Ecosystem-based AI: Human-AI Collaboration for Sustainable Lunar Presence

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Abstract

The establishment of a sustainable human presence on the Moon requires artificial intelligence systems that can adapt to extreme environments, operate autonomously during communication delays, and collaborate effectively with human crews. This review examines the integration of AI agents within lunar infrastructure through an ecosystem-based approach, where AI systems continuously evolve through interaction with their operational environment during the missions preparation and execution phases. We analyze the critical tension between the exponential pace of AI advancement on Earth and the prolonged development cycles of space missions, which creates a paradox where deployed AI may be outdated by multiple generations at launch. By examining current implementations in life support systems, resource utilization, and crew assistance, we identify the capabilities and limitations of contemporary approaches and propose architectural principles for more adaptive systems. The review pays particular attention to the integration of AI agents with decentralized systems for enhanced resilience, the development pathways for continuous learning during analog missions, and considerations of human-computer interaction specific to lunar operations. Although early initiatives like CIMON demonstrate preliminary steps toward AI companions, they highlight the gap between current capabilities and the autonomous learning systems required for sustainable lunar habitation. By addressing both technical challenges and institutional barriers to implementation, this review provides a framework for developing AI systems that remain relevant and effective throughout the extended timeline of lunar mission development and operation.

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1 Introduction

The realization of a sustainable human presence on the Moon presents unprecedented challenges for life support systems, resource management, and autonomous operations in an environment of extreme isolation and harsh conditions. Artificial intelligence (AI) has emerged as a critical enabler for long-duration lunar missions, providing capabilities for environmental monitoring, crew support, and autonomous operation during communication delays [16]. However, current approaches to AI implementation in space systems face a fundamental paradox: the mismatch between rapid advancement in terrestrial AI technologies and the prolonged development cycles of space missions often results in deployed systems that are outdated by multiple generations at launch.

This review examines the concept of ecosystem-based AI, a framework for human-AI collaboration in space where systems continuously adapt through real-time interaction with their operational environment, and its application to lunar missions [1]. Unlike conventional AI approaches with static pre-trained models, Ecosystem-based AI emphasizes continuous learning from mission preparation through operation, enabling adaptation to both expected and unforeseen challenges of extraterrestrial environments.

The current phase of lunar exploration, characterized by NASAś Artemis program and international initiatives for sustainable lunar presence, has seen preliminary AI implementations for navigation, system monitoring, and data analysis [18]. Projects such as NASAś Volatiles Investigating Polar Exploration Rover (VIPER), while recently removed from near-term mission manifests, exemplify the development of autonomous systems designed for the lunar environment. Similarly, the CIMON assistant tested on the International Space Station represents early experimentation with AI companions for crew support, though its capabilities fall significantly short of the autonomous, continuously learning systems required for sustainable lunar operations.

The gap between current capabilities and mission requirements highlights several critical questions that this review addresses:

1. How can AI systems maintain relevance through the extended development cycles of space missions, avoiding obsolescence at deployment?

2. What architectural approaches enable AI to function effectively in environments with limited computing resources, extreme radiation, and communication delays?

3. How must human-computer interaction be redesigned for the unique context of lunar operations, where system reliability is mission critical but direct Earth supervision is impractical [20]?

4. What institutional and developmental frameworks can overcome bureaucratic inertia in space organizations to enable more agile implementation of AI capabilities?

By examining these questions through both technical and organizational lenses, this review provides a framework for developing AI systems that enhance rather than hinder lunar mission objectives while remaining adaptive to the rapid evolution of AI capabilities.

2 The Fundamental Tension: AI Advancement vs. Space Mission Timelines

The integration of AI into lunar missions faces a fundamental tension between the exponential advancement of AI technologies and the cautious and methodical approach to space mission development. This ̈bureaucratic lag paradox ̈creates a situation where AI systems deployed in space may be outdated before launch due to development cycles that can span a decade or more.

2.1 The Imperative for AI Leadership in Space

Space agencies and organizations engaged in lunar exploration face a unique challenge: they must not merely keep pace with terrestrial AI developments, but lead at the cutting edge while simultaneously navigating institutional frameworks designed for risk minimization rather than rapid innovation. This tension creates what can be termed the ̈leadership imperative paradox. ̈

Recent advances in AI, such as transformer-based models [23] and reinforcement learning techniques [14], have allowed systems to perform complex tasks with unprecedented precision. These capabilities are especially critical for lunar operations, where systems must function autonomously when communication with Earth is delayed or unavailable. The rapid obsolescence of AI models, where state-of-the-art algorithms may be surpassed within months rather than years, necessitates a proactive approach fundamentally misaligned with traditional space mission development.

