A New World on Another Planet: Human Settlement and Architectural Design on Mars with Artificial Intelligence

Serdar KASAP[1*], Gizem SERİ YEŞİL[2]

[1]Associate Professor, Faculty of Fine Arts and Design, Bilecik Şeyh Edebali University, Bilecik, Türkiye

[2]M.Sc. Architect, Philadelphia, United States

[*]Corresponding Author

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ABSTRACT

Exploration of living possibilities on different planets, such as the Moon and Mars, has become one of the primary focuses of current scientific and technological research. Humanity's quest to understand the universe, combined with the desire to explore the limits of nature, encourages the development of new approaches that could make life in space possible. In this context, a detailed examination of the physical and chemical properties of planets, an analysis of atmospheric conditions, and the design of sustainable life support systems are among the fundamental elements of these studies.

Space missions, continuously conducted since the 1950s, have deepened humanity's knowledge of the universe, marking significant milestones in the exploration processes of this field. Initially limited to the exploration of Earth's orbit and the goal of reaching the Moon, these endeavors have taken on a much more comprehensive and sophisticated dimension with the rapid advancement of technology. Technological developments in spacecraft and observation systems, the widespread use of artificial intelligence-supported analytical methods, and increasing international cooperation have significantly accelerated progress in space research, allowing for the collection of more detailed and comprehensive data about the depths of the universe. Systematic research aimed at examining the conditions of space has led to large-scale innovations in the fields of science and engineering.

In the context of expanding human habitation, Mars is predicted to be the next target. However, building a sustainable living environment on Mars requires the coordinated and integrated efforts of many disciplines beyond architecture, including engineering, biotechnology, material science, and others.

This article will evaluate possible life scenarios and living conditions on Mars in line with predictions of living in space. It will also comprehensively analyze the architectural and engineering principles when designing human settlements and sustainable living spaces on Mars.

Keywords: Space Architecture, life on Mars, sustainability in space, Mars Architecture

INTRODUCTION

Humanity's interest in space exploration has continued since the 1950s and has grown with contemporary technological and scientific advancements. Organizing manned missions to Mars and establishing permanent habitats are important in plans. The possibility of life on Mars has become one of the main topics of modern space research, leading to a concentrated scientific focus on examining the planet as a potential settlement site.

Mars stands out as the first extraterrestrial location due to its potential to harbor many essential resources for sustaining human life [1]. In this context, one of the primary objectives of human-crewed missions to Mars is the comprehensive analysis of the planet's geophysical features and extreme environmental conditions. Such research is critical for assessing the possibilities of sustainable life on Mars and determining whether suitable infrastructure for human habitation can be developed.

Robots that have conducted various research on Mars from the past to the present have provided valuable data on the planet's surface conditions, atmospheric structure, and other natural features. Considering the success of these robots over the years, it is anticipated that modern robotic technologies will play a supporting role in future human missions to Mars. In this context, this study aims to analyze Mars' structural and environmental conditions and propose architectural design principles for sustainable living spaces to be built there.

Land conditions, energy supply methods, the selection of building materials, and the development of structures resistant to extreme environmental factors are among the key topics to be considered. The study analyzes the architectural and engineering strategies necessary for designing sustainable structures on Mars that meet human comfort and ergonomic needs over the long term. Various design approaches and evaluations regarding construction techniques and material choices that could be integrated into the Martian surface are presented.

RESEARCH METHODOLOGY

This study adopts a qualitative and conceptual research methodology supported by a comprehensive literature review and AI-assisted architectural design approaches. The research focuses on evaluating environmental conditions on Mars and developing architectural strategies that respond to these extreme conditions.

In the first stage, existing scientific literature on Mars’ environmental characteristics, including temperature, radiation, atmospheric structure, and material availability, was systematically reviewed. These environmental parameters were identified as primary constraints influencing architectural design decisions.

In the second stage, architectural design criteria were established based on these constraints, with particular emphasis on sustainability, structural durability, and human comfort.

In the third stage, AI-assisted design approaches, including parametric design, generative design, and data-driven optimization methods, were conceptually integrated into the study. These approaches were used to explore adaptive design solutions capable of responding to environmental variables.

Finally, a conceptual design framework and a hypothetical scenario were developed to demonstrate how AI-based architectural strategies can be applied to Mars habitats. These proposals aim to provide a structured approach for future research and practical applications in the field of space architecture.

Although this study does not include experimental or numerical simulation results, it presents a systematic and interdisciplinary framework that contributes to the theoretical development of AI-assisted architectural design in extraterrestrial environments.

Mars and Humanity's Vision: The Path to Space

The development of space exploration began in the mid-20th century and has progressed significantly with advancements in science and technology. Milestones such as the launch of Sputnik 1 in 1957 and the first human space missions marked the beginning of humanity’s exploration beyond Earth, expanding scientific understanding of extraterrestrial environments.

Although the Moon remains the only celestial body where humans have physically landed, its lack of atmosphere and extreme environmental conditions limit its suitability for long-term habitation. In contrast, Mars has emerged as the most feasible candidate for human settlement due to its relatively similar gravity conditions and the potential availability of essential resources such as water and minerals [2].

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Recent robotic missions and scientific studies have provided detailed data on Mars' surface conditions, atmospheric structure, and resource potential. These findings play a critical role in identifying suitable landing sites and developing strategies for sustainable human habitation. In parallel, technological advancements in spacecraft systems, along with increasing international and private sector initiatives, have accelerated efforts toward human-crewed missions to Mars [3].

In addition, private sector initiatives play a significant role in accelerating Mars exploration. For example, Elon Musk, through SpaceX, has proposed long-term plans for establishing a human settlement on Mars, emphasizing the importance of developing sustainable habitat systems for future missions [3].

Conditions on Mars and Comparison with Earth

Scientific studies define Mars as a terrestrial planet with environmental characteristics that differ significantly from those of Earth. The planet is widely referred to as the "Red Planet" due to the presence of iron oxide on its surface, which gives it a distinctive reddish appearance [4].

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Although Mars shares certain similarities with Earth, such as comparable day length and a solid planetary structure, its environmental conditions are considerably more extreme. A Martian year lasts approximately 687 Earth days, while a day is slightly longer than that of Earth. These planetary characteristics influence surface processes and environmental dynamics, which are critical for evaluating potential habitation scenarios.

