation, and Information Processing	*Secondary Txnmy:* Autonomous Systems

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
						X	**X**	**X**											

Title: Cislunar Depots for OSAM Capabilities

Description: **In order to reduce the time needed to repair, refuel, or deploy a spacecraft in cislunar space, depots for Servicing, Assembly, and Manufacture must be deployed in in this region (rather than in orbit).**	*Cislunar considerations:* **Special considerations for supply chain, logistics, automation**
	Cislunar benefits: **Enabling of cislunar missions with many and more complicated assets (which need more supplies). Longer lifetime for cislunar mission assets.**
Primary Taxonomy (NASA): Materials, Structures, Mechanical Systems, and Manufacturing	*Secondary Txnmy:* Exploration Destination Systems

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
			X	**X**				**X**	**X**				**X**	**X**					**X**

Title: **OSAM: Robotic Manipulation**

Description: **Involves manipulating payloads and spacecraft subsystems with a robotic manipulator. Includes robotic activities such as driving/releasing bolts, cutting, placing modules, and assisted deployment.**	*Cislunar considerations:* **(no special considerations beyond GEO)**
	Cislunar benefits: **Potential automation/reduction of human presence in cislunar space**
Primary Taxonomy (NASA): Robotic Systems	*Secondary Txnmy:* Exploration Destination Systems

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
			X	**X**				**X**	**X**				**X**	**X**					**X**

Title: **OSAM: Rendezvous & Proximity Operations, Capture, Docking, Mating**

Description: **Involves two spacecraft maneuvering in proximity to each other and could include connecting the two spacecraft together. Includes crewed or autonomous docking/berthing, remote inspection, and formation flying.**	*Cislunar considerations:* **(no special considerations beyond GEO)**
	Cislunar benefits: **(no anticipated unique benefits for cislunar)**
Primary Taxonomy (NASA): Robotics Systems	*Secondary Txnmy:* Exploration Destination Systems

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
			X	**X**				**X**	**X**				**X**	**X**					**X**

Title: **OSAM: Relocation**

Description: **Involves one spacecraft maneuvering another spacecraft into a new orbit or orientation. Includes boosting, repositioning, deorbit, debris removal, and life extension.**	*Cislunar considerations:* **Gravity environment/orbit paths more complex in cislunar space**
	Cislunar benefits: **(no anticipated unique benefits for cislunar)**
Primary Taxonomy (NASA): Materials, Structures, Mechanical Systems, and Manufacturing	*Secondary Txnmy:* Exploration Destination Systems

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
			X	**X**				**X**	**X**				**X**	**X**					**X**

Title: **OSAM: Planned Repair, Upgrade, Maintenance, Installation**

Description: **Involves adding or replacing components on a spacecraft that is prepared to receive those components. This is done to repair or upgrade that component, perform a maintenance swap-out, or install a new component that expands the capability of the spacecraft. Includes systems with modular interface connections and payload/component swap-out or upgrade.**	*Cislunar considerations:* **(Possible) lack of depots/maintenance stations in cislunar**
	Cislunar benefits: **Enabling of cislunar missions with many and more complicated assets. Longer lifetime for cislunar mission assets.**
Primary Taxonomy (NASA): Materials, Structures, Mechanical Systems, and Manufacturing	*Secondary Txnmy:* Exploration Destination Systems

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
			X	**X**				**X**	**X**				**X**	**X**					**X**

Title: **OSAM: Unplanned or Legacy Repair**

Description: **Involves adding or replacing components on a spacecraft that was not intended to receive those components. Includes more complex operations to access the interfaces and make new connections.**	*Cislunar considerations:* **(Possible) lack of depots/maintenance stations in cislunar**
	Cislunar benefits: **Enabling of cislunar missions with many and more complicated assets. Longer lifetime for cislunar mission assets.**
Primary Taxonomy (NASA): Materials, Structures, Mechanical Systems, and Manufacturing	*Secondary Txnmy:* Exploration Destination Systems

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
			X	**X**				**X**	**X**				**X**	**X**					**X**

Title: **OSAM: Refueling and Fluid Transfer**

Description: **Involves transferring fluid from one spacecraft to another. Includes cryogenic and non-cryogenic propellants/fluids and transfer in orbit or on a planetary surface**	*Cislunar considerations:* **(no special considerations beyond GEO)**
	Cislunar benefits: **Enabling of longer-term cislunar missions**
Primary Taxonomy (NASA): Materials, Structures, Mechanical Systems, and Manufacturing	*Secondary Txnmy:* Exploration Destination Systems

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
			X	**X**				**X**	**X**				**X**	**X**					**X**

Title: **OSAM: Structural Manufacturing and Assembly**

Description: **Involves creating or assembling structures in space to create spacecraft components or subsystems. Includes manufacturing (3-D printing, extruding, etc.) and assembly of structures with various interfaces, joining approaches, and precision.**	*Cislunar considerations:* **(Possible) lack of depots in cislunar**
	Cislunar benefits: **At-location, on-demand deployment of assets**
Primary Taxonomy (NASA): Materials, Structures, Mechanical Systems, and Manufacturing	*Secondary Txnmy:* Exploration Destination Systems

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
			X	X				X	X				X	X					X

Title: **OSAM: Recycling, Reuse, Repurposing**

Description: **Involves the use of spacecraft components already in space in a new spacecraft. Includes recycling the material from old spacecraft parts for new manufacturing feedstock and reusing old spacecraft parts as-is in new spacecraft.**	*Cislunar considerations:* **(no special considerations beyond GEO)**
	Cislunar benefits: **(no anticipated unique benefits for cislunar)**
Primary Taxonomy (NASA): Materials, Structures, Mechanical Systems, and Manufacturing	*Secondary Txnmy:* Exploration Destination Systems