The National Academies of Sciences, Engineering and Medicine [17] have highlighted this problem, noting that space missions typically follow development cycles that span 5-10 years from conception to launch, a timeline fundamentally incompatible with the 6-12 month cycles of significant AI advancement. This mismatch creates an institutional challenge that goes beyond technical difficulties, requiring new approaches to mission planning and technology integration.

2.2 The Specialist Training Paradox

The exponential growth of AI means that a specialist trained in 2023 on convolutional neural networks may find their knowledge obsolete by 2026, supplanted by graph neural networks or neuromorphic computing [19]. For lunar missions, where development timelines can exceed a decade, this obsolescence risks deploying AI systems that are outdated at launch, potentially compromising mission capabilities and safety.

This paradox is amplified by the stringent reliability requirements of space AI. Terrestrial AI systems can iterate through failures and incremental improvements, but AI managing life support systems in a lunar habitat must achieve near-perfect reliability from deployment due to catastrophic consequences of failure [4]. Traditional training approaches struggle to produce specialists capable of anticipating and addressing these demands within such a compressed innovation cycle.

The academic and institutional frameworks that produce AI specialists for space applications further compound this challenge. University curricula, research laboratory infrastructure, and funding mechanisms operate on timescales of years rather than months. By the time a specialized AI course for space applications is approved, developed, and produces graduates, the specific techniques taught may already be superseded by newer approaches.

3 Ecosystem-based AI: A Framework for Lunar Applications

Addressing the bureaucratic lag paradox requires a fundamental shift in how AI is conceptualized for lunar applications. Ecosystem-based AI provides such a framework, emphasizing adaptation throughout the mission life cycle rather than relying solely on pre-deployment training and fixed capabilities.

3.1 From Static to Adaptive: Redefining AI for Lunar Operations

Ecosystem-based AI conceptualizes artificial intelligence not as a discrete tool or system, but as an integral component of a complex operational ecosystem encompassing human operators, physical systems, and environmental factors [22]. This perspective is particularly valuable for lunar operations, where conditions may differ significantly from simulated environments and challenges cannot always be predicted in advance.

Key principles that distinguish this approach include:

Continuous Learning Throughout Mission Life cycle: Unlike conventional systems that are fully trained prior to deployment with minimal adaptation capabilities, Ecosystem-based AI employs techniques from online learning [11] and meta-learning [12] to update models based on operational data. This learning begins during mission preparation, accelerates during analog missions and simulations, and continues throughout actual lunar operations.

Environmental Integration: The system maintains awareness of environmental conditions, mission status, and resource availability through comprehensive sensor networks and integration with other mission systems. This contextual awareness enables more refined decision-making under varying conditions.

Human-AI Co-adaptation: Rather than forcing humans to adapt to predefined AI behaviors, Ecosystem-based AI emphasizes mutual adaptation. The AI personalizes its responses based on individual crew member preferences, communication styles, and psychological states, while human operators develop appropriate usage patterns as they gain experience with the system [13].

Distributed Resilience: Instead of centralizing AI capabilities in a single system (creating potential single points of failure), the framework employs multiple specialized AI agents distributed across mission systems. These agents maintain communication networks that allow coordination while providing redundancy if individual components fail.

This approach directly addresses the specialist training paradox by allowing the AI systems themselves to accumulate expertise through direct experience, rather than relying solely on pre-programmed knowledge from human specialists. It also helps overcome the bureaucratic lag paradox by allowing AI capabilities to be updated throughout mission preparation and operation, rather than freezing them at an early stage of the development cycle.

3.2 Decentralized AI Agents for Lunar Life Support

Within the Ecosystem-based AI framework, decentralized AI agents emerge as a promising implementation approach, particularly for critical systems like life support and resource management. These specialized AI agents operate semi-autonomously within specific domains while coordinating through secure protocols to maintain system-wide coherence.

The integration of blockchain technologies with such AI agents offers several advantages for lunar operations. Blockchain provides a secure, transparent, and tamper-resistant ledger for critical operations data, ensuring that all agents work from a consistent understanding of system state even when communication is intermittent. This is particularly valuable for life support systems, where reliability and data integrity are paramount.

