Envisioning Extraterrestrial Construction and the Future Construction Workforce: A Collective Perspective

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Abstract

Humanity's evolution toward an interplanetary species poses a new frontier for the construction industry: extraterrestrial construction. With fast technological advancements in manufacturing and robotics, it is a matter of when, not if, before humans make perpetual habitats on nearby planetary bodies. We envision the emerging frontier of the construction industry as extraterrestrial construction, where the role of workers and their required skills will change dramatically. Due to the extreme and hazardous outer-space conditions, the future of extraterrestrial construction will be technology-intensive, from using onsite machine and robot operations to using cyber-physical systems for managing logistical operations. Accordingly, the role and skillsets of construction workers in future extraterrestrial construction projects will contrast with the current practices on Earth. We aim to present a collective perspective on the nature of future extraterrestrial construction and the hierarchy of the skills required by future workers, as well as emerging technologies that can be used for developing a future-ready workforce. To accomplish this, we convened a national interdisciplinary workshop, engaging diverse stakeholders in the United States, including researchers, educators, and professionals, from academia, industry, and government. This paper summarizes the outcomes of our workshop, structured around three core themes: future work (extraterrestrial construction), future workers (extraterrestrial workforce), and future technology (emerging technologies for workforce training). The detailed exploration within these three themes marks an initial endeavor to chart a course for training in extraterrestrial construction, particularly with NASA's Moon to Mars Program in mind.

Keywords – Extraterrestrial Construction; Workforce Training; Construction Technology; Robotics.

1 Introduction

The construction industry is evolving at an unprecedented speed through advancements in materials, manufacturing, and technologies. In addition, in recognition of the 50th anniversary of the first manned lunar landing, the National Aeronautics and Space Administration (NASA), together with the European Space Agency (ESA), revealed plans to resume diversely crewed exploration missions and to establish permanent human habitats on the Moon and Mars by 2040 [1]. The vision of becoming an interplanetary species presents an unprecedented challenge to the construction industry: extraterrestrial construction. Extraterrestrial construction, constructing structures on a planetary body outside of the Earth and its atmosphere, will be a significant part of the future market for the construction industry [2].

We consider extraterrestrial construction as the theory and practice of building anthropogenic environments in outer space to enable temporary or perpetual human presence or activities [3]. Conventional construction processes, which require massive human-labor intervention, may be less suited for extraterrestrial construction due to near-vacuum conditions, meteors, radiation, and other extremes. Building a human habitat in uninhabitable environments on other planetary bodies will require automated construction processes optimized for that environment [4]. To promote feasible and sustainable space exploration, these habitats and other structures are envisioned to require in-situ construction [5], shaping a new generation of the construction workforce. Regarding the construction process, NASA researchers believe robotics and additive manufacturing (AM) technologies have enormous potential to become a game-changer for space exploration. However, we will need appropriate construction technology to advance and simplify the complexity of the construction process in hostile and extreme extraterrestrial environments [6, 7]. To achieve such advancement and simplicity, NASA believes robotics and AM technologies require advancement beyond their current achievements [8]. Robotic and AM technologies can also transform future construction work on Earth [9]. However, the non-repetitive nature of construction tasks may result in semi-automated construction robots, requiring humans and robots to collaborate [10]. In this scenario, human workers must learn to adaptively perform construction work (i.e., improvise) based on evolving site conditions, supervisor input, the constraints of the co-worker robots, and accrued experience [11]. Therefore, advancement in construction technologies (both in near-future terrestrial construction and far-future extraterrestrial construction) may require new roles for human workers. Accordingly, the role of construction workers in future extraterrestrial construction projects will be significantly different from the current practice on Earth.

On the other hand, the current construction industry is facing enormous technological and institutional transformations with their resultant difficulties and challenges [12]. The lack of adequately trained personnel has been identified as a major hindrance to adopting and implementing emerging construction technologies [13]. This issue is becoming more significant due to the unprecedented speed of technological advancements in this industry [14]. Therefore, construction workers must deal with a rapid pace of technological change, a highly interconnected world, and complex problems that require multidisciplinary solutions. While it is obvious that training programs must maintain some likeness to the current practices of the construction industry, keeping the construction workforce development in line with future needs is an important challenge, given that the construction industry is poised for rapid transformation. With the advancement of construction technologies and the changing role of construction workers, a new set of skills is required to enable the future workforce, which necessitates closer scrutiny of the procedures for workforce development. The need for a future-ready workforce that can be adapted to meet the constantly evolving workplace has turned attention to the development and integration of transferable skills into training programs [15].

