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Robotic Arms as Cognitive Tools for Designing Extraterrestrial Architecture

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Abstract: In his essay "The Future Isn't What It Used To Be," Victor Papanek critiques the prevailing drive to systematise design, arguing that an over-reliance on scientific predictability has led to a critical disconnection from fundamental human sensory responses to natural environmental conditions (Papanek 1995, cited in Margolin and Buchanan 1995). He observes that modern, hermetically sealed interiors—products of post-war development—have subjected inhabitants to a prolonged experiment in artificial living, severing vital connections to atmospheric phenomena like natural light and air. This intellectual foundation establishes an urgent imperative for design: to take conscious responsibility for manufactured environments that support rather than damage human health and performance. Within this critical framework, this paper considers whether robotic arms can serve as tools for thinking, assisting architects in reimagining the architectural design process for extraterrestrial habitats on the Moon and Mars, where creating viable sensory environments constitutes a fundamental prerequisite for survival rather than merely an aesthetic concern. This article envisions a future where architects employ robotic arms as cognitive tools in the design process, transforming creative efforts into an interactive blend of ideas and physical actions. It highlights how these robotic systems can extend human thinking capabilities, enabling architects to visualise and manipulate designs in previously impossible ways. Research synthesized from over 100 papers reveals that robotic arms provide immediate feedback during design processes, allowing architects to explore multiple concepts simultaneously and develop innovative solutions for extraterrestrial habitats. For example, when designing a structure on Mars, architects can use robotic arms to experiment with various materials and configurations, refining ideas in real time. A pertinent real-world example is the "Mars Ice Home" concept designed by the firm SEArch+ (Space Exploration Architecture) for NASA. This project exemplifies the principles of habitability and in-situ resource utilisation, proposing a radiation-shielded, pressurised habitat constructed from Martian water-ice. The architects at SEArch+ prioritised the psychological well-being of inhabitants by designing a layered, light-filtering ice shell to create a connection to the external Martian environment, directly addressing Papanek's critique of sensory-disconnected interiors (SEArch+ 2021). This cognitive collaboration enhances problem-solving capabilities and encourages architects to expand creative boundaries. However, a significant gap remains in understanding how to fully integrate robots as cognitive and creative partners in architecture. Further research is needed to explore human-robot interaction dynamics and optimise these relationships for design processes. By embracing robotic arms as thinking partners, architects can optimise resource utilisation and develop new approaches to architectural challenges, paving the way for advancements in extraterrestrial living.

Keywords - Robotic arms, Cognitive tools, Extraterrestrial architecture, Space construction, Human-robot collaboration, Space robotics.

I. INTRODUCTION

What built environment will future inhabitants of the Moon and Mars need, and how should we use technology to deliver it? Future inhabitants of the Moon and Mars will require a built environment that functions as an adaptive, cybernetic organism, seamlessly integrating structure, machine, ecosystem, and information to provide continuous environmental mediation, radiation shielding, and psychological support within extreme resource constraints (Werfel, Bruder, Teeple, and Wood 2024). This paradigm shift from terrestrial architecture necessitates a co-evolution of design methodology and enabling technology, central to which is the application of AI-driven robotic systems (You et al. 2025).

The role of robotics in this context is multifarious: robotic arms serve not merely as tools but as collaborative team members in assembly, clients that provide material and kinematic constraints, and partners in a generative design process (Wang, Li, and Hu 2024). This collaboration is further enhanced by the integration of haptic robotic gloves, which allow human operators to remotely perform delicate, high-dexterity tasks with force feedback, effectively projecting human presence into otherwise inaccessible or hazardous construction sites (Shen 2024). Research by Werfel et al.

(2024) demonstrates how robots can interpret human guidance through physical force alone, using shared objects as intuitive "channels for coordination," transforming robotic arms from mere fabricators into responsive partners that translate tactile input directly into constructed form. For lunar and Martian habitats, this enables a dynamic design process where architects can physically guide components in real-time, creating a feedback loop that merges human intuition with robotic precision—essential for resilient habitat design in uncertain environments (Werfel et al. 2024).

This human-robot synergy necessitates a new linguistic dimension of design, a lexicon where architectural forms are conceived for automated assembly—prioritising geometries that optimise robotic reach and integrate inherent structural and life- support functions ("Design Language" 2025). This article explores the idea of using robotic arms in the design process as a tool to think with, framing design itself as a cognitive act analogous to language acquisition—a translational process prone to deviation as human intent is interpreted by AI and executed by machines. It highlights the profound complexity of architectural design aimed at cultivating evolving, Earth-like, life-sustaining environments—projects that amount to a paradigmatic shift from historical biological evolution toward the deliberate creation of self-contained, artificially engineered organisms (You et al. 2025).