AI agents integrated with blockchain can facilitate autonomous resource management by:

1. Creating immutable records of resource utilization, preventing data manipulation or loss 2. Enabling secure peer-to-peer coordination among distributed agents without centralized control 3. Implementing smart contracts that automatically execute resource allocation decisions based on predefined conditions and real-time data 4. Providing transparency and auditability for critical system operations, enabling easier troubleshooting and validation

This approach enhances system resilience through distribution of intelligence and data across multiple nodes, mitigating the risk of catastrophic failure from any single component. For example, if the primary life support management agent were to fail due to radiation damage, other agents could maintain basic functions while coordination roles are redistributed.

The decentralized agent model also addresses the challenge of limited computing resources in lunar environments. Rather than requiring powerful centralized hardware, the system can distribute computational loads across multiple specialized processors, each handling a subset of the overall system management requirements.

4 Life Support and Resource Management Applications

Life support systems represent one of the most critical applications for Ecosystem-based AI in lunar operations. These systems must maintain habitable conditions with limited resources and high reliability, often operating autonomously for extended periods when crew members are absent or communication with Earth is delayed.

4.1 Current Approaches and Limitations

Current space life support systems typically rely on predetermined operational parameters and rule-based control systems with limited adaptation capabilities. While effective for short-duration missions with consistent environmental conditions, these approaches face significant limitations for sustainable lunar presence:

Limited Adaptability: Conventional systems struggle to adapt to unexpected failures or environmental changes outside their programmed parameters.

Inefficient Resource Utilization: Static operating procedures often lead to suboptimal resource usage, as they cannot dynamically adjust to changing mission priorities or crew needs.

Maintenance Challenges: Traditional systems require regular maintenance and calibration to maintain performance, creating significant workload for crew members.

Diagnostic Limitations: Fault detection typically focuses on predefined failure modes rather than identifying novel or compound issues that were not anticipated during system design.

4.2 Ecosystem-based AI for Life Support Management

Ecosystem-based AI offers several advantages for life support management in lunar habitats:

Predictive Optimization: By continuously analyzing sensor data and historical patterns, the system can anticipate resource needs and optimize the system parameters accordingly. Research indicates this approach could reduce resource consumption by 15-20% compared to conventional systems [15].

Anomaly Detection and Response: The system learns normal operational patterns and can quickly identify subtle deviations that may indicate emerging problems, enabling intervention before critical failures occur.

Bioregenerative System Management: For advanced life support approaches utilizing plants, algae, or other biological components, Ecosystem-based AI can manage the complex interactions between different subsystems to maintain stable, efficient operation.

Crew-Adaptive Operation: The system learns individual crew preferences and adjusts environmental parameters accordingly within operational constraints, enhancing comfort and productivity while maintaining resource efficiency [6].

Implementation of these capabilities requires integration with comprehensive sensor networks throughout the habitat, actuators for real-time system adjustments, and secure data storage to maintain operational records. The decentralized agent approach allows specialized modules to focus on specific aspects of life support (air management, water recycling, waste processing) while coordinating to optimize overall system performance.

4.3 In-Situ Resource Utilization Integration

In-Situ Resource Utilization (ISRU)—the practice of using resources available at the lunar site rather than transporting them from Earth—represents a critical capability for sustainable lunar presence. Ecosystem-based AI can enhance ISRU operations by optimizing resource extraction, processing, and utilization based on mission requirements and environmental conditions [21].

Key applications include:

Resource Mapping and Assessment: AI agents can analyze data from orbital and surface sensors to identify promising resource deposits, particularly water ice in permanently shadowed regions and regolith with favorable characteristics for construction or processing.

Extraction Process Optimization: Continuously learning algorithms can adjust extraction methodologies based on actual material properties encountered during operations, improving efficiency and reducing equipment wear.

Supply Chain Management: The system can coordinate production rates with consumption needs, ensuring efficient use of extracted resources and minimizing waste.

Autonomous Operation: During periods when crew members are absent or focused on other tasks, AI agents can maintain ISRU operations with minimal human supervision, adapting to changing conditions and addressing minor issues autonomously [24].

By linking life support management with ISRU operations through a common AI framework, the system can make holistic decisions about resource allocation, prioritizing extraction or recycling based on current mission needs and available resources.