Industry 4.0 emerging technologies rooted in digitalization and artificial intelligence can enable this future construction workforce. In the wake of the fourth industrial revolution, highly advanced technologies have made a paradigm shift in the construction workforce training environment. Traditional training methods (e.g., classroom lectures) insufficiently reflect the dynamism of the construction site and replicate the physical construction scenarios, making them ineffective and unengaging [16]. With the advent of computational technologies, such as artificial intelligence and mixed reality, some future learning concepts have been highlighted, overcoming the limitations of traditional approaches. For example, immersive learning, supported by digital media simulations, involves creating artificial environments where learners can experience and interact with the learning contents and lessons [17]. The immersive nature enables learners to grasp abstract concepts and gain hands-on experience in low-risk/secure virtual environments while feeling as though they are actually there (e.g., the construction sites), ideal for extraterrestrial construction workforce training [18]. Another example is adaptive intelligent learning, which uses automated machine learning technologies (e.g., artificial intelligence) to analyze and adapt to a learner's needs and progress; as a result, providing a personalized learning experience [19]. Additionally, this adaptiveness is ideal for an extraterrestrial workforce training environment where workers from diverse backgrounds are involved.

The goal of this study is to converge on the nature of future extraterrestrial construction and build a hierarchy of skills required by future workers, as well as identify emerging technologies that can help integrate transferable skills for developing a future-ready workforce from a diverse set of perspectives. We organized an interdisciplinary perspectives workshop that brought together the expertise and representatives of the different disciplines that will be involved in the envisioned extraterrestrial construction workforce development, including engineering, construction science, architecture, computer science, robotics, human-computer interaction, planetary geoscience, workforce development, learning sciences, and social science. The outcome of this workshop is presented in this paper, which can provide a collective perspective of extraterrestrial construction and the future construction workforce in terms of technological needs and challenges.

2 Methodology

One of the powerful tools for brainstorming about a subject is conducting workshops where varied perspectives can interact with each other to generate new knowledge [20-22]. In addition, Nielsen [23] highlighted that to enhance the effectiveness of brainstorming interaction in workshops, not only do group discussions need to be created, but also group members must be encouraged to cooperate with each other. In such an environment, participants are assisted in revealing their thoughts and engaging in a social process of clarifying, developing, and refining ideas, which will increase the effectiveness of the workshop. Nevertheless, a successful brainstorming workshop should make the participants active learners, allowing them to be engaged instead of passive participants [23].

To create a perspective of visionary extraterrestrial construction and the future construction workforce, we used the brainstorming workshop technique as suggested by the literature [20-23]. A brainstorming workshop was used to identify the needs, challenges, and solutions for creating such a collective perspective from diverse viewpoints. The goal of this workshop was to converge on the nature of future extraterrestrial construction and build the hierarchy of skills required by future workers, as well as emerging technologies that can be utilized for developing a future-ready workforce from a diverse set of perspectives. The workshop was structured as a series of charrettes in which small and diverse groups brainstormed and designed to answer questions associated with each theme. The intended workshop activities include invited plenary talks, panel discussions, and breakout sessions on the three main themes. In addition, instructions for the moderators of these sessions were prepared to facilitate discussion and data collection.

3 Workshop Information

A two-day virtual interdisciplinary workshop, entitled "Roadmap to Future-ready Extraterrestrial Construction Workforce Development: Technological Visions and Needs," was organized on February 20-21, 2023. The experts were meticulously chosen from a pool of distinguished scientists and researchers, meeting three criteria: 1) having authored at least one published paper pertinent to the themes of the workshop, 2) possessing a minimum of five years of experience in the relevant field, and 3) submitting a comprehensive vision statement outlining their perspective on the workshop's topic. In conjunction with the organizational team, a cohort of 26 experts, each bringing unique backgrounds and expertise to the table, actively participated in the event. Table 1 shows the demographic information of the participants.

