PROJECT SUMMARY (max 3 pages)

Objectives and novelty. The project aims to explore models and software technologies for extended reality (XR) to simulate experiences in extreme environments, such as sensory/physical constraints encountered during space mission training, by combining the partners' expertise in the fields of human-computer interaction, extended reality, and software engineering. To this end, we introduce the concept of eXtreme eXtended Reality (XXR) to address unconventional environments, such as those encountered in space mission preparation. The specific objectives, which define the novelty of our project, are: critical analysis of XR applications in extreme environments through a systematic literature review (SLR) to systematize knowledge within the scientific community; development of a conceptual model and design space for XXR interactions to contextualize the application of XR in extreme environments characterized by sensory/physical constraints based on the concept of sensorimotor realities and the transferability of user experience at an interplanetary level; implementation of an XXR software application for experiencing navigation in diverse gravitational environments and collaboration with the Euro Space Center, Belgium and the NASA Mars Desert Research Station, USA.

Key results. We conducted an analysis of the scientific literature on XR technology and extreme environments. For this purpose, we carried out a study following the principles of systematic literature reviews (SLRs) with a dataset of 28 scientific papers published between 2000-2025, from which we extracted information on aspects characterized as "extreme" by their authors. To structure this analysis, we used a theoretical framework comprising three classes of entities for the context of use of interactive systems: users, platforms, and environments. This allowed us to highlight **extreme users** (e.g., users gaining unusual abilities or exhibiting exaggerated behaviors facilitated by specific platforms or environmental conditions), **extreme platforms** (e.g., technologies pushing the boundaries of interactive system design, such as highly immersive multisensory simulations), and **extreme environments** (e.g., environments characterized by severe physical conditions or risky situations with major impact on life and health). These elements constitute distinct dimensions of a conceptual space that, supported by extended reality (XR) technologies, becomes a design space for eXtreme eXtended Reality (XXR), where each dimension has specific categories. For example, extreme users are defined by **the abilities they acquire** (e.g., extreme skiing for people with tetraplegia), **the behaviors they exhibit** (e.g., extreme speech or extreme online posting), and **extreme collaboration** (e.g., communication and information sharing in extreme situations). Extreme platforms are defined by **input modalities and techniques** (e.g., extreme vocal techniques), **output modalities and techniques** (e.g., information presentation on a screen from an extreme perspective), **input-output synergy** (e.g., extreme human-computer collaborations), and **design strategies** (e.g., extreme usability). Extreme environments are specified by their nature: **physical** (e.g., extreme weather), **virtual** (e.g., extreme jumps in a virtual world), **digital** (e.g., extreme online censorship), or **mixed** (e.g., extreme visual perception). The granularity of the XXR space (3x4x4=48 combinations) allows for the exploration of a wide range of extreme interactions, such as users with extreme abilities employing extreme output modalities in mixed reality environments. To illustrate this conceptual space, we developed a software application for the simulation of navigation through environments with diverse gravitational conditions, and conducted three UX evaluation experiments through missions carried out at the Mars Desert Research Station (MDRS). These experiments focused on various computer systems with graphical, haptic, and conversational (LLM/AI) interfaces, as well as on human-drone interactions performed outside the station (Figure 1).