In contrast to Earth, Mars exhibits low atmospheric pressure, limited water availability, and high radiation exposure. These factors create a highly constrained environment for human life and represent fundamental challenges for architectural design and settlement planning.

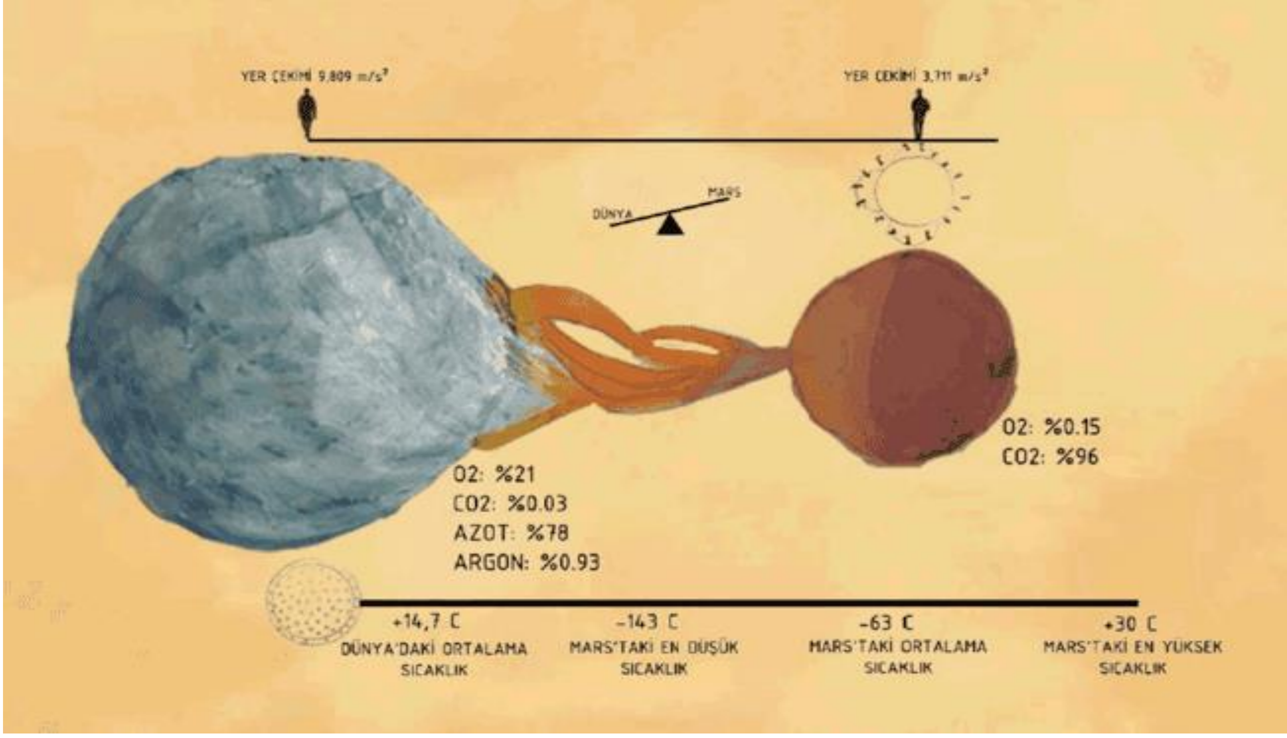

Fig. 1. Comparison of Earth and Mars [5].

Water

On Mars, water exists primarily in solid or vapor phases due to low atmospheric pressure, which causes sublimation. This limitation directly affects both life-support systems and construction processes. From an architectural perspective, minimizing water usage in material production and habitat systems becomes essential for sustainable design [6].

Compared to Earth, Mars represents an extremely arid environment, even drier than the Atacama Desert, which further constrains water-dependent systems in long-term habitation scenarios [7].

Temperature

Mars exhibits extreme temperature conditions, with an average temperature of approximately -60°C and fluctuations exceeding 100°C between day and night. These variations create significant challenges for material durability and thermal regulation in architectural design [6].

Gravity

Mars' gravity is approximately one-third of Earth's, which has critical implications for both human physiology and structural design. Reduced gravity affects long-term human health, including muscle and bone density loss, while also influencing load distribution and structural behavior in built environments [8].

Radiation

Due to its thin atmosphere and lack of an ozone layer, Mars is exposed to high levels of solar and cosmic radiation. This condition represents one of the most critical challenges for human habitation and necessitates the integration of radiation-shielding strategies in architectural design [9][10].

Atmosphere

Mars has a low-density atmosphere composed mainly of carbon dioxide, with surface pressure less than 1% of Earth's. This condition requires pressurized habitat systems and significantly affects thermal stability, material performance, and construction techniques [11][12].

Wind

Although Mars has a thin atmosphere, wind activity plays a significant role in shaping surface conditions. Wind speeds can reach up to 100 km/h, transporting fine dust particles that contribute to erosion processes and surface instability [13].

From an architectural perspective, wind-driven dust represents a critical challenge, as abrasive particles can damage structural surfaces, reduce material durability, and affect mechanical systems. In addition, large-scale dust storms may significantly reduce visibility and solar radiation levels, directly impacting energy systems and operational efficiency.

Therefore, wind conditions on Mars necessitate the development of protective building envelopes, dust-resistant materials, and adaptive design strategies to ensure long-term structural performance and habitability.

Regolith

Martian regolith, composed of fine dust and fragmented mineral particles, forms the primary surface layer of the planet and represents a key resource for in-situ construction. Its widespread availability makes it a strategic material for reducing dependence on Earth-based resources in long-term settlement scenarios [14] [15] [16].

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Structure Physics

The Martian surface has remained relatively stable over time, shaped by geological processes such as volcanic activity and meteor impacts. This stability provides a potential foundation for long-term settlement; however, the absence of water-based geomorphological processes presents unique challenges for site planning and construction [2].