Table 1 Demographic information of the participants

Category	Level	No (Percent)
Organization	NASA-Affiliated	6 (23.1%)
	Technological/Educational	3 (11.5%)
	R1 Research Institution	14 (53.8%)
	R2 Research Institution	3 (11.5%)
Expertise	Extraterrestrial Construction	9 (34.6%)
	Human-Robot Collaboration	6 (23.1%)
	Human-Computer Interaction	4 (15.4%)
	Technology in Education	7 (26.9%)

The brainstorming workshop was structured around three core themes, as illustrated in Figure 1:

- *Theme 1: Future work (Extraterrestrial Construction)* to answer questions such as: How does the construction site environment on the Moon and Mars differ from Earth? What are the main characteristics of construction technologies used in extraterrestrial construction on the Moon and Mars? Is there any robot function in extraterrestrial construction that can't/shouldn't be fully automated?
- *Theme 2: Future Workers (Extraterrestrial Construction Workforce)* to answer questions such as What are the main anthropic tasks, roles, knowledge, and competencies/skills needed by the future civil workforce in extraterrestrial construction? To collaborate with robots effectively, what skills/knowledge are required for the future workforce? How the identified skills can be framed, categorized, or prioritized?
- *Theme 3: Future Technology (Emerging Technologies for Workforce Training)* to answer questions such as: What are the strategies and considerations in developing training scenarios in an AI-XR-based training environment for future workforce development? Among the skills and competencies identified for the extraterrestrial construction workforce, which ones are more suitable to be trained using an AI-XR-based training environment? How can the trained skills and competencies using an AI-XR-based training environment be evaluated in the context of extraterrestrial construction?

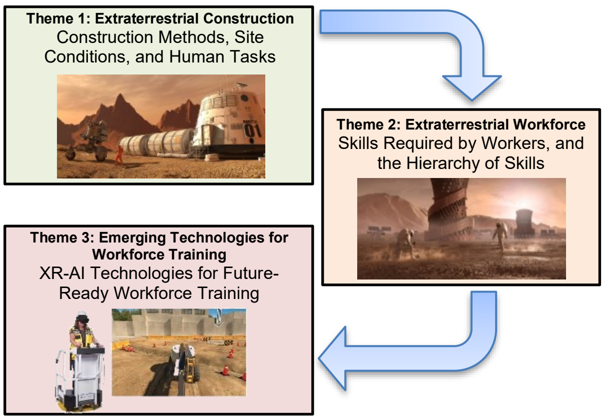

Figure 1. The workshop framework

The answers to these questions, as an outcome of the organized workshop and supported by the literature review, helped to understand how future technologies can help address the needs of future extraterrestrial construction workers in the context of their future work.

4 Summary of Outcomes

4.1 Theme 1: Extraterrestrial Construction

Extraterrestrial construction is an emergent area in which workers have no prior planetary experience. In this situation, planning and testing any idea for extraterrestrial construction is important to transform it into a process of exploration, analysis, discovery, design, implementation, and feedback. Although there are many uncertainties about future extraterrestrial construction, certainties include:

1. The differences between terrestrial and extraterrestrial site conditions should be clearly determined. For example, the intensity and frequency of atmospheric disturbances and quakes will differ across planets. Also, the harsh environment is a major factor that needs to be considered (e.g., radiation, gravity differences, vacuum, diurnal temperature range, abrasive Lunar regolith, variations in soil-regolith composition, and electrostatically adhering dust).
2. The differences between terrestrial and extraterrestrial construction protocols should be clearly identified, particularly in the design phase. In other words, we need to understand how conventional construction tasks change in planetary conditions. For example, in extraterrestrial construction, underground installations would be rare, and even small excavation forces may dislodge massive (i.e., high momentum) objects due to the lower gravity on Mars and the Moon. In addition, different expectations across the building lifecycle, such as construction, operations, and maintenance, may play an essential role during the design phase.
3. For extraterrestrial construction, In-situ Resource Utilization (ISRU) is a necessity, given the prohibitive costs of delivery from Earth. It is important to understand the available materials on different planets and be able to identify and predict those materials and resources from orbit. Also, the resiliency and longevity of construction materials and structures become vital factors in extraterrestrial construction, which are still poorly known and need to be researched.
4. Extraterrestrial construction will be complex in nature, with the involvement of numerous parties (experts in different disciplines from different countries). Therefore, it is important to develop a technical taxonomy to ensure consistent use of technological terms, derived SI units, and even labeling, which may otherwise lead to disasters – epitomized by the unit conversion error that destroyed the Mars Climate Orbiter mission; and the drogue parachute’s failure to deploy in the OSIRIS-REx mission.
5. Although the specifications of robots for extraterrestrial construction may not be clear, it is evident that extraterrestrial construction will be robot-intensive. Although some level of autonomy is required for specific tasks (e.g., establishing landing pads for future landers to a base camp), the role of human workers cannot be overlooked in extraterrestrial construction. The human-in-the-loop approach is required due to:
   a. Due to the general inability of machines to repair themselves or other equipment (even though the machines will be designed for easier maintenance or easier replacement of components), the role of human workers will still be essential.
   b. There is greater efficiency when human workers guide or intervene throughout the construction process, i.e., the human workers can ensure that occasional malfunctions (defects and errors) of equipment do not become catastrophes. Human supervision would always be required even if the monitoring systems provided automated reports.
   c. The machines' inability to replace human instinct or creativity - even automating knowledge exchange via generative large language models (e.g., ChatGPT, Bard) has limited applicability, massive energy demands, and cannot fully replace human knowledge oversight. For example, humans can use subtle visual changes in planetary landscape topography as immediate early warnings of structural weaknesses in construction settings.
6. Human-robot collaboration (HRC) will be a salient feature of extraterrestrial construction. Robots will continue to depend on human workers’ ability to anticipate or preempt changes in response to dynamic construction conditions. Such collaborations will likely change in phases, mirroring how construction as a field evolved on Earth. HRC will be in all aspects of extraterrestrial construction, from automatically built landing platforms to enclosed structures using teleoperations to corporeal collaborations onsite for complex habitats.
7. To effectively integrate human-in-the-loop HRC in extraterrestrial construction, workers need the ability to remotely operate and troubleshoot equipment or processes. In such situations, teleoperation will be the desired and safe solution. However, teleoperation might have several technological limitations in extraterrestrial construction (e.g., latency, typically exceeding 20 min between Earth and Mars), which can significantly impact human behaviors, abilities, and work performance.