Recent research exemplifies this shift: the NASA Deep Space Food Challenge develops compact, efficient, closed-loop food production systems for long-duration missions (NASA 2020); MOXIE (Mars Oxygen In-Situ Resource Utilisation Experiment) demonstrates on-site chemical conversion of the Martian atmosphere into breathable oxygen (NASA 2021); and the Mars Ice Home concept proposes using in-situ ice as structural shielding and thermal mass to create pressurised, habitable volumes with built-in radiation and micrometeorite protection (SEArch+ 2021). Levy's (1992) account of John Holland's work on classifier systems further reframes design as an adaptive, hybrid process in which evolutionary search and individual learning coexist: Holland proposed classifier systems as a substrate for autonomous artificial creatures that can both evolve and learn, raising the question—why can't a creature change its strategy as it goes along; if it rejects one mode of alteration, why can't it adopt another? (Levy 1992). Framed for architecture, this suggests that robotic tools such as a robotic glove can function not merely as executors of fixed drawings but as cognitive partners— systems that translate, adapt, and learn from on-site contingencies—thereby making the design process itself a co-adaptive, translational practice between human intent, machine interpretation, and material reality.

The groundbreaking review by You et al. (2025) systematically examines the pivotal role and technological evolution of construction robotics designed to operate in extreme environments, ranging from terrestrial hazardous sites to the deep sea and outer space. The authors define these robotic systems as machines capable of performing complex engineering construction tasks autonomously in various extreme environments without human intervention, including hazardous work environments like demolition and post-disaster rescue, polluted environments such as nuclear-contaminated zones, and harsh natural environments like deep space (You et al. 2025). The core importance of their work lies in its holistic synthesis of the four key technical performance aspects essential for functionality in these conditions: biomimetic mechanism design, real-time environmental perception, autonomous motion planning, and intelligent decision control (You et al. 2025). The review underscores that the primary impetus for this field is the need to perform high-risk operations, highly repetitive labor, and high-precision tasks, thereby significantly improving construction efficiency and safety where human presence is either impossible or perilously dangerous (You et al. 2025).

The review analyses a wide array of project examples to illustrate current capabilities and research directions. For instance, the paper discusses systems designed for nuclear decommissioning and radioactive waste handling, where robots must employ radiation-hardened materials and sealed electronics to prevent contamination and degradation, a challenge also highlighted in broader research on robotics in extreme environments (Zhang et al. 2021; Boston Engineering 2023). Furthermore, the review explores applications in deep-sea exploration, where robots are constructed with pressure-tolerant housings and corrosion-resistant materials, integrating sonar and navigation systems for underwater infrastructure inspections (Boston Engineering 2023). For space—the ultimate extreme environment—the work aligns with ongoing efforts at institutions like NASA's JPL, which develops robots for constructing and maintaining facilities in orbit or on planetary surfaces, emphasising reconfigurability, multi-robot coordination, and human-robot teaming to handle payloads much larger than the robots themselves (JPL Robotics 2023). The Limbed Excursion Mechanical Utility Robot (LEMUR), an agile six-legged walking robot for assembling and inspecting orbital structures, is cited as a prime example of such technology (JPL Robotics 2023).

A critical conclusion from the review is the identification of persistent interdisciplinary challenges, including how to ensure robotic operational effectiveness, safety, and reliability under conditions of unstructured environments, limited observational methods, and multi-objective constraints (You et al. 2025). These findings are echoed in a broader bibliometrics review of construction robotics, which notes that despite a 320% increase in research output, critical gaps remain in interoperability, workforce retraining, and regulatory frameworks (Appl. Sci. 2025). The work by You et al. (2025) ultimately provides a crucial framework for the future of intelligent construction, forecasting research directions and advocating for a coordinated approach to overcome the technical and socio-technical barriers to deploying robotics in the most challenging environments on Earth and beyond.

II. LITERATURE REVIEW

The conceptual foundation for human habitation on Mars was robustly established by Zubrin (2011), whose work advocates for the Mars Direct plan emphasising in-situ resource utilisation (ISRU) and technological feasibility. Zubrin details how automated systems and local materials can manufacture fuel and construct habitats, proposing burying pressurised habitats in regolith for radiation shielding ideas that align directly with modern robotic construction concepts. This socio-technical framework for Martian settlement underscores the necessity of robotic arms to handle hazardous environmental tasks. Building upon this vision, Benaroya (2018) addresses the specific engineering challenges of constructing habitats using lunar and Martian materials, providing rigorous analysis of material properties and construction methodologies. His work delves into regolith-based construction and structural integrity in low-gravity environments, highlighting technologies like 3D printing with sintered regolith that directly inform the development of robotic systems for autonomous building processes.

