June 2025

Extended Reality Strategy

Image of a Digital Elevation Map of the Moon for use in Virtual Reality (VORTEX)

INTRODUCTION

Extended Reality (XR), is an umbrella term that encompasses Virtual, Augmented, and Mixed Reality.

- ***Virtual Reality (VR)*** fully immerses users in a computer-generated environment.
- ***Augmented Reality (AR)*** overlays digital elements onto the real world.
- ***Mixed Reality (MR)*** blends real and virtual environments and objects that can interact with each other.

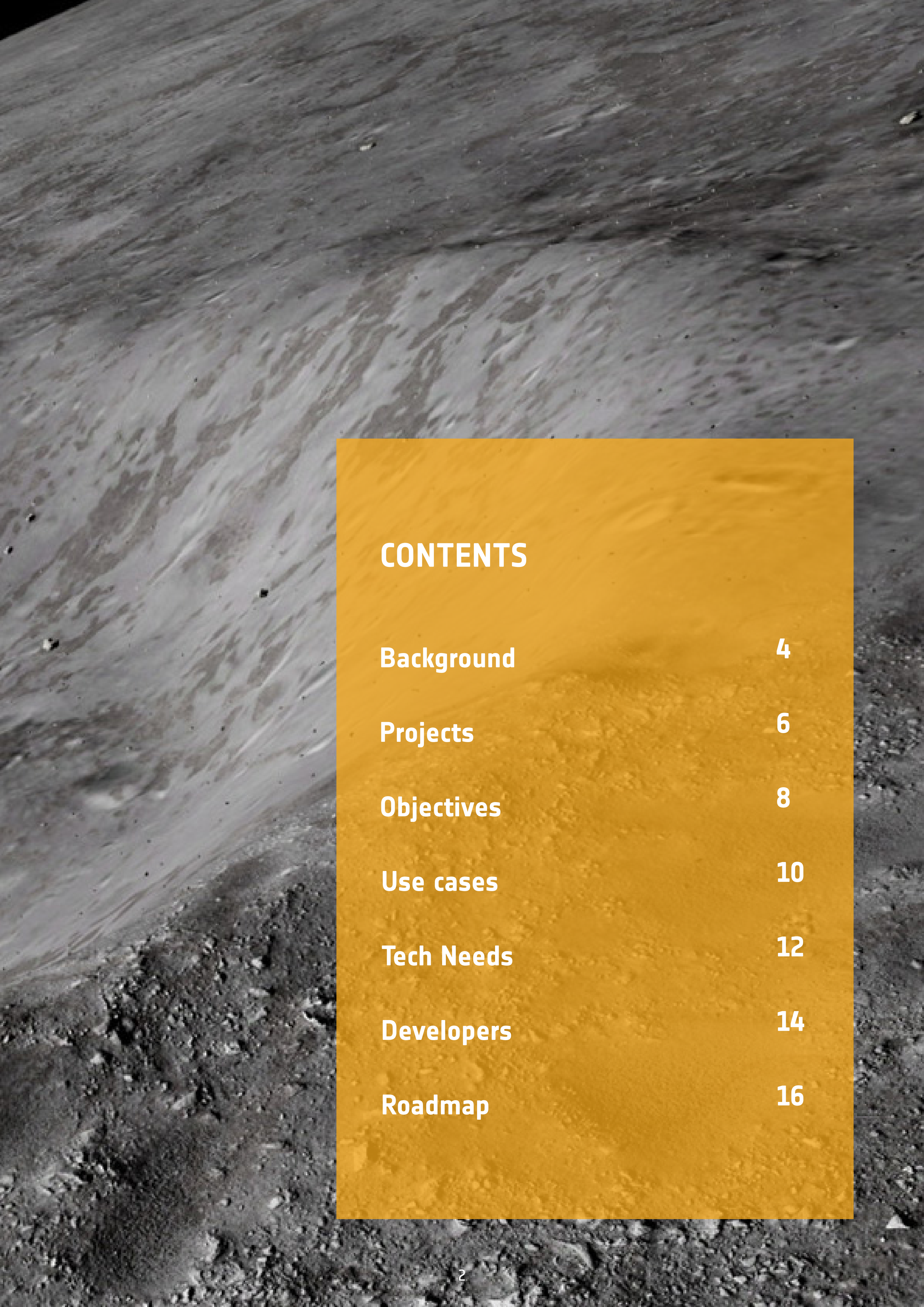
Our vision is to elevate the future of space through the use of XR technologies to create more immersive, interactive, and seamless experiences. XR is revolutionizing by making tasks more intuitive, improving teamwork, saving costs, and helping people better understand data, plan missions, and train for space. More specifically, XR is already making a difference at ESA across four key areas:

- ***Digital Twin & Simulation***: XR helps engineers and mission planners visualize and interact with spacecraft and systems in real time, supporting decision-making, collaboration and design.
- ***Operations Support***: XR enhances how we visualize data and control missions, from Earth observation, Space Safety to robotic operations or crisis response.
- ***Training***: XR is used to train astronauts or operators, providing means to maintain facilities or prepare for space missions in a more immersive, scalable and flexible way.
- ***Outreach***: XR brings space closer to the public, allowing for engaging in gaming, research, divulgation, or educational experiences.

In a highly competitive and rapidly-evolving technological landscape, it is important to have a common ***strategy***, avoiding redundancies and building a consistent framework of knowledge to keep Europe lead and sovereign of our technologies. Therefore, this strategy document is meant to be used as a guide for ESA and European organizations to understand the pathway of Extended Realities in the Space sector in Europe.

The ***ESA XR Team*** is a heterogeneous group of the European Space Agency in charge of allowing knowledge transfer, cross-collaborations and maintaining a common strategy. The main stakeholders of the ESA XR Team are the following:
- ***Technology, Engineering and Quality (TEC) - Coordination***
- ***Human and Robotic Exploration (HRE) - XR Lab***
- ***Operations (OPS)***
- ***Earth Observation Programmes (EOP)***
- ***Science (SCI)***
- ***Commercialisation, Industry and Competitiveness (CIC)***
- ***Connectivity & Secure Communications (CSC)***

This document will be updated on a yearly basis. For further information please contact: **xr@esa.int**



CONTENTS

Testing Virtual Reality in the ESA-DLR LUNA Facility

BACKGROUND

History of XR at ESA

ESA's journey with XR technologies began in the **2000s**, initially exploring how augmented and virtual reality could support engineering and operations. Early efforts like the Wearable Augmented Reality (**WEAR, 2008**), a technology demonstrator that was carried to the ISS to support astronauts following procedures while keeping their hands free. Others, like the Portable Virtual AIT Visualizer (**PVA-ITV, 2010**) applied AR to assist in spacecraft assembly. These formative projects laid the groundwork for a wave of new applications.

By the **2010s**, as the technology matured, ESA moved towards more integrated applications. Projects like **VORTEX (2017)** or **JIVE (2018)**, explored virtual training for astronauts for the Moon or to command the CanadARM robot. Other activities like **MobiPV (2018)** allowed astronauts in the ISS to have a wearable, mobile procedure viewer, with hands-free instructions and augmented reality indications through a tablet device. These tools began to transition from experimentation to mission support, targeting spaceflight operations and ground control.

In recent **2020s**, ESA has embraced XR as a core capability for planning, simulation, monitoring, outreach and real-time decision-making. For example, **Guardians of Earth (2023)** brought XR into planetary exploration and mission preparation, blending AR/VR tools with digital twins. Also, many other applications matured for astronaut training such as **VREVA (2024)** for Extravehicular Activities in VR, **VR-OBT (2024)** as Virtual Reality for On-Board Training, or **LUNA-XR (2025)**, a VR experience in the LUNA Analogue at ESA-EAC. The latest developments reflect a strategic pivot toward operational use: **Space XR (2025)** investigates how to mature the use of Extended Realities in Space and planetary environments, while **XR Devices (2025)** focuses on bringing interaction tools that, combined with XR headsets, can bring new levels of immersion. ESA also has capabilities and frameworks for developing immersive scenario-based content that can support narrative immersion and aid in human-computer interactions.