4.2 Theme 2: Extraterrestrial Construction Workforce

The future workforce in extraterrestrial construction will need to possess a range of knowledge, skills, and competencies to be successful in the new work environment to complete the challenging tasks. Extraterrestrial construction is a process of exploration with numerous uncertainties. Therefore, the future extraterrestrial construction workforce must be ready to expect the unexpected. Given the low population density anticipated for early habitats, workers may face responsibilities typically distributed across professions (e.g., a construction worker at one moment may perform surgical triaging the next). To enable such a workforce, the training should focus on what is certain to foster skills and cognition to handle uncertainties. This requires:

1. Situational Awareness, dating to NASA's first astronaut training, is crucial to make workers focus on their immediate tasks despite constantly monitoring for unrecognized site hazards.
2. Knowing the dramatic changes in geology (including atmospheres) and space environments to construct on the Moon and Mars safely and successfully, including but not limited to
    a. Extreme thermal gradients and low external (confining) fluid pressure (e.g., thin Martian atmosphere and minimal atmosphere on the Moon) and how they affect the degree of mobility in wearing protective suits.
    b. Mission operation times in relation to the planetary body's rotation period (e.g., local day) and how it can affect the workforce.
3. Understanding the associated microenvironment of individual workers in their suits. Given the human body's operational differences under microgravity conditions confined to a spacesuit, training in simulated conditions can provide dexterity.
4. Operating equipment remotely (teleoperation). Previous experience in the transition to teleoperation (e.g., Military transition from fighter pilots to drone operators) can be used for training such workforces. They will have to learn how to deal with several constraints in extraterrestrial construction, such as handling time delay (latency), working on Global Navigation Satellite System (GNSS)-unavailable areas, preventing robotic collisions or breakage, dealing with environmental factors (e.g., ambient temperature, dust, wind), and maintaining robots.
5. Training in Safety. Planetary differences may not necessarily cause collectively more hazards. However, isolated settings with effectively non-existing medical support will dramatically increase the risk of realized hazards.
6. Trusting in technology. The level of trust in technology systems depends on the characteristics of the user, the technological system, and the environment. The dimensions of trust include explainability and interpretability, performance and robustness, reliability and safety, and privacy and security. Preventing credulity is critical, as made obvious in recent fatalities of drivers trusting Tesla's Level 2 autonomy (Society of Automotive Engineers scale) as Level 5.
7. Familiarity with the differences between hybrid collaboration (e.g., human-robot, human-robot-robot) versus human collaboration. Humans and robots may need to build structures as complementary partners, perhaps to the point of co-creating concepts. Therefore, the future workforce needs to understand the HRC and how to use those skills in new circumstances.
8. Compartmentalizing tasks to handle large amounts of information in stressful situations, especially in physically isolated situations.
9. IT Awareness to understand how to run and program robots during teleoperation.
10. Cross-disciplinary collaboration. While the idea of cross-disciplinary collaboration may seem like a cliche, it is still highly relevant and may become more important and prevalent in future work environments.
11. Understanding human-related factors, particularly in new and challenging work environments. Examples of human-related factors include fatigue, collaboration, boredom, isolation, and adaptability to the new work environment.
12. Cross-training at the intersection of mechatronics, electrical engineering, and programming. Skills will go outside the basic skills of a single domain. They will need to understand safety procedures, blueprint reading, programming (main requirement), processes and timing of moving robotic arms, and maintenance operations of such arms. They will need a basic understanding of how AI models are trained and how to employ machine learning algorithms.