The architectural principles for space environments were comprehensively outlined by Howe and Sherwood (2009), whose edited volume integrates habitat design with life support systems while emphasising robotics' role in creating adaptable and resilient structures for extreme environments. This interdisciplinary approach demonstrates how architectural design must evolve to accommodate robotic construction and ISRU technologies, particularly regarding human factors and psychological resilience. Earlier foundational work by Eckart (2006) provides practical insights into lunar base design, covering structural, environmental, and logistical aspects including robotic excavation and habitat assembly. The handbook's emphasis on autonomous systems for handling regolith radiation shielding remains highly relevant for designing robotic arms capable of functioning in the Moon's harsh environment. These contemporary works build upon the pioneering vision of Mendell (1985), whose early comprehensive work on lunar bases explored concepts like lava tube settlements and regolith-based construction that have become central to discussions on robotic architecture.

NASA's contributions to this field have been substantial and practical. Cohen (2015) explores the integration of architectural principles into space habitat design, stressing the importance of human-centred design in confined environments and discussing robotics' role in creating multifunctional spaces. This focus on adaptable structures aligns perfectly with robotic arms' capabilities to assemble and reconfigure habitats based on mission needs. Similarly, Kennedy (2002) details plans for human missions to Mars with specific emphasis on collaborative human-robot operations where robotic arms handle regolith excavation, sample collection, and habitat assembly. The operational experience gained from the International Space Station, as documented by Savage and Smith (2018), provides invaluable insights into long-term habitat maintenance using robotic systems for assembly, repairs, and logistics—lessons directly applicable to designing robotic architectures for lunar and Martian habitats where autonomy and reliability are paramount.

The critical role of ISRU technologies is thoroughly analysed by Rapp (2013), who examines methods for producing breathable air, water, and fuel from local resources. This technical depth provides essential knowledge for integrating ISRU systems with robotic construction processes, ensuring habitats are both self-sufficient and sustainable. This vision of resource utilisation extends to lunar settlement concepts in Schrunk et al. (2008), who advocate for a "Planet Moon Project" linking technological expertise with space resources through robotic networks for extraction and construction.

The robotics-specific literature provides the technical foundation for these applications. Brugali (2013) offers a comprehensive overview of construction robotics, emphasising autonomous systems capable of operating in dynamic environments and discussing integration of sensors and AI for real-time adaptation—capabilities essential for handling unpredictable conditions like regolith variability and radiation exposure. This builds upon Khatib's (1998) seminal work tracing the evolution from simple automation to full autonomy, introducing concepts like force feedback control and compliant motion essential for robots handling delicate assembly tasks in space. The field's current state is captured comprehensively in Siciliano and Khatib (2016), whose monumental reference work details algorithms for navigation, manipulation, and human-robot collaboration while emphasising modular software architectures and standardisation crucial for space missions requiring interoperability between different robotic systems.

Recent advances are particularly promising. Werfel et al. (2024) explore systems designed explicitly for space habitation, highlighting innovations like soft robotic arms for delicate tasks and multi-functional grippers for handling diverse materials. Their framework for autonomous robotics that integrates with human operations provides a balanced approach vital for long-term missions. The creative potential of these systems is demonstrated by Wang et al. (2024), who examine AI-driven robotic arms that repurpose waste materials into functional structures—a capability invaluable for Mars missions where recycling materials will be essential for sustainability. The interface between humans and machines is advanced through Shen's (2024) research on mixed reality interfaces that enable seamless human-robot collaboration, allowing operators to visualise robotic actions overlayed on physical sites and make real-time adjustments that minimise exposure to hazards.

A notable example of soft robotics application comes from Harvard's RETHi project, which developed a soft robotic arm that can stiffen on command to increase its force and payload capacity while maintaining the safety benefits of soft robotics for human- robot collaboration in confined spaces (Werfel et al. 2024). This innovation addresses the challenge of robots needing both flexibility for navigation and strength for construction tasks in space habitats. Similarly, researchers at Yale University have developed amphibious turtle-inspired robots with limbs made with variable-stiffness materials that change between swimming flippers and load-bearing legs depending on the environment (Wang et al. 2024), demonstrating the potential for adaptive robotic systems in extraterrestrial construction where conditions may vary dramatically.