Table 1. Comparison of Mars and Earth Conditions and Characteristics [19][20]

	Mars	Earth
Year Length (The time it takes for the planet to complete a full orbit around the Sun)	687 Earth days	65 Days
Day Length (The time it takes for the planet to complete a full rotation on its axis)	24 hours, 37 minutes	Just under 24 hours
Equatorial Radius (The radius of the planet is measured at the equator.)	3,397 kilometers	6,378 kilometers
Average Distance from the Sun (The average distance between the planet and the Sun)	227,936,637 kilometers	149,597,891 kilometers
Water (Availability and presence of water on the planet)	Traces found.	%79
Temperature (General conditions of heat on the planet)	-153°C / +20°C (minimum/maximum) or -243°F / +68°F (minimum/maximum)	-88°C / 58°C (minimum/maximum) or -126°F / 136°F (minimum/maximum)
Surface Temperature (The average temperature measured on the planet's surface)	63°C or 145.4°F	14 °C or 57.2 °F
Gravity (The force of gravity on the planet compared to Earth)	Approximately 37.5% of Earth's gravity (3.71 m/s²)	Approximately 2.66 times that of Mars (9.81 m/s²)
Atmospheric Pressure (A measure of the force that the atmosphere of the planet exerts on its surface)	7.5 millibars (average)	1.013 millibar (Deniz seviyesinde)
Atmospheric Components (The gases and other substances that make up the planet's atmosphere)	Carbon dioxide (95.32%) Nitrogen (2.7%) Argon (1.6%) Oxygen (0.13%) Water vapor (0.03%) Nitric oxide (0.01%)	Nitrogen (77%) Oxygen (21%) Argon (1%) Carbon dioxide (0.038%)

Survival Conditions and Challenges

Mars presents an extreme environment for human survival, characterized by conditions that differ significantly from those on Earth. The planet's thin atmosphere, extremely low oxygen levels, and absence of stable liquid water create fundamental constraints for sustaining human life.

In addition to these limitations, low humidity and extreme temperature fluctuations pose serious risks to human physiology, including dehydration and hypothermia. Fine dust particles, which are highly abrasive and electrostatically charged, represent another critical challenge, as they can penetrate mechanical systems and pose significant health risks when inhaled.

One of the most severe threats on Mars is exposure to high levels of solar and cosmic radiation due to the lack of a protective atmosphere and ozone layer. Prolonged exposure to such radiation increases the risk of radiation sickness and long-term health issues, including cancer [2].

From an architectural perspective, these environmental conditions necessitate the development of fully enclosed, pressurized, and shielded habitats. Design strategies must integrate advanced life-support systems, dust mitigation solutions, and radiation protection mechanisms to ensure safe and sustainable human habitation on Mars.

Human Survival Strategies on Mars

Mars is not naturally habitable under its current environmental conditions. Factors such as low atmospheric pressure, extreme temperature variations, and high radiation levels create critical challenges for sustaining human life. Therefore, enabling human habitation on Mars requires the development of integrated and technology-driven survival strategies.

These strategies must be based on the design of closed-loop life support systems capable of regulating air, water, and food production. Water extraction from subsurface ice, atmospheric processing for oxygen generation, and controlled agricultural systems are essential components of long-term survival. In addition, habitat systems must be designed as fully enclosed and pressurized environments to maintain stable internal conditions.

A key distinction exists between short-term missions and long-term settlement scenarios. While short-term missions focus on maintaining basic survival conditions through pre-supplied resources, long-term habitation requires self-sufficient systems that minimize dependency on Earth. This includes the integration of energy production systems, resource recycling mechanisms, and modular construction strategies.

From an architectural perspective, these requirements necessitate the development of adaptive, resilient, and scalable habitat systems. The integration of environmental control systems, structural protection, and resource-efficient design approaches plays a critical role in ensuring sustainable human presence on Mars [21].

Architectural Approaches Supporting Human Life in Space

To date, no permanent human habitat has been established on Mars, and exploration has been limited to robotic missions. Spacecraft such as Curiosity, InSight, Perseverance, and Zhurong have provided essential data on the planet's surface conditions, atmospheric composition, and resource availability. These findings form the scientific foundation for the development of future habitation strategies.

The environmental conditions on Mars—including low atmospheric pressure, high radiation levels, and extreme temperature variations—require fundamentally different architectural approaches compared to those on Earth. Designing for Mars necessitates the integration of environmental control systems, structural protection, and resource-efficient construction within a unified architectural framework.

In this context, architectural design is not limited to spatial organization but evolves into a system-based approach that combines material innovation, technological integration, and environmental adaptation. The development of resilient, enclosed, and self-sufficient habitat systems is therefore essential for enabling sustainable human presence on Mars.

Architectural and Settlement Planning Compatible with Mars Terrain

Human history has been shaped by exploration and the continuous search for new living environments. This process, driven by the necessity of survival and development, has historically led humanity to expand beyond existing geographical and environmental boundaries. Today, the depletion of Earth's resources and increasing ecological challenges have directed this search toward extraterrestrial environments, particularly Mars.

In this context, architectural design on Mars must focus on developing structures that are resilient to extreme environmental conditions while ensuring sustainability and functionality. This includes the integration of life-support systems, the efficient use of local materials, and the development of adaptive design strategies capable of responding to environmental constraints [22].

The construction of permanent settlements on Mars requires a multidisciplinary approach that integrates architecture, engineering, and urban planning. Environmental factors such as reduced gravity, atmospheric composition, radiation exposure, and the availability of local resources directly influence settlement design strategies.

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Suitable Material Selection for Building Design on Mars

The selection of construction materials for Mars habitats is a critical factor due to the planet's extreme environmental conditions. Structures designed for long-term human habitation must ensure resistance to radiation, withstand low atmospheric pressure, and adapt to significant temperature fluctuations. Therefore, material selection must be evaluated not only in terms of structural safety but also with respect to performance, durability, and environmental compatibility.

In this context, a dual-material strategy that combines Earth-based materials with locally available resources offers a significant advantage in terms of cost efficiency and sustainability. Regolith, which is abundantly available on the Martian surface, emerges as a primary material for construction, while locally sourced rock materials can serve as supplementary structural components. The utilization of in-situ resources reduces dependency on Earth-based supply chains and enhances the feasibility of long-term settlement projects.

