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The evolution of Computational Design and XR-enhanced Space Architecture Education

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Abstract

Over the past four years, the "Architecture for Human Space Exploration" course at Politecnico di Milano has undergone a significant evolution, marking a shift towards a more computationally designed approach, integrating extended reality (XR) systems to deepen the understanding of human factors and habitability requirements in space environments. This paper synthesizes the pedagogical journey and methodological advancements in teaching and learning space architecture, reflecting on the iterative improvements and the integration of cutting-edge technologies in the curriculum. Initially, the course focused on traditional design methodologies, emphasizing conceptual understanding and manual design skills pertinent to space architecture. As the complexities of designing for extraterrestrial environments became more apparent, there was a clear need to incorporate computational design techniques. This shift not only allowed for the exploration of more complex geometries and space configurations but also enabled the simulation of space environments to better understand the challenges of extraterrestrial habitability The introduction of computational design tools into the curriculum was a turning point, enabling students to experiment with parametric design and digital fabrication techniques. These tools facilitated a more nuanced exploration of the spatial, structural, and environmental aspects of space habitats, allowing for a deeper analysis of how human factors influence design decisions. However, the most transformative development in the didactic activity was the incorporation of XR systems, such as virtual reality (VR) and augmented reality (AR), into the design process. This integration marked a departure from conventional design methodologies towards an immersive design experience. By leveraging XR technologies, students were able to virtually inhabit their designs, gaining immediate feedback on the scale, proportions, and usability of spaces. This hands-on experience was invaluable in understanding the psychological and physiological needs of astronauts, ensuring that designs were not only functional but also conducive to well-being in extreme environments. The use of XR systems in space architecture education represents a forward-thinking approach to design education, one that recognizes the importance of human-centric design in the unforgiving context of space. Through this immersive design process, students have been able to explore innovative solutions to complex problems, considering not just the technical requirements of space habitats but also the human experience of living and working in such environments. This paper presents a comprehensive overview of the evolution of the "Architecture for Human Space Exploration" course, highlighting the pedagogical strategies employed, the integration of computational and immersive technologies, and the impact of these methodologies on students' design outcomes.

Keywords: Computational Design, XR/VR/AR, Space Architecture, Education

Acronyms/Abbreviations

VR = Virtual Reality
AR = Augmented Reality
XR = Extended Reality
AHSE =Architecture for Human Space Exploration
MIT = Massachusetts Institute of Technology
ICE = Isolated, Confined, and Extreme environments
ISRU = In Situ Resource Utilization

1. Introduction

Space architecture is an interdisciplinary field that blends various domains such as engineering, architecture, space science, industrial design, psychology, and human factors to address the challenges of human space exploration. As space missions become more complex, there is a growing need for innovative approaches in designing habitats that support long-term human habitation on celestial bodies like the Moon and Mars. The course "Architecture for Human Space Exploration" at Politecnico di Milano has evolved over the past four years, marking a significant shift towards computational design and immersive technologies such as virtual reality (VR), augmented reality (AR) and mixed reality (XR) to address these challenges.

This paper presents the pedagogical evolution of the course, focusing on the integration of computational design and XR technologies. It highlights the iterative advancements in the teaching methodology, reflecting on how these innovations have contributed to a deeper understanding of habitability and human factors in extreme environments. The course has shifted from a traditional design approach to one that embraces cutting-edge computational tools, enabling students to explore complex geometries, perform multi-objective optimization, and immerse themselves in virtual space environments.

2. Architecture for Human Space Exploration (AHSE) course at Politecnico di Milano

The "Architecture for Human Space Exploration" (AHSE) course has been offered to both undergraduate and graduate students at the School of Architecture, Urban Planning, and Construction Engineering at Politecnico di Milano since the A.Y. 2020-2021. Open to students from various disciplines, including Architecture Built Environment Interiors, Architecture and Urban Design, Building Architecture, and Architectural Engineering, the course fosters a multidisciplinary learning environment. In collaboration with the Massachusetts Institute of Technology—specifically the MIT Senseable City Lab and MIT Media Lab's Responsive Environments group—the course expands its holistic and multidisciplinary approach to space architecture [1].