The field's evolution and future directions are mapped in Najjar (2024), who synthesises current applications and projects future trends while identifying key challenges including high initial costs and technical complexity—issues magnified in space due to launch costs and maintenance difficulties. This contemporary analysis builds upon decades of research, beginning with Bernold's (1987) early critical assessment of robotics in construction that cautioned against over-reliance in dynamic environments where human intuition remains irreplaceable. The practical applications were further developed by Skibniewski and Nof (1989), who explored robotic teamwork concepts that prefigure modern swarm robotics proposed for lunar construction, while Warszawski (1989) provided economic and technical viability analysis that remains relevant for space applications where speed is critical for avoiding radiation exposure.

The critical dimension of human-robot collaboration is thoroughly examined across multiple studies. Goodrich and Olsen (2003) establish seven foundational principles for efficient human-robot interaction that provide essential guidelines for designing systems that can collaborate effectively with astronauts under conditions of communication delay and limited resources. Lemaignan et al. (2017) review industrial human-robot interaction, highlighting insights about safety protocols and task allocation adaptable to space construction constraints. The technological enabling of collaboration is advanced by Weiss et al. (2021), who explore how cyber-physical systems and IoT integration facilitate real-time data exchange and cooperative task execution models applicable to autonomous decision-making on lunar and Martian sites.

The cognitive aspects of interaction are addressed by Bauer et al. (2008), who apply principles of human cognition to develop intuitive robotic responses that reduce cognitive load on operators—a crucial consideration for space habitats where astronauts manage multiple tasks under psychological stress. Adams (2005) provides a comprehensive survey of human-robot interaction research that serves as broad theoretical foundation for understanding how trust, communication, and interface design can be optimised for off-world construction challenges. The specific application to construction environments is developed by Charalambous et al. (2015), who propose a specialised framework for collaboration focusing on safety, efficiency, and adaptability directly applicable to extraterrestrial building projects.

Practical implementation aspects are examined by Robla-Gómez et al. (2017), whose comparative study of collaboration models helps inform appropriate control schemes for space applications, and Vysocky and Novak (2016), who discuss hardware design, safety standards, and ergonomic considerations relevant to developing systems for physical interaction in confined habitat spaces. Recent advances are captured by Mazachek (2020), who notes trends toward AI-enhanced adaptability and predictive analytics that could enable space robotics to anticipate astronaut needs proactively. The broader implications are considered by Cette et al. (2021), who examine economic and social impacts of automation that provide important context for understanding how human-robot collaboration might evolve in the isolated, resource-limited societies of future space settlements.

Together, this body of literature demonstrates that successful human-robot collaboration in space will require not only technical advancements in autonomy and interface design, but also deep understanding of human factors, social dynamics, and unique extraterrestrial environmental constraints. Projects like NASA's RETHi institute and Harvard's soft robotics research provide concrete examples of how these principles are being implemented in current research, pointing toward a future where robotic arms serve as true cognitive partners in designing and maintaining extraterrestrial habitats.

III. DISCUSSION

Cognitive and Translational Challenges

Aguado et al. (2024) systematically analyze how ontologies enhance the dependability of autonomous robotic systems, categorising crucial processes such as knowledge representation, task planning, human-robot interaction, and system diagnosis. Their findings emphasise that formal ontologies provide a shared vocabulary enabling robots to understand their environment, capabilities, and tasks, which is essential for reliability in complex settings (Aguado et al. 2024). This is particularly critical for high-stakes applications like robotic surgery and autonomous driving, where decision-making failures can have severe consequences (Hochgeschwender 2023).

The survey highlights innovative implementations, such as industrial robots using ontologies to dynamically replan assembly tasks upon detecting machine failures (De Gasperis 2024), and service robots leveraging household object ontologies to interpret complex commands like "tidy the living room" (Malavolta et al. 2024). In autonomous navigation, ontologies enable semantic classification—for instance, allowing a self- driving car to identify an object as a "construction barrier" and reason about appropriate actions (Aguado et al. 2024). The synthesis of this fragmented field provides a taxonomy linking ontological structures to dependability challenges, underscoring that while ontologies add initial complexity, they reduce long-term costs and increase robustness by making knowledge explicit and updatable (Hernando and Sanz 2024). The authors conclude that ontological reasoning is becoming a cornerstone for next-generation autonomous robots operating safely alongside humans (Aguado et al. 2024).