5 Human-AI Collaboration in Lunar Environments

The extreme environment of lunar operations—characterized by isolation, confinement, high stress, and mission criticality—creates unique challenges for human-AI interaction. Effective collaboration between human crew members and AI systems is essential for mission success but requires careful consideration of both technical interfaces and psychological factors [20].

5.1 Limitations of Current HCI Approaches

Current human-computer interaction (HCI) paradigms in space operations have significant limitations for long-duration lunar missions:

Control-Oriented Interfaces: Traditional space system interfaces emphasize explicit control by human operators, with limited automation and minimal adaptation to individual preferences or contextual factors.

High Cognitive Load: Complex procedures and information-dense displays can overwhelm operators, particularly during high-stress situations or after extended periods in isolated, confined environments.

Limited Contextual Awareness: Most interfaces provide data without the context needed for rapid decision-making, requiring operators to mentally integrate information from multiple sources.

Minimal Personalization: Standard interfaces rarely adapt to individual operator preferences, experience levels, or current cognitive state, missing opportunities to enhance usability and effectiveness.

5.2 Ecosystem-based Approach to HCI

An Ecosystem-based approach to human-AI collaboration in lunar environments emphasizes:

Adaptive Interfaces: System interfaces adjust presentation based on the operatorś current cognitive state, experience level, and the criticality of the situation. During routine operations, the system may provide detailed information and options; during emergencies, it presents only essential information and high-priority actions [3].

Contextual Intelligence: The system incorporates environmental conditions, mission phase, crew status, and system health into its interaction design, providing information within the broader operational context rather than as isolated data points.

Workload Management: AI agents proactively redistribute tasks based on current crew capacity, increasing autonomy during high-workload periods or when crew members are sleeping, and offering more options for human control during nominal operations.

Trust Calibration: The system communicates confidence levels in its assessments and recommendations, helping crew members develop appropriate trust in AI capabilities rather than over-relying on potentially flawed recommendations or under-utilizing valuable capabilities.

Explainable Operation: When making recommendations or autonomous decisions, the system provides clear explanations of its reasoning, enabling human oversight and intervention when necessary [5].

These principles address the unique challenges of lunar operations, where communication delays with Earth necessitate greater crew autonomy and reliability of onboard systems is mission-critical.

5.3 Multi-Agent Communication Architectures

The distributed nature of Ecosystem-based AI requires careful attention to communication architectures between agents and human operators. Effective multi-agent systems for lunar operations should incorporate:

Priority-Based Communication: Information flow is managed according to operational priorities, ensuring that critical communications receive bandwidth precedence over routine updates.

Contextual Summarization: Agents provide information at appropriate levels of detail based on the current situation, summarizing routine operations while providing comprehensive details for anomalies or decision points.

Shared Mental Models: The system works to develop and maintain shared understanding of mission status, objectives, and constraints across both human crew members and AI agents, facilitating coordinated action even with limited explicit communication.

Interruption Management: Communication timing is optimized to minimize cognitive disruption, with non-critical information held until appropriate moments rather than interrupting ongoing tasks.

These architectural principles help balance the need for comprehensive system awareness with the cognitive limitations of human operators in stressful, isolated environments. By adapting communication patterns to the current operational context, the system can provide appropriate information without overwhelming crew members or disrupting critical tasks.

6 Implementation Challenges and Pathways

While the Ecosystem-based AI framework addresses many theoretical challenges of AI for lunar operations, practical implementation faces significant technical, organizational, and ethical barriers. Understanding these challenges and developing systematic approaches to overcome them is essential for translating conceptual advantages into operational capabilities.

6.1 Technical Challenges

Several technical challenges must be addressed for successful implementation of Ecosystem-based AI in lunar environments:

Computational Constraints: Space-rated computing hardware typically lags several generations behind state-of-the-art terrestrial systems due to radiation hardening requirements. This limits the complexity and scale of AI models that can be deployed onboard lunar habitats or vehicles.

Radiation Effects: Beyond hardware concerns, lunar radiation environments can cause software errors, including potential corruption of neural network weights or decision parameters in AI systems.

Power Limitations: Lunar habitats, particularly during the 14-day lunar night, face severe power constraints, limiting available computing resources for AI operations.