During the various academic years, the AHSE course focused on the design of resilient and sustainable infrastructure for human missions on the Moon and Mars. This new challenge required an innovative and holistic design approach, reflecting the highly interdisciplinary nature of space architecture.

Students worked in cross-disciplinary teams, addressing design challenges across multiple scales, from urban planning to architectural and interior design. They built upon technologies and knowledge developed for space applications, while also considering how these designs could influence both space and terrestrial architecture.

By examining the relationship between human activities and the resources that sustain them, students created architectural solutions for the Moon and Mars that not only advanced space architecture but also offered insights for addressing terrestrial challenges. These efforts aligned with the United Nations Sustainable Development Goals of Agenda 2030, demonstrating how methodologies developed for extreme space environments can inspire intelligent solutions for Earth-based challenges.

The AHSE course syllabus covered a wide range of expertise, including an introduction to computational design and multi-objective optimization algorithms. This gave students the tools to manage the complexity of balancing multiple requirements and objectives within their designs [1].

3. Evolution of the Course: From Traditional to Computational Design

Initially, the course focused on traditional design methodologies, with a strong emphasis on developing a conceptual understanding of space architecture through manual design techniques and basic structural analysis. Students were introduced to essential principles, such as how to withstand internal pressurization loads caused by the absence of external atmospheric pressure, and the effects of varying gravity loads in extraterrestrial environments. However, as the scope and complexity of space design became more apparent, it became clear that these traditional approaches were not sufficient to address the full range of challenges posed by the harsh and unique conditions of space. Beyond reduced gravity and pressurization, students needed to account for other critical factors such as intense radiation (due to Galactic Cosmic Rays and solar flares), extreme thermal gradients, micrometeoroid impacts, and the psychological and physiological effects of isolation in confined environments—known collectively as ICE (Isolated, Confined, and Extreme environments) [2, 3].

To effectively tackle these multifaceted challenges, the course began integrating computational design tools. Grasshopper© [4], along with advanced plugins such as Karamba3D© [5], Octopus© [6] and Ameba© [7] enabled students to move beyond manual methods and into the realm of parametric design, form-finding, and multi-objective optimization. These tools empowered students to explore the spatial and structural complexities of space habitats in a more dynamic way, allowing them to experiment with a wider array of geometries, materials, and environmental constraints than was possible with traditional methods. Computational design facilitated the real-time optimization of various design parameters, fostering a more nuanced understanding of how human factors, such as ergonomics and psychology, influence architectural decisions in space environments. Afterwards, architectural projects have been verified for space radiation exposure with OLTARIS - NASA© [8].

What made this computational approach even more transformative was its algorithm-based design process, which allowed students to embed multiple physical and environmental factors directly into the generative design phase. From the very beginning of the design process, students were able to define key mission parameters, such as the duration of the mission, number of astronauts, mission objectives, and environmental characteristics. These inputs were fed into the algorithm, which would then generate initial habitat shapes that were automatically correlated with the physical realities of the target environment. This included considerations such as internal pressurization, the effects of reduced gravity, the minimum habitable volume required for various functions inside the habitat, radiation protection shielding, and even the optimization of payload mass.

In addition to the physical constraints, the algorithms incorporated the potential for In Situ Resource Utilization (ISRU), which allowed students to explore how resources found in the local environment—whether on the Moon, Mars, or another celestial body—could be used to support habitat construction and sustainability. The multi-objective optimization methods provided by the computational tools enabled students to assess various trade-offs and visualize the most optimal solutions on a Pareto front. This gave students a comprehensive view of the design space, allowing them to select the options that best aligned with their project's goals.