XR Technology Landscape

Current XR technologies have reached varying levels of maturity, from well-established VR platforms to emerging AR and MR solutions.

VR headsets have advanced significantly with high-resolution displays, improved motion tracking, and better user comfort, supported by powerful computing systems. **AR and MR**, however, are seeing faster innovation due to lighter, more portable devices such as AR glasses and mobile AR apps. These technologies are increasingly integrating spatial mapping, gesture recognition, and real-time environmental interaction, though challenges such as battery life, processing power, and user comfort remain.

It is crucial to acknowledge that the future of XR doesn't rest solely on headsets; a variety of **interaction devices** such as haptic devices, neural sensors, or eye-tracking tools are essential to enhancing virtual presence.

Emerging trends in XR technologies to monitor include the integration of **Artificial Intelligence (AI)** for real-time content generation, advancements in XR for **collaborative virtual workspaces**, and improvements in **wearable form factors**. AI is expected to play a major role in creating dynamically responsive virtual environments, personalizing user experiences, and enabling intelligent avatars.

Additionally, the shift towards standalone XR devices with less reliance on external computing power, such as **cloud-based XR**, promises to expand accessibility and usability. The incorporation of 5G connectivity will also enable smoother, faster, and more reliable experiences, reducing latency in XR applications, which is vital for real-time collaboration and immersive gaming. These developments will push the boundaries of XR in both enterprise and entertainment sectors.

In addition to the core XR technologies, several other fields are influencing the development and potential of XR. One significant area is **neurology and cognitive science**, where research into brain-computer interfaces (BCIs) is creating pathways for controlling XR environments directly through neural impulses. This could revolutionize how users interact with virtual worlds, bypassing traditional input devices altogether.

The field of **materials science** is also playing a crucial role, with innovations in light, flexible, and responsive materials leading to more comfortable and durable XR devices. For instance, advanced optics and display technologies are enhancing the visual experience by improving brightness, contrast, and field of view.

Furthermore, the integration of **biometric sensors**—such as heart rate monitors, EEG headsets, or eye-tracking technology—into XR systems could enable more personalized and adaptive experiences, where the system responds to the user's emotional state or cognitive load.

In **robotics**, XR can be further used for teleoperation and remote control, where real-time 3D visualization and interaction with robotic systems enhance precision and efficiency.

Moreover, advancements in **electronics**, such as flexible and lightweight materials, could lead to more comfortable and durable XR wearables, while **force-feedback technologies**, like exoskeletons, could further simulate physical presence in virtual environments.

These cross-domain synergies will shape future XR applications, making them more adaptable, immersive, and applicable, also for the Space sector.

XR Lab explores the use of VR for future lunar missions inside the ATLAS analogue spacesuit.

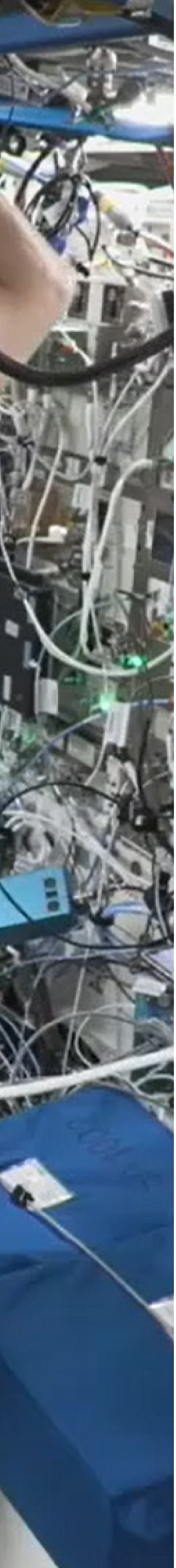
PROJECTS

ESA has already executed **more than 80** activities and initiatives on XR topics. More details can be found in Nebula[1] or by contacting ESA XR email[2]. Some of the most relevant are included in the following table.