4.3 Theme 3: Emerging Technologies for Workforce Training

The future extraterrestrial construction workforce should be trained using hands-on and real-world experiences. Practice in real-world environments is essential in training the future workforce; however, currently, extraterrestrial construction experiences are limited to orbital space stations. In this situation, simulations can provide the key immersive training required to address the differences in tasks (e.g., manipulating objects under low gravity, the limited set of available tools, and different lighting conditions) for extraterrestrial construction settings compared to Earth counterparts. In this situation, AI-XR can provide immersive, interactive, and intelligent training environments that other educational technologies cannot match. Additionally, digital twin systems are an effective tool in such simulations. The simulation should also expose workers to the inevitable sensory deprivation when trapped in a space suit on a remote planetary site. Enabling the refinement of the framing with a feedback loop can ensure advancements from failures and lessons learned. Sensory degradation (such as visual ambiguity and limited perception of orientation extending to proprioception) and physiological impacts should be considered in such simulations. Such simulations should have the following features:

- **Realism.** The training environment should be as realistic as possible, representing extraterrestrial construction scenarios. But this does not suggest all training scenarios or their objects should be in their highest fidelity to reality. Use cases and technologies (e.g., HMD) define the level of fidelity that is needed and possible. The level of fidelity required depends on the goal of the simulation. However, the simulation of real extraterrestrial environments may be very complex, making the creation of learning scenarios using AI-XR technology computationally intensive and, as a result, expensive.
- **Interaction.** The training environment would be more effective if it were interactive. Interactive training fosters the development of essential skills by providing opportunities for individuals to collaborate, share ideas, and tackle challenges.
- **AI-enabled.** The use of AI to generate unforeseen scenarios since much of the planning and training focuses on what we expect to happen. AI-enabled training can bring in the worst-case and adaptable scenarios for training safety and situational awareness.
- **VR.** VR-based training enables more unique scenarios than other approaches. In a simulation, there is a scenario, and there is a consequence. Current training scenarios are very repeatable. Different variables of a simulation can be used to create a unique scenario for different trainees. This is where VR-based training becomes effective.
- **Physical and Emotional Responses.** Simulations need to immerse other senses beyond visual while creating both physical and emotional responses. Learning outcomes will be improved if trainees have a experience that evokes not only physical reactions but emotional ones. Effective use of visual, auditory, and haptic feedback will be necessary.
- **Decision-making protocol.** It is imperative to train the workforce to follow guidelines or procedures used to make decisions in extraterrestrial construction environments.

In addition, it is important to develop an internally consistent knowledge taxonomy for training purposes, which may help prevent unexpected skill failures. Furthermore, considering the complexity of extraterrestrial construction work, the needed skills and knowledge should be prioritized/classified by their importance, frequency of use, and practicality (hands-on experience) and broken down into small, digestible pieces for trainees.

An AI-XR training environment can be used to train several skills for enabling the future extraterrestrial construction workforce, including:

1. *Technical skills*
    a. Construction procedures/protocols specific to extraterrestrial construction
    b. Human-in-the-loop teleoperation for troubleshooting and repairing the robots.
    c. HRC skills such as trust-related issues, collaboration/teamwork, and safety
    d. Safety training
2. *Social skills*
    a. The capacity to resolve interpersonal conflicts between workers without risking human lives. Such conflicts may disrupt the team's operations together and, in some cases, even cause the entire project to fail.
    b. Cross-disciplinary collaboration in teleoperation to work with diverse people with different cultures.