Once these optimal designs were generated, they could be further tested and refined through immersive design experiences using XR systems. This integration of real-time feedback through XR allowed students to virtually inhabit their designs and adjust parameters such as scale, proportions, and spatial organization directly within the immersive environment. This iterative process, combining computational optimization and immersive XR feedback, not only enhanced the design's technical feasibility but also ensured that human-centric considerations, such as habitability and astronaut well-being, were thoroughly integrated into the final design.

4. XR/VR/AR Systems and Immersive Learning

The most transformative development in the didactic activity was the incorporation of XR technologies into the design process. Students were introduced to virtual, augmented, and mixed reality environments, enabling them to virtually inhabit their designs and receive immediate, real-time feedback on critical aspects such as scale, proportions, and usability of their space habitats. This immersive experience provided invaluable insights into the psychological and physiological needs of astronauts, particularly in ICE environments—where factors like spatial organization, human comfort, and usability can be vital to mission success.

What set this approach apart was not just the ability to visualize designs in XR but also the interactive capabilities offered by the integration of HoloLens 2 and Grasshopper© through the Fologram©[9] interface. With this setup, students were no longer passive observers of their virtual designs; they could actively engage with and manipulate their projects in real-time. By using the HoloLens, students could interact directly with holographic representations of their space habitats, making real-time adjustments to mission and design parameters while experiencing the model as a full-scale, immersive environment (see Fig. 1).

This interactive XR environment allowed students to change mission parameters—such as mission duration, the number of astronauts, and objectives—directly through the hologram. They could adjust design parameters such as habitat dimensions, structural configurations, and material properties, all while viewing the impact of these changes in real time. This provided a more intuitive, hands-on method for optimizing their designs than traditional screen-based simulations.

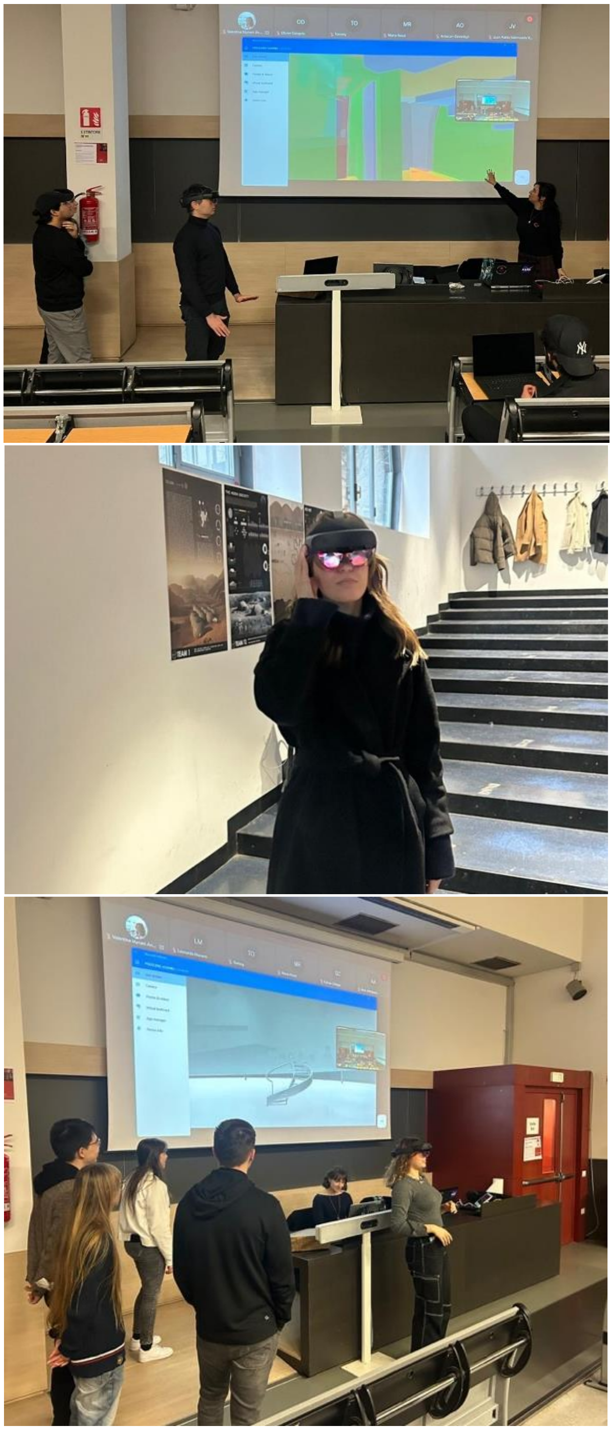


Fig. 1. Photos taken during XR experience during the AHSE course, A.Y. 2023-2024 (source: authors).