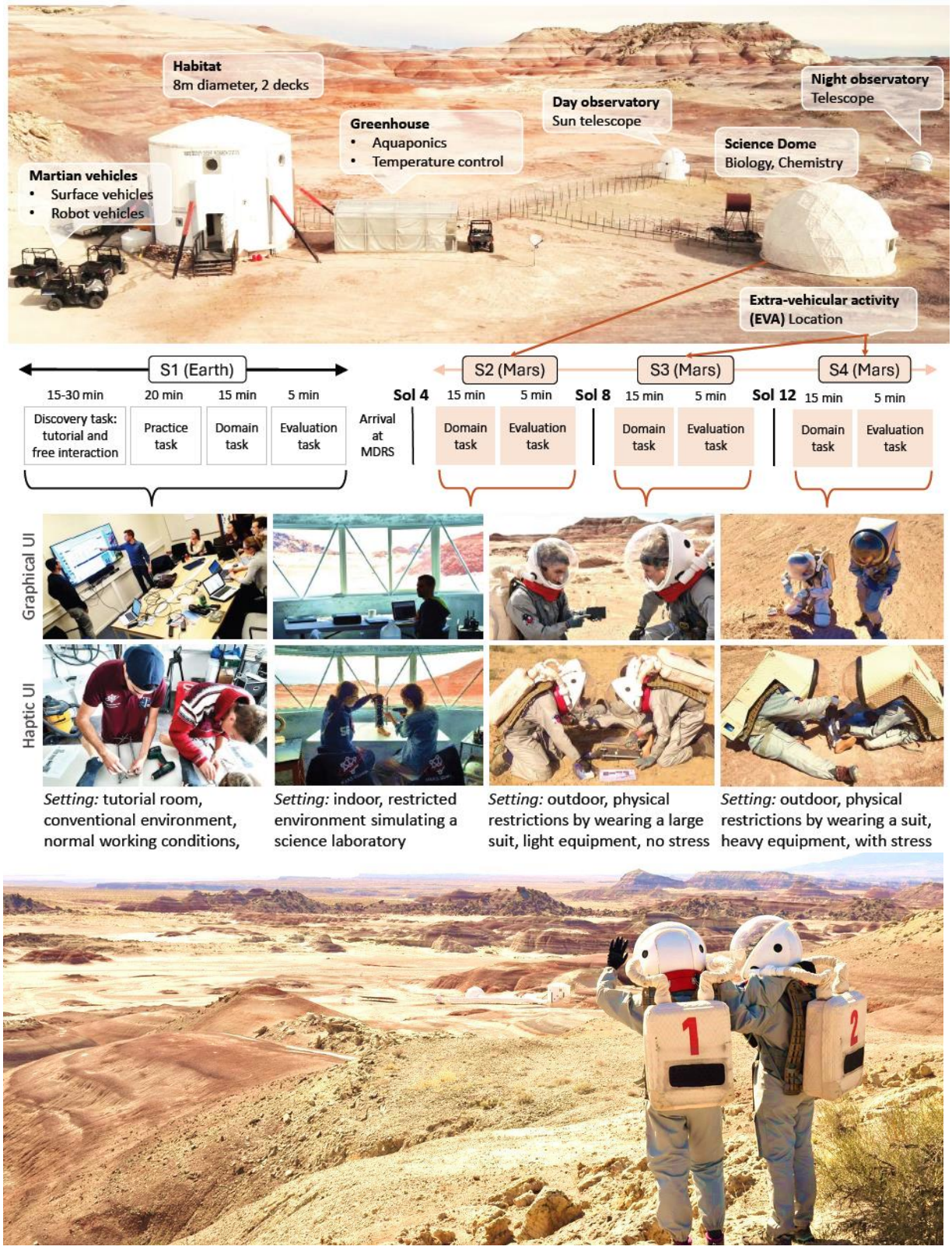

Figure 1. *Top:* Mars Desert Research Station, where the experimental sessions took place. *Middle:* timeline of the various stages of the experimental procedure (discovery, practice, and repeated performance of a task, followed by its evaluation). *Bottom:* illustration of extreme conditions. Details in Vanderdonckt et al. (2025a).

Project impact. The results obtained are highly relevant both for the fields of space technologies and XR. In particular, the context of space technology development provides significant opportunities with a global space

industry valued at USD 630 billion in 2023, expected to triple by 2035,[1] alongside major EU investments, e.g., the European Space Agency (ESA) budget of EUR 7.7 billion in 2025.[2] Moreover, the proposed concept of eXtreme eXtended Reality (XXR) offers a novel framework that can be leveraged through new XR technologies, for which the global market was USD 40.4 billion in 2024.[3] From a scientific and technological perspective, the project generated five peer-reviewed publications, of which two developed in collaboration with NASA Ames Research Center. These publications have been downloaded over 1200 times, showing a strong engamented in the scientific community, while outreach via professional networks reached over 10000 views.