Year	Short Name	Full Name	Description
2008	PVAITV	Portable Virtual AIT Visualizer	Development of an AR system to support AIT/AIV operations using an HMD and IR tracking system, tested in ESTEC test center clean room
2008	MISSIVE	Multi-Purpose ISS Interactive Virtual Environment	VR platform for ISS used for outreach and dissemination
2008	WEAR	Wearable Augmented Reality	First AR application used in Space (ISS) using an ad-hoc ODF procedure and model-based tracking
2010	3D-PAT	3D Procedure Authoring Tool	Extension of NASA PAT tool to author 3D animated procedures, based on Rapid-Author from Cortona3D, used for ISS procedures
2012	GEV	God's Eye View	VR environment showing ISS and ATV docking phase, used for PR purposes and qualified for deployment at ATV-CC
2013	DECLARE	Augmented Reality enabled Collaboration	Remote real-time assistance for operations, tested in Erasmus User Center Columbus mock-up, using Unity and Meta HMD
2014	EdcAR	Engineering Data in Cross-Platform AR	AR Procedure viewer/Executor application with IoT capabilities, developed in Hololens
2017	HORUS	Holographic Wearable Display for Manual Assembly	Use of holographic technology in AR HMDs to produce virtual objects at the right distance, reducing visual fatigue
2017	MARVIN AR	Telemetry and Traverse simulation of a small rover in AR	AR application displaying rover telemetry to EVA astronaut, using Vuforia object tracking and Hololens
2017	VORTEX	Virtual Reality for Lunar Exploration	VR project representing lunar south pole surface for early depiction, science preparation, future operations, and training
2018	LSR AR	Complementary AR training system for LSR	AR device enhancing Life Support Rack crew training, tested at EAC, using markers and CAD-based solutions
2018	MOBIPV	Mobile Procedure Viewer	Modular network enabled application for an operator to use as an interactive electronic technical manual (IETM) browser
2018	NGV	Norut GeoViz	General purpose geospatial-enabled 3D globe displaying EO imagery, 3D models, point clouds, and elevation data
2018	VIPER	Visualization of Industry Processes in Enhanced Reality	Advanced industrial instruction manuals using AR with a mobile app, automating creation and offering interactive presentations
2018	JIVE	Joint Investigation for Virtual Reality Education	VR initiative in collaboration with NASA to complement classical robotics training for astronauts
2019	VR/AR Kickstart	Virtual and Augmented Reality Kick-Start	Support for companies developing VR/AR applications using satellite data, offering funding, technical guidance, and commercial support
2019	GATEWAY4U	Remote virtual collaborative environment for Design Evaluation	VR tool using Unreal Engine, to simulate and improve LUNAR module design, tested with ESA astronauts
2019	PANGAEA VR	Collaborative VR Tool to support PANGAEA training	VR representation of Lanzarote analogue site for collaborative teaching, integrating point-clouds data and portable deployment
2019	AR-IoT	AR Surface exploration tool for geological support	AR-IoT tool allows astronauts hands-free geological inspections with data logging, photodocumentation, site mapping, verbal notes, and suit diagnostics.
2019	HLPV	Hololens procedure viewer	AR application using CAD recognition to support procedure viewing.
2019	ARCE	Augmented Reality for Concurrent Engineering activities	Development of an interactive collaborative AR application for multidisciplinary design teams, tested in concurrent engineering design exercise
2019	AROGAN	Augmented Reality based Orbit and Ground Application	Extension of mobiPV system to support AR capabilities and creation of AR-based procedures for AIT/AIV activities
2019	VREVA	Astronaut training with Virtual Reality for Extravehicular Activities	VR for EVA focused on a teaching tool to familiarize the user to EVA in terms of tools, suits, protocols... to complement NBF (Neutral Buyocy Facility) training
2020	EXOSUIT	Virtual Presence for Astronaut Training using VR and Exoskeleton	Usage of exoskeleton with VR to enhance Virtual Presence while doing EVA training, simulating motion restriction and haptic feedback
2020	VR OBT	Virtual Reality On-Board Training	Technology demonstration for effective ways to deliver on-board training to astronauts through virtual reality
2020	VR EXERCISE	Enhance crew training on CEVIS via VR	VR enhancement for CEVIS exercise on ISS, providing city or landscape views
2020	PILOTE	VR neuroscience experiment applied to remote robotics	VR experiment for remote robotics neuroscience, enhancing operator control and decision-making