The integration with Grasshopper© through Fologram© also extended to interior design decisions, such as the placement and arrangement of furniture within the habitat. Students could interact with the furniture layouts in XR, moving and resizing objects directly within the hologram. This capability allowed them to better understand the spatial relationships between different functional areas inside the habitat and ensure that their designs optimized for both comfort and efficiency in a reduced-gravity environment. For instance, by adjusting the layout of workspaces or sleeping quarters, students could immediately see how these changes impacted both usability and the psychological well-being of the astronauts inhabiting the space.

The ability to dynamically modify key design and mission parameters in XR also facilitated a more advanced form of multi-objective optimization (see Fig. 2). Rather than running multiple simulations offline and selecting from a pre-generated set of options, students could explore optimal trade-offs directly within the immersive environment. Using the algorithmic processes embedded in Grasshopper© and the live feedback from Fologram©, they could visualize and select the most appropriate solutions from the Pareto front—adjusting parameters until they found a balance that satisfied both technical constraints (such as payload mass or radiation shielding) and human factors (such as interior habitability and user comfort). This integration of XR and computational tools allowed for a more fluid and iterative design process, where students could experiment with numerous possibilities and directly evaluate their trade-offs without ever leaving the immersive design experience.

This hands-on, interactive approach to design using XR technologies significantly enhanced students' understanding of space architecture. By enabling real-time interaction with both the physical and mission-related parameters of their habitats, the course fostered a deeper understanding of how various elements of space architecture—from structural systems to human factors—interact to create a livable, sustainable environment in space.

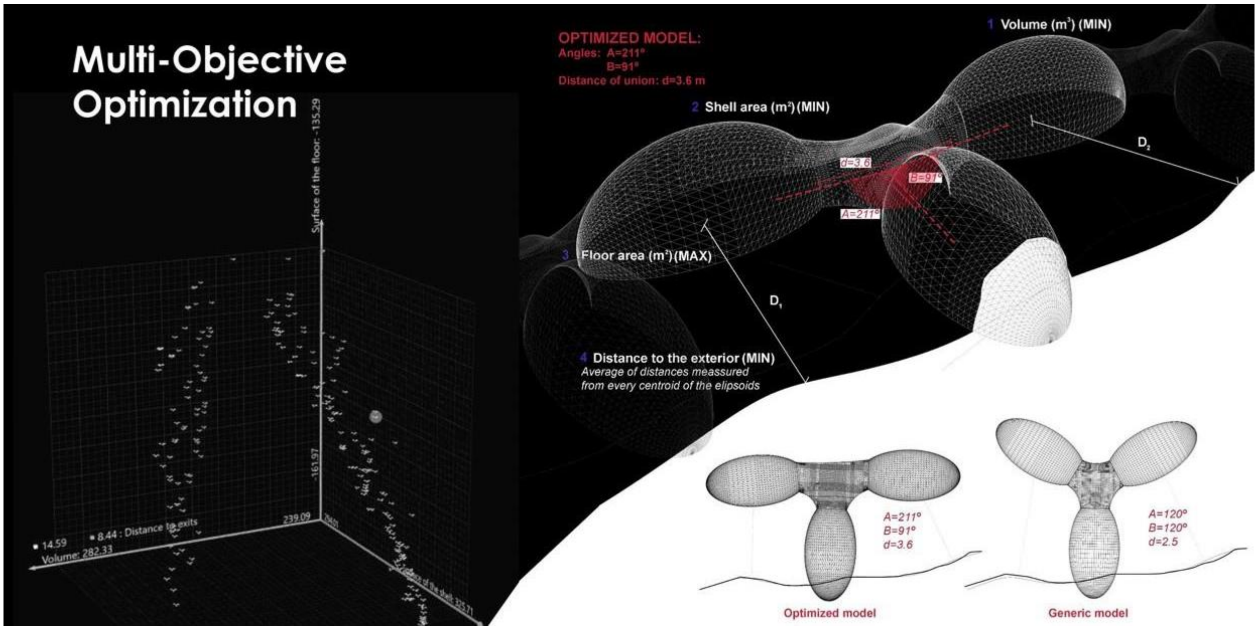
Moreover, the integration of XR into the computational design workflow bridged the gap between theoretical learning and practical, real-world application, preparing students to tackle the real challenges of space architecture in the future.