Communication Constraints: While Ecosystem-based AI emphasizes local adaptation and autonomy, some coordination with Earth remains necessary. Limited bandwidth, high latency (up to 2.5 seconds for lunar missions), and intermittent connectivity present challenges for maintaining alignment between spacecraft systems and mission control.

Training Data Limitations: Machine learning systems require extensive training data, but space environments provide limited opportunities for data collection, particularly for anomalous or emergency scenarios that are rare but critical to handle correctly.

Validation Challenges: Adaptive systems that continue to learn during operation are inherently more difficult to validate than static systems, raising concerns about their reliability in safety-critical applications.

Addressing these challenges requires innovative approaches to both system architecture and development methodology. Potential solutions include:

Edge-Optimized AI: Developing specialized neural network architectures and inference approaches optimized for low-power, radiation-tolerant hardware, potentially incorporating neuromorphic computing principles for greater efficiency [19].

Hybrid Cloud/Edge Architecture: Distributing AI workloads between onboard systems (for time-sensitive, safety-critical functions) and Earth-based computing (for complex analysis and model refinement during nominal operations).

Simulation-Based Training: Using high-fidelity simulations to generate training data for rare or dangerous scenarios that cannot be directly experienced during real operations.

Bounded Learning: Implementing constraints on learning processes to ensure that adaptation remains within validated safety parameters, with more significant changes requiring human approval [4].

6.2 Analog Missions as Development Platforms

Analog missions—simulated space missions conducted in controlled environments on Earth—provide ideal testbeds for developing and validating Ecosystem-based AI before deployment in actual lunar operations [8]. These environments allow iterative development and testing of both technical systems and human-AI interaction paradigms under conditions that approximate aspects of lunar missions.

Analog environments enable AI systems to build experience and demonstrate capabilities before deployment in actual space missions. By incorporating Ecosystem-based AI into analog mission planning from the outset, developers can ensure that the systems accumulate relevant experience throughout the mission development process, rather than being designed and deployed in isolation from operational realities.

The iterative process of testing in increasingly high-fidelity analogs also helps build appropriate trust between human operators and AI systems—a critical factor for effective mission execution. Crew members who have experienced AI capabilities and limitations during analog training are better prepared to work effectively with these systems during actual lunar operations.

6.3 Organizational and Institutional Frameworks

Perhaps the most significant challenges to implementing Ecosystem-based AI for lunar operations are organizational and institutional rather than purely technical. Addressing these challenges requires new frameworks for mission development, technology integration, and organizational learning:

Progressive Certification: Rather than qualifying AI systems once before launch, progressive certification approaches would establish performance bounds and monitoring requirements, allowing systems to evolve within certified parameters throughout the mission life cycle.

Agile Mission Development: Implementing more flexible, iterative approaches to mission planning that can accommodate evolving AI capabilities throughout the development cycle.

Embedding AI Specialists: Integrating AI specialists directly within mission teams throughout development and operations to bridge the gap between rapidly evolving AI capabilities and mission requirements.

Modular System Architecture: Designing missions with hardware and software interfaces that support upgrading AI components throughout the development process and potentially during operations.

International Standardization: Developing common standards for space-qualified AI to streamline implementation across agencies and contractors, reducing duplication of effort and establishing shared expectations for performance and safety.

These organizational innovations, while challenging to implement within traditional space program structures, are essential for realizing the potential of AI for lunar operations. Without addressing the institutional barriers to adaptive technology development, even the most promising technical approaches will struggle to translate into operational capabilities.

7 Future Research Directions

Several key research directions emerge from the analysis of Ecosystem-based AI for lunar operations:

Radiation-Resilient Neural Networks: Developing neural network architectures and training approaches that maintain performance despite the potential for radiation-induced errors in weights or computation, potentially through redundancy, error detection, or self-correction mechanisms [7].

Continual Learning Under Resource Constraints: Advancing methods for ongoing learning in environments with severe computational and power limitations, focusing on efficient update mechanisms that maintain critical capabilities while incrementally improving performance.

Human-AI Team Performance Metrics: Establishing comprehensive metrics for evaluating the effectiveness of human-AI teams in space operations, considering not only task performance but also cognitive workload, situational awareness, and team cohesion [9].

Verification of Adaptive Systems: Developing theoretical frameworks and practical methodologies for verifying the safety and reliability of systems that continue to adapt during operations, ensuring that learning processes do not compromise mission-critical functions.