1 https://nebula.esa.int/
2 xr@esa.int

Year	Short Name	Full Name	Description
2020	VARIAS	Virtual and Augmented Reality for Industry and Space	Extension of VIPER tool for VR training on crew operations, supporting procedure generation
2020	VIRWAIT	Virtual Workplace for AIT	Extending AROGAN to support AIT/AIV via sensor placement, config tracking, CAD updates, and remote access.
2020	VOGUE	Zero-G simulator inside photorealistic ISS	Model and simulation of navigation in Zero Gravity using VR for astronaut IVA training.
2021	MSR Surface VR	Represent MSR landing surroundings in VR	VR reconstruction of Perseverance rover surroundings, supporting outreach and science, with real-time terrain model updates
2021	Robotics Gesture Control	Demonstrate usefulness of multimodality	Prove usage of gesture and voice commanding system for robot control, comparing performance and user friendliness
2021	ARVR4GS	AR/VR for Ground Station maintenance and Telescopes	AR/VR support for remote maintenance tasks in Ground Stations and Telescopes, reducing physical presence requirement
2021	AR/VR4MO	AR/VR supported Mission Operations	Specification of scenarios for AR/VR adoption in spacecraft operations, identifying meaningful application areas
2021	ARVRAI	AI aided AR/VR applications and VR aided ML	AI techniques optimizing data feed into AR/VR/MR environments, enhancing visual precision and user experience
2021	ARVR4S2P	AR/VR for Space Safety Programme	Visualization of Space Safety Programme data using AR/VR, providing immersive experience and contextualizing results
2021	DTUP	Digital Twin Urban Pilot	Digital Twins of Frascati and ESRIN site, enriched with data sources for urban mobility and city planning
2022	X-ARM	Force-Feedback Device to Train Future Astronauts with XR	Combination of force-feedback and XR for astronaut training, increasing TRL of exoskeleton prototypes
2022	DT PHILAB	Digital Twin Philab	Digital Twin of Philab building, fully experienceable in VR
2022	LIGHTFIELD	Lightfield-enhanced immersive teleoperation system	Integration of lightfield data into XR environment for immersive teleoperation
2022	VIOLA	Virtually Increased Operational space for Lunar rover simulations	Rover simulation space using augmented reality, continuing simulation virtually beyond physical boundaries
2022	MARA	Medical Augmented Reality Assistant	AR application supporting astronauts during medical procedures, focusing on ECG and extending to multiple procedures
2022	SCIFLEET MUSEUM	VR of the science fleet spacecraft models in a virtual museum	VR visualization of science fleet spacecraft models in a museum-like setup
2023	MUSE	Modular User-centred Spaceflight Experience	Virtual spaceflight experience onboard conceptual spacecraft Human Inspirator, studying spacecraft design and situational awareness
2023	VETRA	Virtual Environment Training for Robotic Arms	VR training simulator for KUKA robotic arm, exploring suitability of Godot game engine for VR
2023	GUARDIANS OF EARTH	VR and MR representation of the HERA mission	VR experience of Hera's mission, accessible to anyone with VR devices, featuring narration by Brian May
2023	GRAVITAS	Gateway Review And Virtual Interior Tool for Astronaut Systems	VR/MR environment for Lunar Gateway interior design, addressing ergonomics, habitability, and safety
2024	LARS Sim	LARS Sim	XR simulation infrastructure in the cloud for multi-variable optimizations
2024	MUSE Journey	The Journey onboard MUSE spacecraft	Short narrative VR experience for public outreach, simulating lift-off, flight, re-entry, and splashdown
2024	EXPOSE	EL3 eXPerience Operations Simulation Environment	VR for lunar surface operations, mapping telemetry directly into VR simulation
2024	IMMERSEON	Immersive Visualization and Metaverse for EO	VR experience for flood modeling, integrating explainable AI capabilities
2025	PLUGIN	XR Lab Plugin	General purpose XR framework for Unreal Engine to streamline development efforts
2025	LUNA XR	Luna Analogue in Extended Reality	Digital Twin of the Luna Analogue, used for astronaut training
2025	ISDE	Immersive space design environment	XR prototype enabling intuitive collaboration, model editing, and visualization for early-phase mission design.