As they navigated their designs, adjusted parameters, and inhabited the environments they created, each student had a truly immersive experience—one that made them feel like an astronaut, virtually living and working in the very habitats they were designing for space exploration.

5. Examples of immersive design reviews in XR

The projects developed during the course were extensively tested in XR to evaluate habitability criteria and assess the structural performance of space habitats. Through the integration of displacement and stress maps into the form-finding process, students were able to visualize the structural behavior of their designs in real time. XR allowed them to interact with their projects at a 1:1 scale, providing a highly immersive experience where they could observe potential structural issues such as stress concentrations, deformations, or weaknesses in critical components.

This immersive evaluation was particularly useful for identifying areas of concern that might not have been as easily detectable in traditional 2D or 3D simulations.



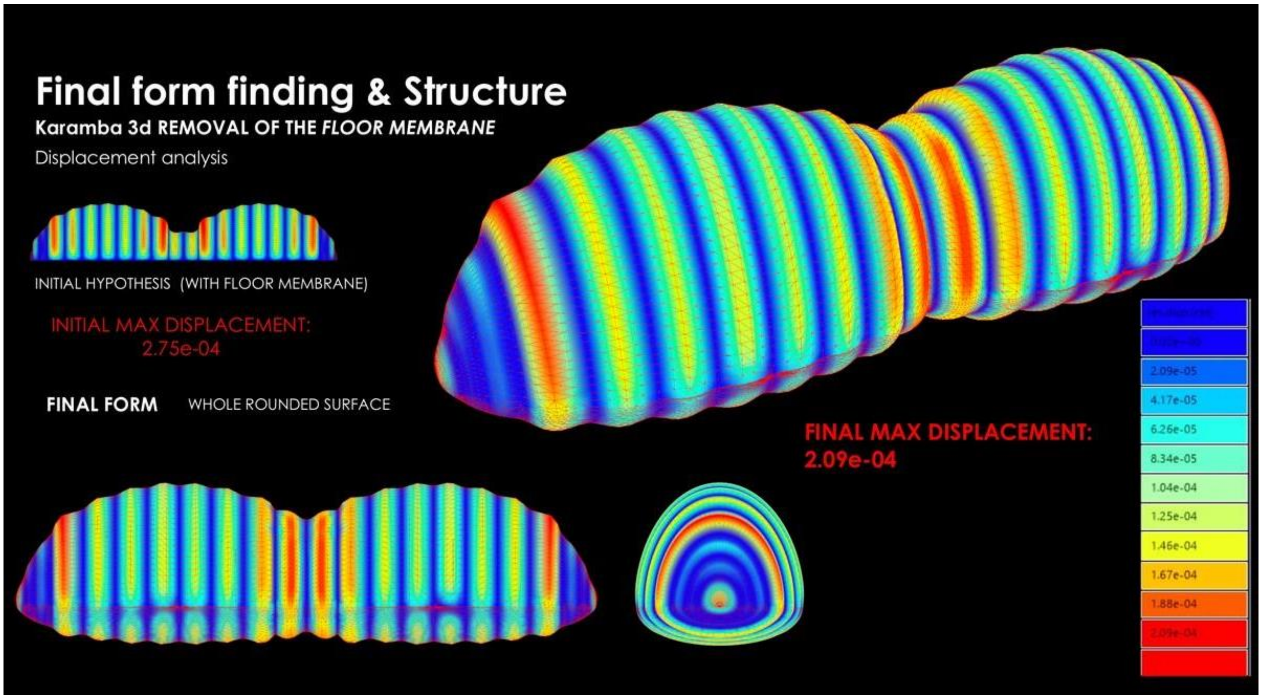


Fig. 2. Project Insiders – Structural analysis (source: A.Y. 2022-2023 AHSE project by the students Anna Garcìa, Carlos Fuentes, Alejandro Pérez, Iñaki Hurtado, David Gala, Adrien Lotz. Prof. Valentina Sumini, T.A. Marta Rossi).