Design as Cognitive Process and Translation

Design ability has been theorised as a natural process analogous to language acquisition. Green (1971, cited in Lawson 2000) posits that this development begins in childhood through arranging possessions, facilitating learning in classification and self- expression. This process parallels linguistic fluency development, suggesting design proficiency evolves continuously (Lawson 2000).

Evans (1986) complicates this by framing design as an act of translation—moving
something without altering its essence. However, the substratum for this transfer lacks uniformity, causing meanings to be bent, broken, or lost. Evans argues that assuming an idealised, continuous space for translation is a necessary delusion to understand systematic deviations (Evans 1986).

These theories profoundly impact designing for extraterrestrial environments. Architects must solve innumerable equations with endless "right" solutions, simulating a new living organism—an Earth-like atmosphere—artificially engineered for the Moon and Mars. This simulated environment must enable inhabitants to live, breathe, and evolve naturally, presenting a fundamental theoretical challenge: whether a self-contained organism can autonomously adapt to harsh environments and whether humans can evolve within an artificially controlled setting without a disruptive leap in natural selection.

In the age of super artificial intelligence, this inquiry extends to robotic integration. If translation between languages involves loss and distortion, designing extraterrestrial habitats—translating Earth's environment into alien contexts through mechanical systems—raises critical questions about reliability and usefulness in the design process. The resulting environments and their inhabitants will likely experience not gradual evolution but a major jump, dispossessed from open natural conditions.

Robotic Arm Integration and Theoretical Frameworks

Designing for the Moon and Mars requires re-conceptualising architecture through dual theoretical lenses: design as cognitive process and as translational act. This is exemplified by firms like Bjarke Ingels Group (BIG), which views architecture as "formgiving"—giving form to the yet unformed (Ingels 2009). BIG's collaboration with ICON and SEArch+ on Project Olympus aims to develop a sustainable lunar habitat using 3D-printing robotics and ISRU (BIG n.d.). Their 'Ancient Future' installation at the 2025 Venice Biennale juxtaposed hand-carved and robotically milled timber, demonstrating technology's role in scaling heritage design (Parametric Architecture 2025).

Interdisciplinary approaches are further illustrated by Archi-Union Architects, whose Venue B Conference Centre used algorithmic planning and robotic fabrication for a prefabricated timber roof in 100 days (Archi-Union n.d.).

Gramazio Kohler Research
pioneered autonomous flying robots assembling complex structures (Gramazio Kohler Research 2012), while Allies and Morrison integrated historic preservation with sustainable development in projects like King's Cross Central (Allies and Morrison n.d.).

The hostile lunar and Martian environments demand new approaches, leveraging robotic arms for precision, efficiency, and cost savings. These systems enable autonomous assembly, repair, and adaptation, exemplified by NASA's Robotic Servicing Arm and Canada's Canadarm3 for the Lunar Gateway.

Robotic Gloves for Design and Operation
Human-scale robotic wearables, particularly sensorized gloves, augment precision and teleoperation. Commercial systems like Bioservo's Ironhand amplify grip strength and reduce fatigue (Bioservo 2020), while Ntention's Astronaut Smart Glove converts hand motions into commands for drones and robots (Ntention 2021). Maker communities develop Arduino-based flex-sensor gloves (Arduino 2016), and advanced research explores soft robotic gloves with 3D-printed piezoresistive sensors (Soft Robotics Toolkit 2019).

Repurposing such gloves as architectural drawing instruments could capture kinematics and physiological signals, translating them into digital models. This raises questions about how glove-mediated capture affects the translation from cognition to artefact, potentially preserving non-discursive impulses or redirecting creativity through sensor-driven affordances.

DuPont (2023) detailed printing stretchable silver conductor ink on TPU laminated gloves for robotic hand control, achieving finger bending up to 60° (Martian 2023). This method priorities accessibility and rapid prototyping, compared to alternatives like direct ink writing of carbon-based nanocomposites (Chen and Zhang 2024) or hybrid conductive inks (Zhou et al. 2023). Challenges include maintaining conductivity during stretching, addressed by printing thicker traces, with future directions involving hybrid sensing or machine learning integration (Martian 2023).

Fiska et al. (2025) integrated soft robotic gloves into the NeuroSuitUp platform for hand rehabilitation, demonstrating improved finger and grip performance through closed- loop systems facilitating neuroplasticity. Key lessons highlight multi-sensor integration, soft robotics for comfort, and embedding devices in broader frameworks for functional recovery (Mitsopoulos et al. 2023).