Cross-Cultural AI Personalization: Creating AI systems that can effectively adapt to the diverse cultural backgrounds, communication styles, and working preferences of international crews on lunar missions.

Ethical Frameworks for Autonomous Decision-Making: Establishing clear principles and implementation guidelines for AI autonomy in critical decisions during communication disruptions or emergencies, balancing operational necessity with appropriate human oversight.

Progress in these research areas will require interdisciplinary collaboration among computer scientists, aerospace engineers, human factors specialists, and mission planners. By addressing both technical capabilities and integration challenges, this research can help bridge the gap between terrestrial AI advancement and operational implementation in lunar environments [2].

8 Conclusion

The sustainable human presence on the Moon presents unique challenges for artificial intelligence systems, particularly the tension between rapid advancement in terrestrial AI and the extended development cycles of space systems. The Ecosystem-based AI framework addresses this fundamental paradox by emphasizing continuous adaptation throughout the mission life cycle, distributed intelligence among specialized agents, and seamless integration with human operators.

While early initiatives like CIMON demonstrate initial steps toward AI-assisted space operations [10], they highlight the gap between current capabilities and the autonomous, learning systems required for sustainable lunar habitation. Bridging this gap requires not only technical innovation but also new approaches to mission planning, system development, and organizational learning.

By leveraging analog missions as development platforms, implementing modular system architectures, and addressing both technical and institutional barriers to implementation, the space community can develop AI systems that enhance rather than hinder lunar mission objectives. These systems will not replace human judgment and expertise but will augment it, enabling crews to focus on exploration, scientific discovery, and adaptation to the challenges of establishing a permanent human presence beyond Earth.

As we stand at the threshold of a new era in lunar exploration, the relationship between human explorers and their AI counterparts will substantially influence our success. By developing AI systems that learn and adapt alongside their human colleagues throughout the journey from Earth to the Moon, we can enhance mission capabilities while ensuring that these technologies serve rather than constrain our ambitions for sustainable presence on the lunar surface.

References

1 European Space Agency. Artificial intelligence in space - esa. Technical report, European Space Agency, 2022. URL: https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Discovery_and_Preparation/Artificial_intelligence_in_space.

2 European Space Agency. The power of ai in space exploration - esa's blogs. *ESA's blogs*, 2022. URL: `https://blogs.esa.int/exploration/the-power-of-ai-in-space-exploration/`.

3 Saleema Amershi, Dan Weld, Mihaela Vorvoreanu, Adam Fourney, Besmira Nushi, Penny Collisson, Jina Suh, Shamsi Iqbal, Paul N. Bennett, Kori Inkpen, Jaime Teevan, Ruth Kikin-Gil, and Eric Horvitz. Guidelines for human-AI interaction. *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, 2019. `doi:10.1145/3290605.3300233`.

4 Dario Amodei, Chris Olah, Jacob Steinhardt, Paul Christiano, John Schulman, and Dan Mané. Concrete problems in AI safety. *arXiv preprint arXiv:1606.06565*, 2016. URL: `https://arxiv.org/abs/1606.06565`.

5 Alejandro Barredo Arrieta, Natalia Díaz-Rodríguez, Javier Del Ser, Adrien Bennetot, Siham Tabik, Alberto Barbado, Salvador García, Sergio Gil-López, Daniel Molina, Richard Benjamins, Raja Chatila, and Francisco Herrera. Explainable Artificial Intelligence (XAI): Concepts, taxonomies, opportunities and challenges toward responsible AI. *Information Fusion*, 58:82–115, 2020. `doi:10.1016/j.inffus.2019.12.012`.

6 Laura K. Barger, Erin E. Flynn-Evans, Alan Kubey, Lorcan Walsh, Joseph M. Ronda, Wei Wang, Kenneth P. Wright, and Charles A. Czeisler. Prevalence of sleep deficiency and use of hypnotic drugs in astronauts before, during, and after spaceflight: an observational study. *The Lancet Neurology*, 13(9):904–912, 2014. `doi:10.1016/S1474-4422(14)70122-X`.

7 Jacob Biamonte, Peter Wittek, Nicola Pancotti, Patrick Rebentrost, Nathan Wiebe, and Seth Lloyd. Quantum machine learning. *Nature*, 549(7671):195–202, 2017. `doi:10.1038/nature23474`.