Final indicators. Five scientific articles have been published, including two in ISI journals (one Q1), two in A/B-ranked conferences in the field of human-computer interaction, and one at the only conference dedicated to interactive technology for space. All articles are indexed in international databases (ACM DL, DBLP, Scopus), three in Web of Science, and two were produced in collaboration with NASA Ames Research Center.

1. Radu-Daniel Vatavu, Jean Vanderdonckt, Julie Manon, Michael Saint-Guillain, Philippe Lefevre, Romain Maddox, Jessica J. Marquez. (2025). Conducting Human-Computer Interaction Scientific Experiments in Extreme Environments: Insights from Analog Mars Missions. *Romanian Journal of Information Science and Technology.* Romanian Academy, 247-259. http://dx.doi.org/10.59277/ROMJIST.2025.3.01
   WOS:001565907000001 | IF: 3.9 | 5-Year IF: 2.2 (Q1 în Computer Science, Theory & Methods)
2. Jean Vanderdonckt, Radu-Daniel Vatavu, Romain Maddox. (2025). Between Bulky Suits and Isolated, Deserted Landscape: Measuring the User Experience of Astronaut-Drone Interaction. *Proceedings of the ACM on Human-Computer Interaction* 9(5). ACM, New York, NY, USA, Article no. MHCI005, 20 pages. https://doi.org/10.1145/3743712
   WOS:001575057300008
3. Jean Vanderdonckt, Radu-Daniel Vatavu, Julie Manon, Romain Maddox, Michael Saint-Guillain, Philippe Lefevre, Jessica J. Márquez. (2025). UX, but on Mars: Exploring User Experience in Extreme Environments with Insights from a Mars Analog Mission. *Proceedings of the Designing Interactive Systems Conference.* ACM, NY, USA, 3235-3250. https://doi.org/10.1145/3715336.3735706
   WOS:001555741000193 (A-ranked conference, according to ARC CORE)
4. Radu-Daniel Vatavu, Jean Vanderdonckt. (2025). What is Extreme in Human-Computer Interaction Research? *Adjunct Proceedings of the 27th International Conference on Mobile Human-Computer Interaction.* ACM, New York, NY, USA, Article. no. 17, 1-7 https://doi.org/10.1145/3737821.3749561
   (B-ranked conference, according to ARC CORE)
5. Hippolyte Hilgers, Jean Vanderdonckt, Radu-Daniel Vatavu. (2025). Human-AI Interaction in Space: Insights from a Mars Analog Mission with the Harmony Large Language Model. *Proceedings of SpaceCHI '25, Advancing Human-Computer Interaction for Space Exploration.* Open Access Series in Informatics. Dagstuhl, Article no. 1, 20 pages. https://doi.org/10.4230/OASIcs.SpaceCHI.2025.1
   (the only conference specialized in human-computer interaction and space research)

[1] https://www.statista.com/topics/5049/space-exploration/?srsltid=AfmBOopYDM_N_HrvgMBFMUShr6QmLyU-hTRV2eLI3mGfR9rYAd98wbPj#topicOverview
[2] https://www.statista.com/topics/13455/space-industry-europe/?srsltid=AfmBOorLWvJXrf4BaZNNL9AnHfpC8uVrqaMdV03_Eb114LjszaS6h167#topicOverview
[3] https://www.statista.com/topics/6072/extended-reality-xr/?srsltid=AfmBOorOkGgvM3ANphsIwNoO7T-acTtdjLCUJig8pxtAH1IzP2e0dMKA#topicOverview