OBJECTIVES

The objectives of this document are aligned with ESA Strategy 2040:

1. Explore and discover: XR can provide realistic simulations of lunar, Martian, and deep space environments for training astronauts, mission planning, and public engagement, making complex scientific exploration more accessible and enhancing preparedness for space missions.

2. Strengthen European autonomy and resilience: XR can model and visualize space infrastructure, disaster scenarios, and satellite systems in real time, aiding in strategic decision-making, emergency response training, and improving situational awareness for secure and autonomous space operations.

3. Boost European growth and competitiveness: XR can accelerate design, testing, and collaboration in space tech development by enabling virtual prototyping, remote teamwork, and real-time simulation, reducing costs and time-to-market while attracting innovation and investment across the sector.

4. Protect our planet and climate: XR can simulate the impact of climate change and space debris through immersive, interactive environments, helping policymakers and the public visualize complex data and outcomes, fostering informed action and support for sustainability initiatives in space and on Earth.

5. Inspire and engage: XR can transform education and outreach by offering immersive learning experiences that inspire future talent, increase public engagement with space initiatives, and build widespread support for Europe's role in the global space landscape.

More specifically, the ESA XR Strategy is intended to support the following key pillars:

1. Knowledge-transfer: Provide a comprehensive and up-to-date analysis of European and global initiatives in the field of Extended Realities, highlighting key developments, strategic priorities, and opportunities for collaboration or differentiation.

2. Needs alignment: Regularly update the use cases and conduct comprehensive studies to identify which XR features are most relevant and valuable across various space sectors, ensuring alignment with evolving industry needs and maximizing the impact of XR technologies.

3. Optimize resources: Promote the adoption of a common, modular and interoperable XR framework that provides a foundational set of tools to streamline efforts by European companies, drive innovation, reduce redundancies, and enhance overall efficiency.

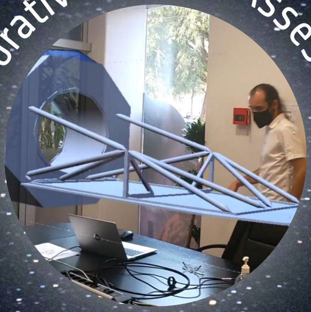
4. Strategic coordination: Establish a shared European roadmap for XR development in the space sector to align strategic goals, coordinate research and innovation efforts, and ensure coherent progress across stakeholders. This roadmap should serve as a reference point for public and private initiatives, helping to prioritize investments, avoid fragmentation, and accelerate the adoption of XR technologies.