Due to strict limitations in payload capacity for interplanetary transport, the selection of pre-tested, reliable, and lightweight materials is essential. These constraints necessitate the development of modular construction systems that can be efficiently transported and assembled on-site. Such systems not only optimize logistics but also improve structural reliability under Martian conditions.

Furthermore, material selection can be enhanced through data-driven and computational approaches, where environmental parameters and performance criteria are evaluated simultaneously. In this regard, integrating advanced design methodologies allows for more efficient decision-making processes and contributes to the development of adaptive and resilient construction systems.

Structural Materials Available from the Martian Surface

The use of locally available resources on Mars represents a fundamental strategy for achieving sustainable construction processes. Due to the high cost and logistical limitations associated with transporting materials from Earth, in-situ resource utilization (ISRU) emerges as a critical approach in Martian construction.

In this context, materials derived from the Martian surface—primarily regolith and rock-based components—can be processed and adapted for structural applications. These materials offer significant advantages in reducing transportation dependency while enabling scalable construction processes.

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Therefore, the effective use of local materials on Mars depends not only on their availability but also on the development of appropriate processing technologies and construction methodologies that ensure structural reliability and long-term performance.

Sulfur Concrete

The use of local resources in extraterrestrial construction, particularly under NASA’s In-Situ Resource Utilization (ISRU) strategies, represents a key approach for sustainable building on Mars and the Moon. Among these materials, sulfur concrete has emerged as a promising composite for structural applications due to its compatibility with local resource availability [23].

Sulfur concrete can be produced by combining sulfur with heated aggregate, such as Martian regolith, allowing on-site manufacturing through techniques like Contour Crafting (CC). This approach minimizes dependency on Earth-based materials while enabling automated and scalable construction processes [24][25].

From a material science perspective, sulfur undergoes a phase transformation during cooling, transitioning from monoclinic sulfur (Sβ) to a stable orthorhombic polymorph (Sα). This phase change significantly enhances the mechanical stability and durability of the material, making it suitable for structural use under Martian conditions [25].

In terms of performance, sulfur concrete offers several advantages, including rapid curing time, high compressive strength, recyclability, and stability under low-temperature environments. These properties make it particularly suitable for prefabricated or additively manufactured structural components in Mars habitats.

Furthermore, the abundance of sulfur on Mars and the favorable particle distribution of regolith contribute to the feasibility of producing durable construction elements. Under the planet’s low atmospheric pressure and extreme temperature conditions, sulfur-based materials demonstrate long-term stability, making them a viable solution for load-bearing and protective structural systems [25].

Regolith

Regolith, which is abundantly available on the Martian surface, plays a critical role as a construction material due to its capacity to provide natural protection against radiation, micrometeoroid impacts, and surface debris. These properties make it particularly suitable for shielding applications in Martian habitats.

However, regolith exhibits significant structural limitations. Its brittle behavior, especially under high slope angles, and its instability under dynamic loads restrict its direct use in load-bearing systems. The natural angle of repose of loose regolith is approximately 40°, beyond which structural stability cannot be maintained. Consequently, unprocessed regolith demonstrates limited performance in complex architectural applications.

To enhance its usability, regolith must undergo processing techniques such as compaction, molding, and sintering. Sintering, performed using microwave or solar energy, enables the transformation of loose regolith into solid construction elements such as bricks or blocks. These elements can be applied in a manner similar to masonry systems on Earth and can function within pressurized environments when combined with appropriate reinforcement and connection strategies.

Despite these advancements, the material’s mechanical performance remains limited. Experimental studies indicate that the tensile strength of sintered regolith ranges between 9–18 MPa, with comparable compressive strength values. The relatively low strength and heterogeneous structure of regolith restrict its use in advanced structural systems such as beams or large-span elements.

Therefore, regolith is more suitable for non-critical structural applications, including external shells, protective layers, and radiation shielding systems. In this context, it serves as a complementary material rather than a primary load-bearing component in Mars habitat design [26].

Structural Materials Obtainable from Earth Resources

In addition to locally available resources, materials transported from Earth play a critical role in the initial phases of Mars construction. These materials have been extensively tested in space missions and are known for their reliability under extreme environmental conditions, making them suitable for early-stage habitat development.

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Structural materials such as steel, aluminum, titanium, and advanced composite materials are commonly used in aerospace engineering due to their high strength-to-weight ratios, durability, and resistance to thermal and mechanical stresses. These properties make them particularly suitable for use in pressurized structural systems, modular habitat units, and critical load-bearing components.

In this context, Earth-sourced materials are most effectively utilized within hybrid construction systems, where they are combined with locally produced materials such as regolith-based elements. This approach enhances structural performance while maintaining logistical and economic feasibility in Mars habitat construction.

Steel

Steel is widely used as a structural material due to its high strength, durability, and adaptability through various processing techniques. Its mechanical properties, including high load-bearing capacity and resistance to thermal and mechanical stresses, make it a reliable material for structural applications.

In the context of Mars construction, steel can play a critical role in primary load-bearing systems, connection elements, and pressurized structural components where high strength and reliability are required. Its performance under extreme conditions makes it suitable for use in modular habitat frameworks and reinforcement systems.

However, the high density of steel presents a significant disadvantage in terms of transportation from Earth, leading to increased launch costs and logistical limitations. For this reason, its use in Mars construction is expected to be limited to essential structural components that require high mechanical performance.

Therefore, steel is best utilized as part of hybrid construction systems, where it is combined with locally produced materials to optimize both structural performance and resource efficiency [27].

Aluminum

Aluminum is a lightweight and versatile material widely used in aerospace engineering due to its high strength-to-weight ratio and ease of fabrication. Its ability to maintain mechanical performance at low temperatures while preserving ductility makes it particularly suitable for use in extreme environments.

In the context of Mars, aluminum offers significant advantages for structural and non-structural components, especially in modular systems and lightweight assemblies. Its reduced density compared to steel minimizes transportation costs and supports efficient deployment in early-stage construction.

Additionally, aluminum's compatibility with various joining techniques enables the development of prefabricated and modular habitat systems. These characteristics make it a suitable material for interior structural elements, enclosure systems, and secondary load-bearing components in Mars habitats.