By walking through the full-scale holographic models, students could assess how the structural performance (see Fig. 2) aligned with habitability requirements, ensuring that spaces designed for astronauts were not only functional but also structurally sound. Additionally, this real-time feedback loop allowed for rapid iteration, enabling students to make adjustments to their designs on the fly, improving both the safety and usability of their habitats (see Fig. 3).

Moreover, this approach proved to be invaluable for evaluating the overall livability of the designed spaces. By visualizing the space at full scale, students could assess key habitability factors such as spatial organization, ergonomic design, and how astronauts would interact with their environment and machines during long-duration missions. This iterative, immersive process ensured that the designs balanced both structural integrity and human-centric design, addressing both technical and psychological needs in extreme environments.

6. Results

The integration of computational design tools and XR technologies in the "Architecture for Human Space Exploration" course at Politecnico di Milano has resulted in substantial advancements in both student learning outcomes and project complexity. The course evolved from traditional architectural design techniques to a more

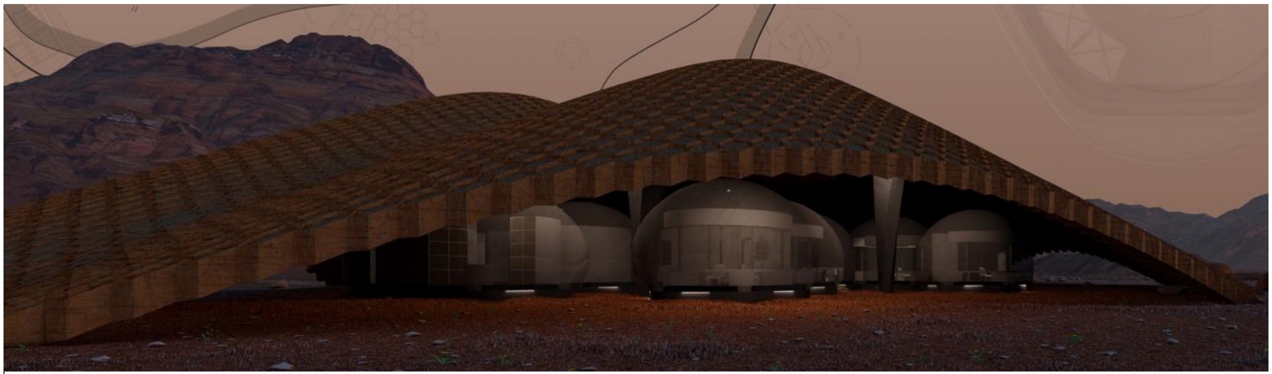


Fig. 3. Project HEXAscape – Example of a project enhanced with the use of XR (source: A.Y. 2023-2024 AHSE project by the students Julija Nikolic, Marija Ivljanin, Marta Komljenovic, Luka Milic, Mustafa Erkus. Prof. Valentina Sumini, T.A. Marta Rossi).

sophisticated approach that combines computational modeling, real-time optimization, and immersive technologies.