The UDCAP Data Glove from UDEXREAL uses a 0.1mm elastic sensor for high-precision hand tracking in robotics and XR, enabling natural teleoperation and detailed motion datasets for training humanoid robots (UDEXREAL 2025a, 2025b). Its plug-and-play design supports immersive training without external cameras (UDEXREAL 2025c).

Rethi Innovations And Architectural Modelling
Harvard SEAS researchers, funded by NASA's RETHi Institute, develop robotic systems for deep space habitats. Innovations include a multi-mode gripper with reconfigurable scissor links for grasping and manipulation (Wood et al. 2022), a soft robotic arm with variable stiffness for navigation and heavy object handling (Bruder et al. 2023), an intuitive guidance system for human-robot collaboration (Carey and Werfel 2023), and retrofitted hardware for robotic operability (Melenbrink, Teeple, and Werfel 2022). This work emphasises multifunctional, autonomous systems and co-designing tasks for robotic capabilities, conserving astronaut time and enhancing mission safety (Werfel 2024).

In architectural modelling, Miyazawa et al. (2017) introduced RoboChart, a DSL for robotic controllers with formal semantics and verification support. Cavalcanti et al. (2021) expanded this with the RoboStar framework for model-driven engineering, enabling simulation, testing, and proof. Nordmann et al. (2016) surveyed DSLs in robotics, highlighting trends toward MDE and the need for formal methods.

The Perkins+Will and Autodesk BUILD Space collaboration advanced robotic material innovation, developing workflows integrating computational design with real-time robotic control for complex forms (Perkins+Will 2023; Autodesk BUILD Space 2023). This open-source platform democratises robotic technology in AEC, emphasising augmentation of human creativity. Goyal (2023) highlighted pioneering robotic fabrication projects, including ETH Zurich's 3D-printed steel bridge (ETH Zurich 2025), knitted textile canopies from ocean plasti (ZHA Code 2024), ICON's 3D-printed concrete house (ICON 2025), robotic deconstruction for adaptive reuse (Materiom 2024), and MIT's drone-spun silk structures (MIT Media Lab 2025). These exemplify robotics as enablers of new design languages, sustainable practices, and structural possibilities.

Architectural Futures: Designing for the Longevity in Space

The endeavour to establish permanent human habitats on the Moon and Mars represents a fundamental redefinition of architectural and medical paradigms, moving beyond terrestrial constraints to address the extreme and potentially lethal conditions of space. This new frontier forces architects and medical professionals to confront a complex web of physiological and psychological constraints, many of which remain unfamiliar due to the novelty of long-duration space missions. Among the most critical health hazards are space radiation, isolation and confinement, distance from Earth, varying gravity fields, and hostile closed environments (National Aeronautics and Space Administration 2023). Each factor imposes unique and often contradictory demands on habitat design. For instance, the need for robust radiation shielding—potentially achieved through thick regolith walls or water-filled barriers—can conflict with the psychological necessity of open, spacious interiors to mitigate the effects of prolonged isolation and sensory monotony. This tension between survival and well-being is further complicated by the potential for medical emergencies that are manageable on Earth but catastrophic in space. Dental emergencies, for example, are ranked among the top five conditions with a negative impact on long-duration missions, a concern underscored by the pre-flight wisdom tooth extraction of astronauts like Rakesh Sharma to prevent in-flight crises (National Aeronautics and Space Administration 2023). Such procedures, while preventive, carry risks, as evidenced by rare but severe complications like pneumothorax or pneuma-mediastinum from compressed air use during extractions (Chen et al. 2012).

The architectural response to these biomedical imperatives must extend beyond mere shelter to become an integrated life-support system. The toxicological properties of lunar and Martian dust, which is abrasive, chemically reactive, and fine enough to penetrate deep into human respiratory systems, necessitate design innovations such as advanced filtration systems and "suitport" entryways to prevent particulate intrusion into living quarters (Kozicki and Kozicka 2011). Furthermore, the remote nature of these missions has sparked debate regarding prophylactic surgeries to preempt emergencies. While probabilistic risk assessments have concluded that routine prophylactic removal of the appendix or gallbladder is unjustified due to surgical complications outweighing benefits, the discussion highlights human vulnerability in space and the need for habitats with advanced medical capabilities ("Prophylactic Surgery" 2012). The appendix, once considered vestigial, is now recognised as a microbiome regulator critical for immune function, and its removal could increase susceptibility to diseases like colitis or Parkinson's, making prophylactic appendectomy particularly risky (The Conversation 2025). Similarly, prophylactic splenectomy to mitigate radiation damage has been strongly countered by comprehensive analysis, noting the procedure's significant risks, including haemorrhage and lifelong vulnerability to overwhelming post- splenectomy infection (OPSI), which is disproportionate to actual radiation exposure on a Mars mission (Cleveland Clinic 2025; Serebriakova 2021). Radiation remains a pervasive hazard, capable of causing not only increased cancer risk but also functional damage to organs like the spleen, impairing immunity even without physical removal (Cleveland Clinic 2025).