However, the reduction in mechanical strength at elevated temperatures must be considered in design processes. Despite this limitation, aluminum remains a viable and efficient material for Mars construction due to its balance between weight, strength, and adaptability [26].

Titanium

Titanium is a high-performance material known for its exceptional strength-to-weight ratio and corrosion resistance. Being significantly lighter than steel while maintaining high structural strength, it is widely used in aerospace and space engineering applications where weight efficiency is critical.

In the context of Mars construction, titanium offers significant advantages for critical structural components, particularly in pressurized systems, connection elements, and high-performance structural joints. Its resistance to extreme environmental conditions, including temperature variations and potential chemical interactions, enhances its suitability for long-term space applications.

However, the production and processing of titanium are complex and costly, which limits its widespread use. For this reason, its application in Mars habitats is expected to be restricted to specialized components where high performance and reliability are essential.

Considering transportation constraints, titanium's low density provides an advantage over heavier materials such as steel, making it a strategic material for use in hybrid construction systems on Mars [26].

Glass

Glass is a critical material in space architecture due to its superior optical properties and resistance to environmental degradation compared to alternative transparent materials such as plastics. In space environments, glass demonstrates high resistance to atomic oxygen, whereas most plastics rapidly degrade, become opaque, and lose structural integrity under ultraviolet radiation exposure.

In the context of Mars, glass plays a vital role in maintaining visual connection with the external environment while ensuring protection against harsh atmospheric conditions. It is primarily used in window systems, observation panels, and controlled daylight openings within pressurized habitats.

However, glass exhibits several structural limitations, including brittleness, sensitivity to static fatigue, and vulnerability to impact damage. These properties pose significant risks in the Martian environment, where micrometeoroid impacts and pressure differentials are critical design concerns.

To overcome these limitations, multi-layered glazing systems are required. Similar to the International Space Station (ISS), protective outer and inner layers can be integrated with pressure-resistant glass, separated by buffer zones to absorb external impacts. Additional design solutions, such as integrated heating systems, can prevent condensation and maintain visual clarity under extreme temperature conditions [28].

Despite its structural challenges and transportation limitations, glass contributes significantly to the psychological well-being of astronauts by providing natural light and visual access to the external environment. This aspect is particularly important for long-term missions, as it enhances spatial perception, reduces isolation, and improves overall quality of life within confined habitats.

Membrane

Membrane materials, including architectural fabrics and polymer-based foils, are considered advanced construction materials due to their lightweight nature, flexibility, and high strength-to-weight ratio. These properties make them particularly suitable for applications where minimizing structural mass is critical, such as space architecture.

In the context of Mars, membrane systems are highly advantageous as external envelopes for habitats, especially in inflatable or expandable structural systems. Their low weight significantly reduces transportation costs, while their flexibility allows compact deployment and rapid assembly on the Martian surface.

However, membrane materials exhibit limited مقاومت to bending and compression, requiring them to function primarily under tensile forces. Therefore, their structural performance depends heavily on proper form-finding processes, internal pressurization, and controlled stress distribution. These design parameters are critical for ensuring stability and safety in pressurized Martian environments.

Membrane systems can be enhanced through multi-layered configurations combined with local materials such as regolith. This hybrid approach improves resistance against radiation, thermal fluctuations, and micrometeoroid impacts. High-performance fibers such as aramid (Kevlar), polyamide, and advanced polymers are commonly used due to their high strength and durability.

Additionally, coating materials such as PTFE and PVC contribute to environmental resistance and structural protection. The layered composition of membrane systems allows them to meet insulation, safety, and durability requirements simultaneously, making them a promising solution for long-term Mars habitat design [26].

Plastics or Plastic-Based Materials

Fiber-reinforced plastics (FRPs), as a type of composite material, consist of reinforcement fibers embedded within a polymer matrix, resulting in improved mechanical performance compared to conventional materials. These materials offer high strength-to-weight ratios, making them particularly suitable for applications where reducing structural mass is essential.

In the context of Mars construction, plastic-based composite materials provide significant advantages due to their lightweight nature, durability, and resistance to environmental degradation. Compared to metallic materials, composites can achieve similar or superior performance while minimizing transportation costs and simplifying construction processes.

Advanced material technologies, such as carbon nanotubes, further enhance the potential of plastic-based systems. Due to their exceptional strength and extremely low weight, carbon nanotube-reinforced composites enable the development of high-performance structural elements that were previously not feasible with traditional materials [26].

In architectural applications on Mars, plastic-based materials can be used in modular components, interior structural systems, insulation layers, and secondary load-bearing elements. Their adaptability and ease of fabrication support prefabrication and rapid assembly processes, which are critical for extraterrestrial construction.

Overall, plastic-based composite materials represent a highly efficient solution for Mars habitats, offering a balance between structural performance, lightweight construction, and adaptability to extreme environmental conditions [26].

Structural Models and Typologies for Mars Habitats

One of the primary challenges in Martian architecture is the design of safe pressurized structures, due to the extremely low atmospheric pressure on Mars, which is approximately 1% of that on Earth. This condition creates structural risks similar to those observed in high-altitude pressurized systems and requires advanced engineering solutions to ensure stability and safety.

The reduced gravity on Mars, approximately one-third of Earth's, allows for lighter structural systems. However, internal pressurization forces remain a dominant design factor. For this reason, geometries such as domes and curved shells are frequently preferred, as they efficiently distribute internal pressure and enhance structural stability.

Current research highlights three primary structural typologies for Mars habitats: rigid structures, inflatable systems, and hybrid configurations. Rigid metal structures provide high reliability and durability, particularly for critical modules such as life-support systems and technical infrastructure. In contrast, inflatable and telescopic systems offer significant advantages in terms of volume-to-mass efficiency, compact transportation, and rapid deployment.

Despite these advantages, inflatable structures present vulnerabilities, particularly against micrometeoroid impacts, due to the lack of atmospheric protection on Mars. Therefore, hybrid solutions that combine inflatable systems with protective outer layers, such as regolith shielding or multi-layered membranes, are considered more effective for long-term applications.