Below are some of the key results observed throughout this transition:

- Enhanced understanding of complex design parameters: The use of parametric design and multi-objective optimization algorithms significantly improved students' ability to address the multifaceted design challenges of space habitats. Students were able to simulate complex geometries and environmental conditions, leading to more robust solutions for extraterrestrial habitability. For example, projects like "HEXAscape" incorporated optimization for radiation shielding and ISRU, demonstrating advanced understanding of the technical constraints involved in lunar and Martian habitation.
- Improved human-centric design: By integrating XR systems, students gained deeper insights into the psychological and physiological aspects of space architecture. The immersive nature of VR and AR allowed students to inhabit their designs virtually, offering real-time feedback on space usability, proportions, and scale. This led to more human-centric designs that took into account not only functionality but also the well-being of astronauts in extreme, confined environments.
- Increased collaboration and knowledge sharing: The international collaboration with MIT Media Lab and Senseable City Lab MIT through the MIT Webinar Series “Design Exploration: Smart Settlements in Extreme Environment on Earth and beyond” broadened the students' perspectives and deepened their engagement with real-world space architecture challenges. The virtual poster sessions and VR presentations (see Fig. 4 and Fig. 5) fostered global interaction, enabling students to share their work with a broader audience and receive diverse feedback from professionals in the field.
- Diverse and innovative project outcomes: The course's multi-disciplinary approach, combined with computational tools and XR technologies, resulted in a wide range of innovative space architecture projects. Teams developed advanced concepts for lunar and Martian settlements, leveraging ISRU, autonomous robotic manufacturing, and sustainable design principles. These projects showcased creative solutions that addressed both the technical challenges of space exploration and the human experience of living in isolated, confined, and extreme environments.

7. Conclusions

The "Architecture for Human Space Exploration" course at Politecnico di Milano has undergone a significant transformation, evolving from a traditional design methodology to a cutting-edge, computationally-driven approach that integrates XR technologies. This shift has profoundly impacted both the pedagogical framework and the learning outcomes for students, preparing them for the future challenges of space architecture.

The use of computational design tools enabled students to explore complex, multi-objective design problems that are critical to space architecture. By leveraging parametric modeling and real-time optimization, students were able to create sophisticated designs that addressed the unique challenges of extraterrestrial environments, such as reduced gravity, radiation exposure, and extreme isolation.

The integration of XR technologies, such as virtual and augmented reality, provided an immersive learning experience, allowing students to virtually inhabit their designs and refine them in real time. This hands-on approach offered invaluable insights into human factors and habitability requirements, ensuring that the designs not only met technical specifications but also catered to the psychological and physiological needs of astronauts.

Fig. 4. VR gallery with the AHSE students’ projects (source: authors).

Fig. 5. VR gallery with the AHSE students' projects (source: authors).

Moreover, this pedagogical approach has opened new avenues for integrating building technology with robotics, a key factor in future space habitats. As space architecture moves toward greater automation and autonomous construction, the ability to simulate and optimize the use of robotics in building processes will be crucial. Through computational design and XR tools, students have begun to experiment with concepts such as autonomous robotic manufacturing and the use of in-situ resources (ISRU). This experience will be invaluable for future space architects, equipping them with the skills necessary to design habitats that incorporate advanced building technologies and robotic systems, essential for creating sustainable and efficient extraterrestrial environments.

The course's collaboration with international institutions like MIT Media Lab and MIT Senseable City Lab further enriched the educational experience, fostering a global exchange of ideas and exposing students to real-world challenges in space architecture. The interdisciplinary nature of the course, combined with its focus on computational design and immersive technologies, has set a new standard for space architecture education.

Looking forward, the course will continue to integrate emerging technologies, such as artificial intelligence and machine learning, to further enhance students' ability to solve complex design problems. The success of this pedagogical approach highlights the importance of innovation in education, particularly in fields like space architecture, where future generations will play a key role in shaping humanity's off-world presence. The ability to simulate the integration of building technology with robotics will be essential in designing resilient, sustainable habitats that can be constructed efficiently in remote, hostile environments such as the Moon and Mars.

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