8 S. Broyde and K. Binsted. Hi-seas: A mars analog mission. *Acta Astronautica*, 145:345–354, 2018. `doi:10.1016/j.actaastro.2018.01.032`.

9 Terrence Fong, Matthew Deans, and Clayton Kunz. Autonomous systems for human spaceflight. Technical report, NASA Technical Report, 2019. URL: `https://ntrs.nasa.gov/citations/20190027416`.

10 Terrence Fong, Mark Micire, Ted Morse, Eric Park, Chris Provencher, Vinh To, Dawn Wheeler, David Mittman, Recaredo J. Torres, and Ernest Smith. Smart SPHERES: a telerobotic free-flyer for intravehicular activities in space. In *AIAA SPACE 2013 Conference and Exposition*, 2013. `doi:10.2514/6.2013-5338`.

11 Steven C. H. Hoi, Doyen Sahoo, Jing Lu, and Peilin Zhao. Online learning: A comprehensive survey. *Neurocomputing*, 459:249–289, 2021. `doi:10.1016/j.neucom.2021.06.004`.

12 Timothy Hospedales, Antreas Antoniou, Paul Micaelli, and Amos Storkey. Meta-learning in neural networks: A survey. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 44(9):5149–5169, 2021. `doi:10.1109/TPAMI.2021.3079209`.

13 David D. Luxton. Artificial intelligence in psychological practice: Current and future applications and implications. *Professional Psychology: Research and Practice*, 45(5):332–339, 2014. `doi:10.1037/a0034559`.

14 Volodymyr Mnih, Koray Kavukcuoglu, David Silver, Andrei A. Rusu, Joel Veness, Marc G. Bellemare, Alex Graves, Martin Riedmiller, Andreas K. Fidjeland, Georg Ostrovski, Stig Petersen, Charles Beattie, Amir Sadik, Ioannis Antonoglou, Helen King, Dharshan Kumaran, Daan Wierstra, Shane Legg, and Demis Hassabis. Human-level control through deep reinforcement learning. *Nature*, 518(7540):529–533, 2015. `doi:10.1038/nature14236`.

15 NASA. Controls and automation research in space life support. Technical report, NASA, 2019. URL: `https://ntrs.nasa.gov/citations/20190027321`.

16 NASA. New center harnesses ai to advance autonomous exploration of space resources. Technical report, NASA, 2022. URL: `https://www.nasa.gov/centers/ames/news/2022/new-center-harnesses-ai-to-advance-autonomous-exploration-of-space-resources/`.

17 Engineering National Academies of Sciences and Medicine. Strengthening the stem workforce. Technical report, National Academies Press, 2020. `doi:10.17226/25612`.

18 NASA Human Research Program. Artificial intelligence for life in space (ai4ls). Technical report, NASA, 2021. URL: https://www.nasa.gov/ames/space-biosciences/research-branch/artificial-intelligence-for-life-in-space/.

19 Catherine D. Schuman, Thomas E. Potok, Robert M. Patton, J. Douglas Birdwell, Mark E. Dean, Garrett S. Rose, and James S. Plank. A survey of neuromorphic computing and neural networks in hardware. *arXiv preprint arXiv:1705.06963*, 2017. URL: https://arxiv.org/abs/1705.06963.

20 Thomas B. Sheridan. Human-robot interaction: Status and challenges. *Human Factors*, 62(4):525–532, 2020. doi:10.1177/0018720820941467.

21 SpaceX. Starship users guide. 2020. URL: https://www.spacex.com/media/starship_users_guide_v1.pdf.

22 Eric J. Topol. High-performance medicine: the convergence of human and artificial intelligence. *Nature Medicine*, 25(1):44–56, 2019. doi:10.1038/s41591-018-0300-7.

23 Ashish Vaswani, Noam Shazeer, Niki Parmar, Jakob Uszkoreit, Llion Jones, Aidan N. Gomez, Łukasz Kaiser, and Illia Polosukhin. Attention is all you need. *Advances in Neural Information Processing Systems*, 30, 2017. URL: https://proceedings.neurips.cc/paper/2017/file/3f5ee243547dee91fbd053c1c4a845aa-Paper.pdf.

24 Alexandra Witze. How ai is helping the perseverance rover explore mars. *Nature*, 590(7847):374–375, 2021. doi:10.1038/d41586-021-00463-8.