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
			X	X				X	X				X	X					X

Title: **OSAM: Parts and Goods Manufacturing**

Description: **Involves creating spare parts, subsystems, and components for use in space or on a planetary surface. Includes internal (to a habitat) and external manufacturing with multiple materials and sizes.**	*Cislunar considerations:* **(Possible) lack of depots in cislunar**
	Cislunar benefits: **(no anticipated unique benefits for cislunar)**
Primary Taxonomy (NASA): Materials, Structures, Mechanical Systems, and Manufacturing	*Secondary Txnmy:* Exploration Destination Systems

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
			X	**X**				**X**	**X**				**X**	**X**					**X**

Title: **OSAM: Surface Construction**

Description: **Involves excavating, constructing, and outfitting structures and infrastructure on a planetary surface. Includes horizontal (landing pads, roads, etc.) and vertical (power, habitation, etc.) construction, using regolith to build, and assembly of erected structures.**	*Cislunar considerations:* **(no special considerations beyond GEO)**
	Cislunar benefits: **(no anticipated unique benefits for cislunar)**
Primary Taxonomy (NASA): Materials, Structures, Mechanical Systems, and Manufacturing	*Secondary Txnmy:* Exploration Destination Systems

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
			X	**X**				**X**	**X**				**X**	**X**					**X**

Title: **OSAM: Inspection and Metrology**

Description: **Involves observation of systems in space to understand their configuration, size and shape, or other features of interest. Includes free-flyer inspection, nondestructive evaluation, close (robotic) inspection, and space situational awareness.**	*Cislunar considerations:* **(no special considerations beyond GEO)**
	Cislunar benefits: **(no anticipated unique benefits for cislunar)**
Primary Taxonomy (NASA): Materials, Structures, Mechanical Systems, and Manufacturing	*Secondary Txnmy:* Exploration Destination Systems

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
			X	**X**				**X**	**X**				**X**	**X**					**X**

Title: **Distributed, Collaborative Spacecraft Systems (Multi-sensor network fusion, interoperability and capability redistribution on node failure)**

Description: **This capability includes all technologies required to interactively coordinate two or more spacecraft to accomplish a specific mission. Such coordination can be planned a priori, designing systems for specific collaboration, or accomplished ad hoc by leveraging existing assets in a new way. Sensing, communications, and computation are examples of spacecraft functions which could be distributed across numerous spacecraft. Numerous subsets of technologies may be listed here including the following non-exhaustive list: sensor fusion, interoperable communications protocols, autonomous spacecraft teaming, …**	*Cislunar considerations:* **Time lag in communication between nodes may require asynchronous message passing**
	Cislunar benefits: **Comprehensive satellite missions achieving multiple simultaneous objectives in large volumes of space**
Primary Taxonomy (NASA): Flight Computing and Avionics	*Secondary Txnmy:* Sensors and Instruments

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
X	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**		**X**	**X**	**X**			**X**	**X**	**X**

Title: **Materials (hull) resistant against damage (dust, MMOD impact, lasing, radiation)**

Description: **The capability includes lightweight structural materials that reduce the mass and increase the efficiency of structures and structural components including advanced metallics, nanomaterials, metamaterials, matrix composites, multifunctional materials, damage detecting/damage tolerant materials, and self-repairing/self-healing materials that include mechanisms for fast, in-situ repairs. This also includes materials for extreme environments to protect against harsh environments and operating conditions, including materials that resist abrasive wear and have high wear resistance in vacuum. Finally, it similarly comprises coatings as materials, nanomaterials, metamaterials, and amorphous materials that provide thin, lightweight barrier protection from environmental hazards that include light, dust, fouling, temperature, harsh gases, chemical attack icing, putative microbial life forms, and atomic oxygen.**	*Cislunar considerations:* **(no special considerations beyond GEO)**
	Cislunar benefits: **Higher reliability/longer lifetime for deep-space mission assets without access to repair**
Primary Taxonomy (NASA): Materials, Structures, Mechanical Systems, and Manufacturing	*Secondary Txnmy:* (none)

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
X	**X**		**X**																

Title: **Verification and Validation Tools, including Digital twin modeling and simulation capability**

Description: **Tools and techniques used in the verification and validation of structural and mechanical systems and associated numerical models for critical loads and environments to understand as-build conditions, accurately characterize structural integrity and environment, and detect and assess anomalies. Includes processing software and AI or ML tools for data reduction and damage location and life prediction. Capability provides the ability to identify possible failure modes early in the design process and continuously use the model throughout the development, testing, and operation of the system. Integrated models that consider physics, simulations, and history of a vehicle or system to mirror its performance.**	*Cislunar considerations:* **(no special considerations beyond GEO)**
	Cislunar benefits: **(no anticipated unique benefits for cislunar)**
Primary Taxonomy (NASA): Software, Modeling, Simulation, and Information Processing	*Secondary Txnmy:* Autonomous Systems

Environmental					*Human*					*System*					*Support*				
Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve	Preempt	Withstand	React	Recover	Evolve
X			**X**							**X**			**X**		**X**			**X**	

Appendix B - Acknowledgements

In its role as an independent office, OTPS relies on the inputs of a broad community of internal and external subject matter experts and stakeholders involved in NASA's future. For the study described in this report, OTPS considered many inputs while shaping the study itself and interpreting and reporting our findings. We thank the report reviewers and many contributors who shared these invaluable inputs, especially those that served on the technology and architecture working groups.

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