In addition to structural performance, the psychological impact of habitat design remains a critical but underexplored factor. The spatial configuration, enclosure type, and material expression of habitats may significantly influence the well-being of astronauts during long-duration missions.

Consequently, the selection of structural typologies for Mars habitats must balance multiple criteria, including structural safety, material efficiency, environmental protection, and human comfort. In this context, hybrid systems integrating rigid, inflatable, and locally reinforced structures are considered the most viable solution for sustainable Mars settlements [30].

Regolith and Stone-Based Construction Systems

Regolith-based construction systems exhibit structural similarities to earthen architecture on Earth, where load-bearing capacity is primarily achieved through compressive strength. Due to the brittle nature of regolith, structural designs must avoid tensile stresses and instead rely on geometries that efficiently transfer loads in compression.

In this context, forms such as domes, arches, and freeform shell structures—particularly inverted catenary geometries—are considered optimal for Martian construction. These geometries enable uniform load distribution and enhance structural stability under pressurized conditions, making them highly suitable for Mars habitats [6].

Construction using regolith can be achieved through methods such as block production, compaction, and layering techniques. However, the most promising approach is on-site manufacturing through additive construction technologies. 3D printing systems enable the direct use of local materials, significantly reducing dependency on Earth-based resources and minimizing transportation costs.

These systems are expected to operate using autonomous or semi-autonomous robotic technologies, allowing construction processes to be carried out with minimal human intervention. Such approaches provide substantial advantages in terms of efficiency, scalability, and operational safety in the Martian environment.

In this context, sintering techniques—applied through microwave or solar energy—play a critical role in transforming loose regolith into structurally stable building components. By heating the material below its melting point, particle bonding is achieved, reducing porosity and increasing mechanical performance [31].

Overall, regolith-based construction systems represent a fundamental strategy for sustainable Mars architecture, combining local material utilization, optimized structural geometry, and advanced manufacturing technologies.

Expandable Structural Systems

Expandable structures are architectural systems capable of changing their volume through mechanisms such as folding, inflation, or shape-memory configurations. These systems offer a significant advantage in space applications due to their ability to be transported in a compact form and deployed into larger volumes after installation.

In the context of Mars, expandable structures provide critical benefits in terms of transportation efficiency, rapid deployment, and spatial flexibility. Their low mass-to-volume ratio makes them particularly suitable for early-stage habitat construction, where minimizing payload is essential.

Structurally, these systems consist of modular components such as rigid frames, articulated joints, and flexible membranes. Once deployed, internal pressurization and geometric stabilization enhance their load-bearing capacity and structural integrity. This allows expandable systems to function as reliable enclosures for pressurized environments.

Expandable structures are especially suitable for functions such as living spaces, laboratories, greenhouses, and temporary operational modules. Their adaptability enables flexible spatial organization and phased expansion of settlements over time.

However, their vulnerability to external factors such as micrometeoroid impacts and material fatigue requires additional protective strategies. These may include multi-layered membrane systems or integration with regolith-based shielding.

Overall, expandable structural systems represent a key architectural strategy for Mars habitats, offering a balance between transport efficiency, spatial adaptability, and construction feasibility [2].

Metal and Plastic-Based Structural Systems

Metal and composite-based structural systems play a critical role in the development of reliable and adaptable habitats on Mars. Unlike material-focused approaches, these systems emphasize the integration of structural components to achieve optimal performance under extreme environmental conditions.

Metal-based systems, particularly those utilizing aluminum and titanium alloys, are widely used in space applications due to their high reliability and predictable mechanical behavior. These systems are especially suitable for primary load-bearing structures, connection nodes, and pressure-resistant modules where structural safety is critical.

However, due to transportation constraints and high material weight, metal-based systems alone are not sufficient for large-scale construction on Mars. In this context, composite-based structural systems offer a more efficient alternative. Their lightweight nature, combined with high strength and adaptability, enables the development of modular and prefabricated structural elements.

Composite systems are particularly advantageous for secondary structural components, internal frameworks, and adaptable enclosure systems. Their flexibility allows integration with membrane systems and expandable structures, supporting hybrid architectural solutions.

Additionally, future scenarios suggest that both metal and composite materials may be partially produced on Mars using in-situ resource utilization strategies. However, current technological limitations indicate that high-performance material production remains a significant challenge.

Therefore, hybrid structural systems combining metal and composite components are considered the most effective solution, balancing structural reliability, material efficiency, and construction feasibility in Martian environments [2] [33].

Modular Structural Systems

Modular structural systems represent one of the most effective architectural strategies for establishing adaptable and scalable habitats on Mars. These systems are based on the assembly of prefabricated units, each designed to perform specific functions such as habitation, research, life support, or storage.

In the context of Mars, modularity provides significant advantages in terms of transportation, construction efficiency, and long-term adaptability. Due to launch constraints, transporting smaller, standardized modules is more feasible than constructing large monolithic structures. Once deployed on the Martian surface, these modules can be assembled incrementally, allowing settlements to grow over time.

Structurally, modular systems often utilize cylindrical or geometrically optimized forms that can efficiently resist internal pressurization. Connection interfaces between modules are designed to ensure airtight sealing, structural continuity, and functional integration.

One of the key advantages of modular systems is their flexibility. Damaged or outdated modules can be replaced or upgraded without affecting the entire settlement. Additionally, modular configurations support reconfigurable spatial layouts, enabling adaptation to changing mission requirements or environmental conditions.

Future Mars habitats are expected to integrate modular systems with other structural approaches such as expandable structures, regolith-based shells, and composite frameworks. This hybridization enhances both structural performance and operational efficiency.

Therefore, modular structural systems provide a robust and flexible foundation for the phased development of sustainable human settlements on Mars [34].

Drilled Structural Systems in Underground Areas

Drilled structural systems represent a critical architectural strategy for protecting human habitats from extreme environmental conditions on Mars. Rather than focusing solely on surface construction, these systems utilize subsurface excavation to create naturally shielded living spaces.

On Mars, underground environments offer significant advantages in terms of radiation protection, thermal stability, and resistance to external hazards such as micrometeoroid impacts and dust storms. Excavation processes are expected to be carried out using autonomous or semi-autonomous robotic systems adapted from terrestrial drilling and mining technologies [35].