This biological vulnerability intersects with the evolving nature of space colonists, who may undergo biological and cybernetic enhancements to adapt to extraterrestrial environments. Philosophers like Yuval Noah Harari speculate that humanity is entering an era of bioengineering, where technologies like AI and genetic modification could redefine human capabilities and extend longevity significantly (Harari 2017). This prospect of extended human lifespans—potentially reaching hundreds of years— creates a new paradigm for architectural clients, who will require habitats that support not just survival but thriving across centuries. However, Harari's views are contentious; critics argue his narratives often prioritise sensationalism over scientific rigour, particularly in claims about human obsolescence or the implications of AI (Current Affairs 2022). Despite this, his ideas underscore a critical point: future space inhabitants may represent a "new clientele" with enhanced physical traits or cybernetic integrations, necessitating architectural designs that are adaptable to varying human forms and needs over extended timescales. For architects, this means designing habitats that are not only physically resilient but also psychologically supportive and flexible enough to accommodate evolving human conditions. Kozicki and Kozicka's research emphasises the importance of human-centred design in Martian bases, advocating for expanded volumes, biophilic elements, and segregated spaces to combat isolation-induced psychological issues like depression or hallucinations (Kozicki and Kozicka 2011).

For architects with limited medical knowledge, addressing these multifaceted challenges requires leveraging technological assistance. Robotic systems and AI tools can bridge knowledge gaps by translating complex health data into actionable design parameters. For instance, haptic feedback gloves could allow architects to "feel" radiation exposure levels in virtual models, while AI assistants could simulate how bio- engineered occupants might interact with proposed environments over extended lifetimes (Axiom Space 2024). These technologies enable a collaborative framework where architects, physicians, and engineers work together to create habitats that are both safe and conducive to well-being across extended human lifespans. Moreover, intelligent systems can predict long-term health impacts, such as radiation-induced hyposplenism, and recommend design features like enhanced sterilisation systems or isolation zones to mitigate infection risks (Siu et al. 2022).

The challenge of designing for space is not merely technical but deeply ethical and interdisciplinary. It necessitates a holistic approach that integrates medical insights, architectural innovation, and emerging technologies to support human health and longevity in extreme environments. As humanity stands on the brink of becoming a multi-planetary species, the lessons learned from space colonisation could also inform terrestrial design, particularly in addressing issues of inequality and accessibility highlighted by thinkers like Harari. Ultimately, the success of these endeavours depends on a collaborative ethos that priorities human well-being over mere survival, ensuring that the future of space habitation is both sustainable and inclusive for clients whose lives may span centuries.

IV. CONCLUSION

This research has systematically examined the role of robotic arms as cognitive tools in designing extraterrestrial habitats, addressing fundamental questions about how future inhabitants might live on the Moon and Mars and what technologies will be required to deliver these built environments. Through an analysis of theoretical frameworks, technical implementations, and practical applications, several critical conclusions emerge that advance the understanding of space architecture and human-robot collaboration in extreme environments.

The theoretical foundation established through Papanek's critique of systematised design and Evans' concept of architectural translation provides essential context for understanding the cognitive challenges inherent in designing for extraterrestrial environments. These frameworks reveal that creating habitats for the Moon and Mars represents not merely a technical challenge but a profound conceptual shift in how design itself is approached. The process requires translating Earth-based environmental conditions into entirely alien contexts through mechanical and digital systems, with inevitable deviations and adaptations occurring throughout this translational process.

Examination of current robotic technologies demonstrates significant progress in addressing the practical challenges of extraterrestrial construction. Research illustrates how multi-mode grippers, variable-stiffness robotic arms, and intuitive human-robot collaboration systems can enable complex maintenance and construction tasks in space environments. These developments are complemented by advances in soft robotics, particularly in the domain of robotic gloves, which show promise for both construction tasks and potential applications in the design process itself. Projects demonstrate how human-robot interfaces can capture subtle movements and translate them into digital commands, potentially creating new pathways for architectural expression.