To ensure successful training, two distinct layers of evaluation should be considered (1) evaluation of the action and (2) evaluation of the learning. They affect each other but are not the same learning objectives; thus, two different kinds of evaluations using different criteria are required. There are several evaluation tools that can be used to evaluate the action:

- **Performance metrics analysis.** A quantitative performance assessment to track progress over time and identify areas of improvement.
- **Data collection/analysis with AI.** Using AI to collect performance data and provide immediate and in-depth performance evaluation.
- **NASA task load index (TLX).** The NASA task load index is a tool for measuring and conducting a subjective mental workload assessment.

Also, the evaluation of the learning can be measured by assessing skill acquisition, skill retention, and performance satisfaction (i.e., usability and user experience metrics as well as skill-based performance metrics).

5 Conclusions and Takeaways

We found the following strategic knowledge gaps in each area:

Future extraterrestrial construction and the role of humans: Building a human habitat in extreme outer-space environments on other planetary bodies will require robotic construction processes optimized for that environment. Regarding the construction process, NASA researchers believe robotics and additive manufacturing technologies have enormous potential to enable space colonization. However, suitable and versatile construction technologies are needed to advance and simplify the complexity of the construction process in hostile and extreme outer-space environments in extraterrestrial construction. While the future of extraterrestrial construction remains uncertain, certain aspects are well-established, including (1) There are significant differences between terrestrial and extraterrestrial site conditions, environment, and climate, which must be determined clearly; (2) It is evident that extraterrestrial construction will be robot intensive. Although some level of autonomy is required for specific tasks, the role of human workers cannot be overlooked. Robots will continue to depend on human workers' ability to anticipate changes in response to dynamic construction conditions, making HRC a salient feature of extraterrestrial construction; and (3) To effectively integrate human-in-the-loop robot operations in extraterrestrial construction, future workers will need the ability to remotely operate and troubleshoot equipment or processes. In such situations, teleoperation is the desired and safe solution. However, teleoperation presently has several technological limitations in extraterrestrial construction.

Future construction workforce and competencies required: The lack of adequately trained personnel has been identified as a major hindrance to adopting and implementing emerging construction technologies. This issue is becoming more significant due to the unprecedented speed of technological advancements in this industry. In addition, the non-repetitive nature of construction tasks may result in semi-automated construction robots, which require humans and robots to work jointly. In this situation, human workers must learn how to perform construction work adaptively (i.e., improvise) based on evolving site conditions, supervisor input, and accrued experience. The future workforce in extraterrestrial construction will need to possess a range of knowledge, skills, and competencies to succeed in the new work environment to complete challenging tasks. Extraterrestrial construction is a process of exploration with numerous uncertainties. Therefore, the future extraterrestrial construction workforce must be ready to handle the unexpected with an acceptable level of success. To enable such a workforce, the training should focus on what is certain to foster skills and abilities to handle uncertainties. This requires (1) situational awareness as a necessity for the future extraterrestrial construction workforce; (2) operating equipment remotely (teleoperation) while dealing with several constraints in extraterrestrial construction; (3) trust in technology, which will play an important role in the future extraterrestrial construction workforce. The level of trust in technology systems depends on the characteristics of the user, the technological system, and the environment; (4) familiarity with the differences between robots and humans, building structures as complementary partners, and how to use those competencies in new circumstances.

Future training environment for future-ready workforce development: While it is obvious that training programs must maintain some likeness to the current practices of the construction industry, keeping the construction workforce development in line with future needs is an important challenge, given that the construction industry is poised for rapid transformation. Traditional training methods (e.g., classrooms) cannot reflect the real dynamics of the construction site or replicate the actual construction scenarios. It is emphasized that the future extraterrestrial construction workforce should be trained using hands-on and real-world experiences. It requires a training transition from traditional behaviorist and cognitivist learning to learner-centered constructivist learning. Constructivist learning, as a contemporary learning paradigm, emphasizes the importance of an immersive and intelligent learning experience. Immersive learning, supported by digital media simulations, will create artificial environments where trainees experience and interact with real-world complexities. Its immersive nature will enable trainees to grasp abstract concepts, processes, and thinking, and gain hands-on experience in low-risk/secure virtual environments while feeling like they are actually there (e.g., the construction sites), ideal for harsh environments (e.g., extraterrestrial construction) workforce training. Adaptive intelligent learning uses AI technologies to analyze and adjust to learners' needs and progress, thus providing a personalized learning experience. It also will be an ideal feature for an extraterrestrial workforce training environment where workers from diverse backgrounds are involved.

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