From a structural perspective, the excavation of rock masses alters the internal stress distribution, enabling the formation of self-supporting geometries under suitable conditions. In particular, basalt formations on Mars have the potential to form stable arch-like structures, reducing the need for additional structural reinforcement. However, in cases where geological stability is insufficient, engineered support systems must be introduced.

These systems typically consist of a primary support layer that stabilizes the surrounding rock and an internal structural shell that ensures airtightness and habitability. Intermediate layers, such as air gaps or insulating materials, can be incorporated to improve thermal performance and structural safety.

Underground habitats can be constructed using a combination of locally sourced materials, such as regolith-based concrete, and transported structural components. The integration of robotic construction technologies further enhances the feasibility of these systems.

Overall, drilled underground structural systems provide one of the most effective solutions for long-term human habitation on Mars by combining environmental protection, structural efficiency, and spatial continuity [2] [35].

Interior Layouts and Design Approaches in Mars Structures

Interior design in Mars habitats presents unique challenges due to the necessity of integrating pressurized environments with non-conventional architectural forms. Unlike traditional Earth-based structures, which are typically designed with orthogonal geometries for ease of construction, Mars habitats are often shaped by structural and environmental constraints, leading to curved or shell-based forms.

One of the primary design challenges is the relationship between the exterior structural form and the interior spatial organization. To address this, several design strategies have been proposed. The first approach involves designing interior spaces independently from the outer shell, allowing the external form to remain structurally optimized while maintaining conventional interior layouts. The second approach integrates the interior structure with the external geometry, adapting internal frameworks to curved surfaces and creating a more cohesive architectural system. The third approach prioritizes spatial continuity by minimizing internal subdivisions, resulting in larger, open interior volumes that enhance flexibility.

Each of these approaches offers specific advantages and limitations. Independent interior systems provide familiarity and ease of use but may reduce spatial efficiency. Integrated systems maximize structural coherence but introduce complexity in construction and furnishing. Open-plan configurations improve flexibility and visual continuity but may create challenges in functional zoning and privacy.

In the context of Mars, interior design must also respond to additional factors such as limited space, psychological well-being, long-term habitation, and the need for efficient circulation. The absence of natural environmental stimuli requires carefully designed interior environments that support human comfort and mental health.

Therefore, successful interior design solutions for Mars habitats must balance structural constraints, functional requirements, and human-centered design principles. Future developments are expected to integrate adaptive and flexible interior systems that can evolve alongside the growth of Martian settlements [36].

Ai-Assisted Architectural Design Approaches in Possible Life Scenarios on Mars

The design and construction of habitats on Mars require approaches that go beyond conventional architectural methods due to the planet’s extreme environmental conditions. In this context, artificial intelligence (AI) emerges as a critical tool for developing adaptive, data-driven, and optimized architectural solutions.

AI-assisted architectural design on Mars is primarily based on parametric and generative design methodologies. These systems utilize environmental input data—such as solar radiation, temperature fluctuations, wind patterns, and radiation exposure—to generate and evaluate multiple design alternatives. Through iterative optimization processes, AI algorithms can identify configurations that maximize structural performance, energy efficiency, and environmental resilience.

In this framework, machine learning models can be trained using datasets derived from planetary simulations and previous space missions. These models enable predictive analysis, allowing designers to assess how architectural forms and materials will perform under Martian conditions. For instance, AI can simulate the thermal behavior of structures, optimize material distribution, and determine the most efficient structural geometries for pressurized habitats.

Furthermore, AI plays a significant role in construction processes through the integration of robotic systems. Autonomous construction technologies, such as AI-driven 3D printing systems, allow the use of local materials (e.g., regolith) to fabricate building components directly on-site. These systems reduce dependency on Earth-based resources and enhance construction efficiency in remote environments.

AI-based decision-making systems also support resource management strategies, including energy optimization, water recycling, and environmental control. By continuously analyzing real-time data, these systems can dynamically adjust habitat conditions to ensure long-term sustainability and human comfort.

In this context, AI is not only a design tool but also an integral component of the entire architectural lifecycle, from conceptual design to construction and operation. Therefore, AI-assisted architectural approaches represent a fundamental paradigm for enabling sustainable human life on Mars.

Definition of AI: Its Role as a Technology in Mars Designs

Artificial intelligence (AI) can be defined as a computational system capable of processing data, learning from patterns, and generating optimized decisions toward specific objectives. Rather than focusing on historical definitions, AI in architectural design is understood as a data-driven methodology that enables adaptive and performance-based solutions.

In the context of Mars, AI functions as a critical design and decision-making tool that integrates environmental data into the architectural process. Through parametric modeling and generative algorithms, AI systems can analyze variables such as radiation levels, temperature fluctuations, atmospheric pressure, and solar exposure to generate optimized architectural configurations.

These systems operate through iterative processes in which multiple design alternatives are evaluated simultaneously. Optimization algorithms identify the most efficient solutions in terms of structural performance, energy efficiency, and environmental resilience. This approach allows the development of architecture that is not only responsive but also predictive.

In addition to design processes, AI contributes to construction and operational phases. AI-integrated robotic systems, particularly those based on additive manufacturing (3D printing), enable the autonomous construction of structures using local materials such as regolith. This reduces reliance on Earth-based resources and enhances construction feasibility in remote environments.

Furthermore, AI-based control systems support real-time environmental management, including air quality regulation, thermal control, and resource optimization. By continuously adapting to changing conditions, these systems ensure the long-term sustainability and habitability of Mars settlements.

In this framework, AI is not merely a supportive technology but a central component that connects design, construction, and operation processes. Therefore, its role in Mars-oriented architectural design represents a fundamental shift toward data-driven and adaptive architectural systems [36][38].

Mars Design Experiments with AI

AI-based design experiments for Mars habitats are conducted through parametric modeling, generative algorithms, and simulation-based approaches. These methods enable the evaluation of architectural solutions under extreme environmental conditions while optimizing structural performance, energy efficiency, and spatial organization.

In this context, AI systems process environmental data such as solar radiation, temperature variations, and atmospheric conditions to generate multiple design alternatives. These alternatives are assessed through iterative optimization processes, allowing the identification of the most suitable configurations for sustainable habitation on Mars.