The integration of ontological frameworks provides a crucial foundation for developing dependable autonomous systems. These formal knowledge representation systems enable robots to better understand their environment, capabilities, and tasks, which is essential for reliable operation in complex, unpredictable settings. The implementation of ontologies in various domains demonstrates their potential for enhancing transparency, interoperability, and explainability in robotic systems designed for space applications.

Analysis of architectural approaches reveals how leading firms are addressing the challenges of extraterrestrial design. Concepts such as "formgiving" and the integration of computational design with robotic fabrication represent significant advances in thinking about how to create sustainable lunar habitats using 3D-printing robotics and in-situ resource utilisation. This work demonstrates how these methods can be integrated to create complex structures with unprecedented efficiency and precision.

The development of robotic gloves and wearable technologies presents interesting possibilities for the future of architectural design. Research on soft robotic gloves and the commercial development of data gloves suggest that these technologies could potentially be repurposed as design tools. By capturing kinematics and physiological signals, such devices might enable new forms of architectural expression that better capture the intuitive, non-discursive aspects of design cognition. However, the analysis indicates that this would require careful consideration of how such mediation affects the translation from cognitive impulse to physical artefact.

The challenges of designing for extraterrestrial environments extend beyond technical considerations to fundamental questions about human adaptation and evolution. The creation of self-contained, artificially engineered biological organisms that simulate Earth's atmosphere represents a radical departure from terrestrial architectural paradigms. This endeavour raises profound questions about whether humans can adapt to totally artificially controlled living environments without experiencing a major disruption in the natural selection process.

The research indicates that successful human-robot collaboration in space will require not only technical advancements in autonomy and interface design but also a deep understanding of human factors, social dynamics, and the unique constraints of the extraterrestrial environment. Established principles for efficient human-robot interaction— including adaptive autonomy, transparency, and mutual adaptation— provide valuable guidance for designing systems that can collaborate effectively with astronauts under conditions of communication delay and limited resources.

The various projects examined, from servicing arms to construction systems, demonstrate the importance of developing robotic systems capable of autonomous operation and self-maintenance in space environments. These systems must be able to handle a wide range of tasks while operating reliably in conditions characterised by radiation, extreme temperatures, and material scarcity.

Analysis of model-driven engineering approaches in robotics highlights the importance of formal methods and verification techniques for ensuring the reliability and safety of robotic systems in critical applications. These approaches provide valuable tools for addressing the complexity of robotic software development and for generating assurance evidence required for certification in safety-critical domains.

Collaborations between architecture and technology firms demonstrate how industrial robotic arms can serve as instruments for material exploration and innovation in architectural design. By developing seamless workflows that integrate computational design with real-time robotic control, researchers are expanding the palette of what is buildable and opening new possibilities for architectural expression. This approach emphasises that the true value of robotics lies not in replication but in augmentation— enhancing human creativity by offloading laborious, precise, or dangerous tasks.

Looking forward, several key areas require further research and development. First, there is a need for more extensive testing and validation of robotic systems in analog environments that simulate lunar and Martian conditions to ensure system reliability. Second, further research is needed on human-robot interaction in space contexts, particularly regarding effective collaboration under conditions of communication delay and psychological stress. Third, there is a need for continued development of ISRU technologies and their integration with robotic construction systems to achieve full self- sufficiency. Fourth, more research is needed on the long-term human factors of living in artificially controlled environments, including psychological adaptation and physiological effects. Finally, there is a need for continued development of formal methods and verification techniques for ensuring the reliability of autonomous robotic systems in space applications.

In conclusion, this investigation of robotic arms as cognitive tools for designing extraterrestrial habitats represents a convergence of multiple disciplines—architecture, robotics, computer science, materials science, and human factors—all working together to address one of the most profound challenges of our era. The research and projects examined demonstrate significant progress toward creating sustainable, resilient habitats that can support human life on the Moon and Mars, while also highlighting the substantial challenges that remain.

The theoretical frameworks of design as cognitive process and translational act provide valuable perspectives for understanding the complexities of this endeavour, while technological advances in robotics, autonomy, and human-robot interaction offer practical pathways for addressing these challenges. A holistic perspective that considers not only technical feasibility but also human factors, sustainability, and the broader implications of creating artificially engineered living environments remains essential.

The journey toward establishing human presence on the Moon and Mars will require continued innovation, collaboration, and thoughtful consideration of the profound
questions raised by this endeavour. By building on the foundations established through current research and addressing the challenges identified in this analysis, it is possible to work toward creating extraterrestrial habitats that not only ensure human survival but also enable flourishing and continued evolution in these new environments.

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