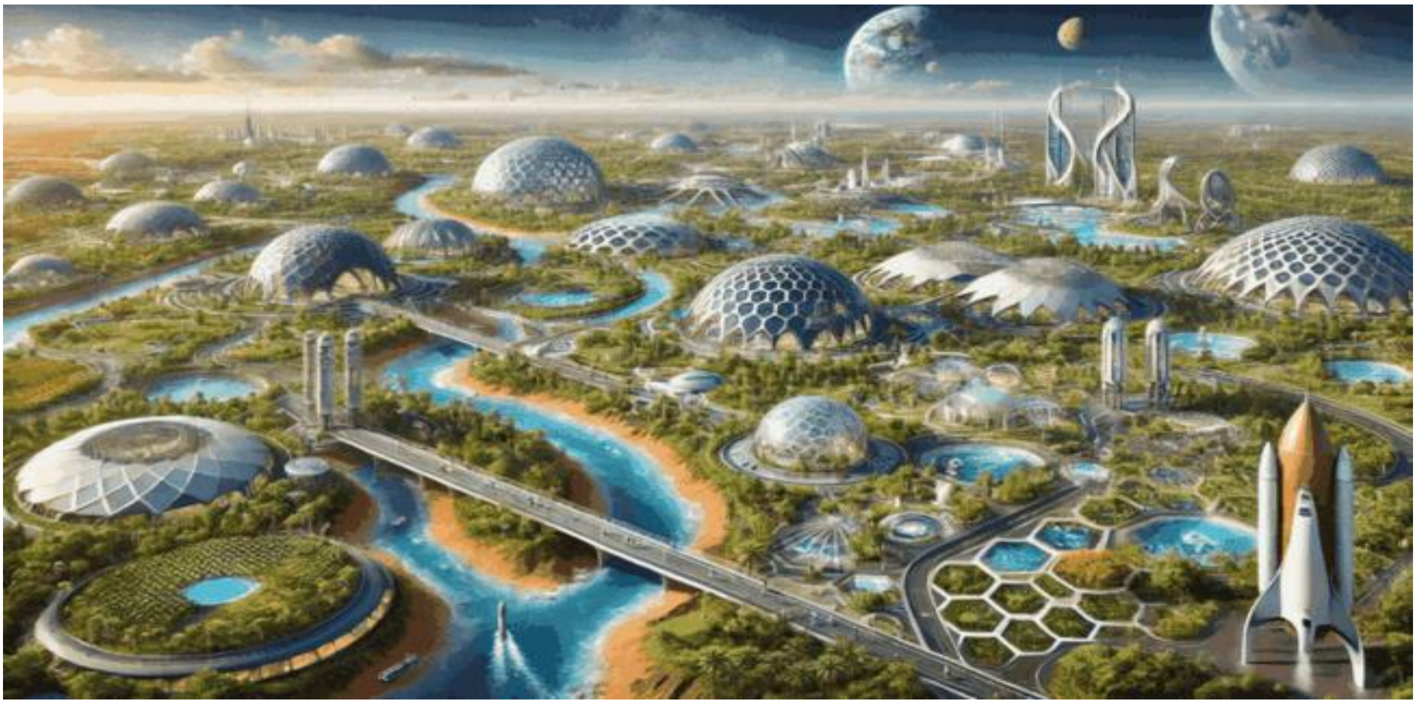

Fig. 2. AI-generated conceptual Mars architectural structures [41].

Fig. 3. Conceptual sustainable Mars colony model based on AI-assisted design [42].

As illustrated in Fig. 2 and Fig. 3, AI-generated conceptual models demonstrate how adaptive, modular, and environmentally responsive settlement configurations can be developed through generative design approaches. These models highlight the integration of renewable energy systems, dome-based geometries, and modular spatial organization strategies.

Additionally, dome-shaped structural solutions, as shown in Fig. 5, offer efficient resistance to internal pressure and environmental loads, making them a preferred architectural form for Mars habitats. Biomimetic design approaches, illustrated in Fig. 4, further contribute to the development of structurally efficient and environmentally adaptive architectural systems inspired by natural formations.

Fig. 4. Conceptual biomimetic Mars settlement model [39].

Fig. 5. Dome-shaped Mars habitat concept [40].

These AI-assisted design experiments not only support aesthetic and functional requirements but also provide a data-driven framework for sustainable and resilient habitat development. In this sense, AI acts as a bridge between environmental constraints and architectural solutions, playing a fundamental role in shaping future Mars settlement scenarios.

CONCLUSION

Space research, which began in the mid-20th century, has evolved into a highly advanced and interdisciplinary field with the rapid development of technology. In particular, robotic exploration systems have provided extensive data on planetary environments, enabling detailed analysis of surface conditions, atmospheric structures, and potential resource availability.

This study has examined Mars as a potential environment for human habitation by analyzing its environmental conditions, including surface characteristics, atmospheric structure, and climatic factors. Based on these analyses, key architectural parameters such as structural systems, material selection, and spatial organization strategies have been evaluated.

One of the primary contributions of this study is the integration of architectural design approaches with environmental constraints specific to Mars. In this context, regolith-based construction systems, modular and expandable structures, underground habitats, and adaptive interior design strategies have been discussed as potential solutions for sustainable settlement development.

Furthermore, the study highlights the critical role of artificial intelligence in Mars-oriented architectural design. AI-assisted methodologies, including parametric modeling, generative design, and simulation-based optimization, provide a data-driven framework for developing adaptive and resilient architectural solutions. These approaches enable the efficient use of local resources, support autonomous construction processes, and enhance long-term sustainability.

The findings of this study suggest that the combination of advanced structural systems and AI-supported design strategies has the potential to significantly improve the feasibility of human settlements on Mars. As technological developments continue, such integrated approaches will play a decisive role in transforming conceptual Mars habitats into practical and implementable solutions.

In conclusion, this study contributes to the field of space architecture by providing a comprehensive and interdisciplinary framework that connects environmental analysis, architectural design, and technological innovation. This framework is expected to support future research and guide the development of sustainable human settlements on Mars.

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Conflicts of interest

The authors declare no conflict of interest.

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