Testing

Mission Planning

Digital Twin & Simulation

Collaborative Design Assessment



USE C

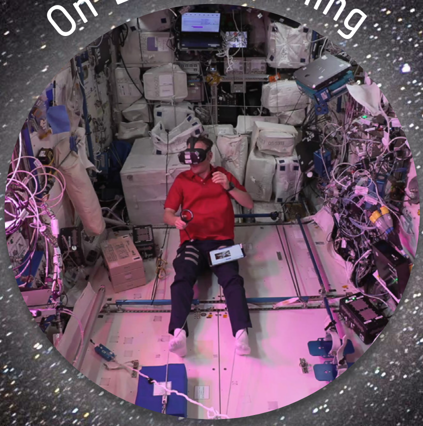
Medical training

Extravehicular Activities

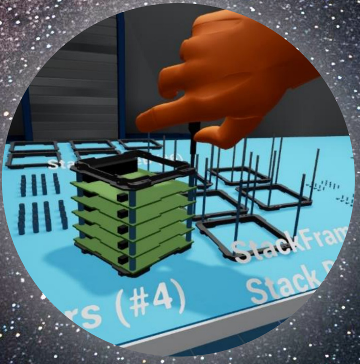
Robotics training

Training

On-Board Training



AIT/V



CASES

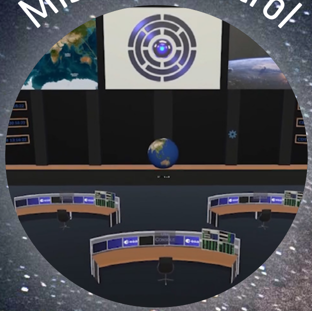
Operations Support

Earth Observation

Facility Maintenance

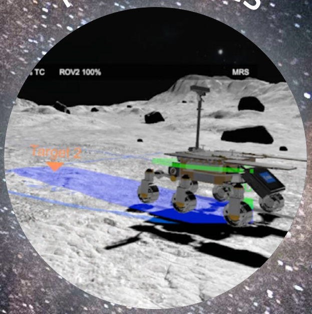
Visualization

Mission Control

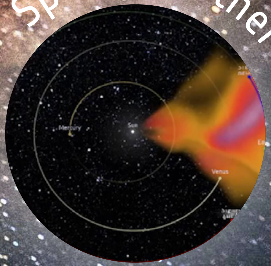


Remote Assistance

Telerobotics



Space Weather



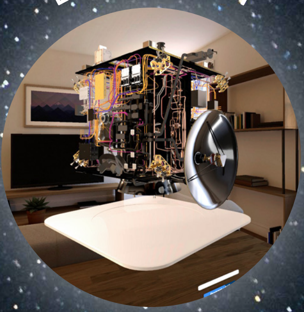
Outreach

Education

Research

Gaming

Divulgation



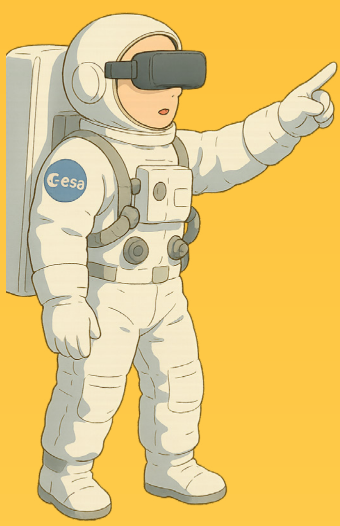
TECH NE

Some XR features need higher maturity to bring usefulness to Space endeavors. The following Table introduces sor organizations focalize their efforts and avoid redundancies.

BUSINESS WITH ESA

Companies or organizations willing to apply to ESA funding programmes can find more information at:

https://www.esa.int/About_Us/Business_with_ESA



Category	Feature	
Interaction	Digital Twin Integration*	Real-time XR interaction with sp
	Object localization	Detection and tracking of object
	Multimodal framework*	Monitoring and Orchestrator of r
	Virtual Presence	Merging multiple sensors and a
	Accurate Physics	Deterministic, accurate simulatio
	Accessibility	Ensuring XR is accessible for all
	AI assistant	Chat or voice assistant to guide
	Interfaces	Finding new ways to interact ar
	Adaptive learning	Set of tools that obtain learning
Infrastructure	Internet of Things	Framework to connect XR with
	Cloud rendering	Stream visuals from remote serv
	Procedure AI generation	Automatic creation of procedure
	XR hardware for Space*	Mature XR headsets for their us
	Cross-platform	Make XR applications compatibl
	Connectivity and Security	Use communication and data en
Standardization	Procedure format	Harmonised format to exchange
	Procedure authoring	Capability of creating procedures
	Procedure visualization	Unified representation to display
	Robotic-XR standards	Full integration with ROS for tel
	Multimedia Standard	Common framework to take and
	XR Character Standard **	Common, modular and open-sou
	Instructor tools **	Provide supervisors with a set c
	Replay tool **	Allow the recording and visualiz
	Metaverse Standard **	Allow multiple users to connect

Important — Desirable — Optional

EDS

me of these features to guide European companies and

COMMON TOOLS

As of 2025, ESA typically uses common tools and standards to streamline solutions:

- **Game Engine:** Unreal Engine 5.6
- **XR Framework:** OpenXR
- **HMD:** Meta Quest 3
- **Workload analysis:** NASA-TLX
- **Situational awareness analysis:** SAGAT
- **User Experience**: System Usability Scale

Description	Priority			
	Digital Twin & Simulation	Operations Support	Training	Outreach
pacecraft or hardware digital twins				
s for automatic verification in MR				
multiple stimuli in XR				
ctuators for enhanced immersion				
ons in real-time in XR				
individuals, including those with disabilities				
through XR experiences				
nd engage with content in XR				
analytics and customize training in XR				
other devices, sensors or databases				
vers, reducing processing demands locally				
s from models or text				
se in microgravity or planetary environments				
e with desktop or mobile and viceversa				
ncryption standards to connect in XR				
procedures				
s with visual scripting (no-code authoring)				
y and navigate in procedures				
eoperation of robots in XR				
view text, image, video or voice notes in XR				
urce XR Character to streamline efforts				
of tools to monitor and teach users in XR				
ation of previous XR sessions				
seamlessly and remotely to a virtual space				

*These features have been pushed in current ESA funding programmes

** These features are included or planned to be released in the Open Framework (see next Section)

DEVELOPERS

The **ESA XR Plugin** it is an optional tool made for European organizations and developers with the objective of streamline efforts, avoid redundancies, and allow a deeper focus on pushing state-of-the-art solutions in Extended Realities for Space applications. This plugin proposes a modular, building-blocks solution that allow organizations and independent creators to contribute.

Features

- XR Lab Character: A versatile and customizable pawn tailored for XR applications, incorporating modular components that facilitate various functionalities like walking, grabbing and interaction.
- Locomotion modes: A list of different ways to navigate in Space environments.
- Multiplayer support: Having multiple users collaborating in the same virtual environment for the Metaverse.
- Procedural gripping: Realistic hand-object interactions.
- (Upcoming) Instructor tools: Third-person visualization to interact with the users for education purposes.
- (Upcoming) Replay: Functionality to record and visualize past exercises.
- (Upcoming) Notes: Taking text, voice and multimedia annotations during runtime.

How to install?

The plugin can be found together with installation and documentation guidelines in the following repository:

Link Coming Soon...

Based on open industry standards

The plugin is made for Unreal Engine 5.5 (latest version, 2025). The plugin is based on other public sub-systems:

- Open XR[1]: royalty-free, open standard that provides high-performance access to XR platforms and devices.
- VR Expansion Plugin (VRE)[2]: a powerful and modular plugin with advanced locomotion or grip interaction systems.
- Advanced Sessions Plugin[2]: it enables more control over multiplayer sessions, friend invites, voice chat integration, and exposes many useful nodes to Blueprints.
- Mimic Pro[3] (Optional): Inverse Kinematics System for full body with automatic adjustable sizing.

How to contribute?

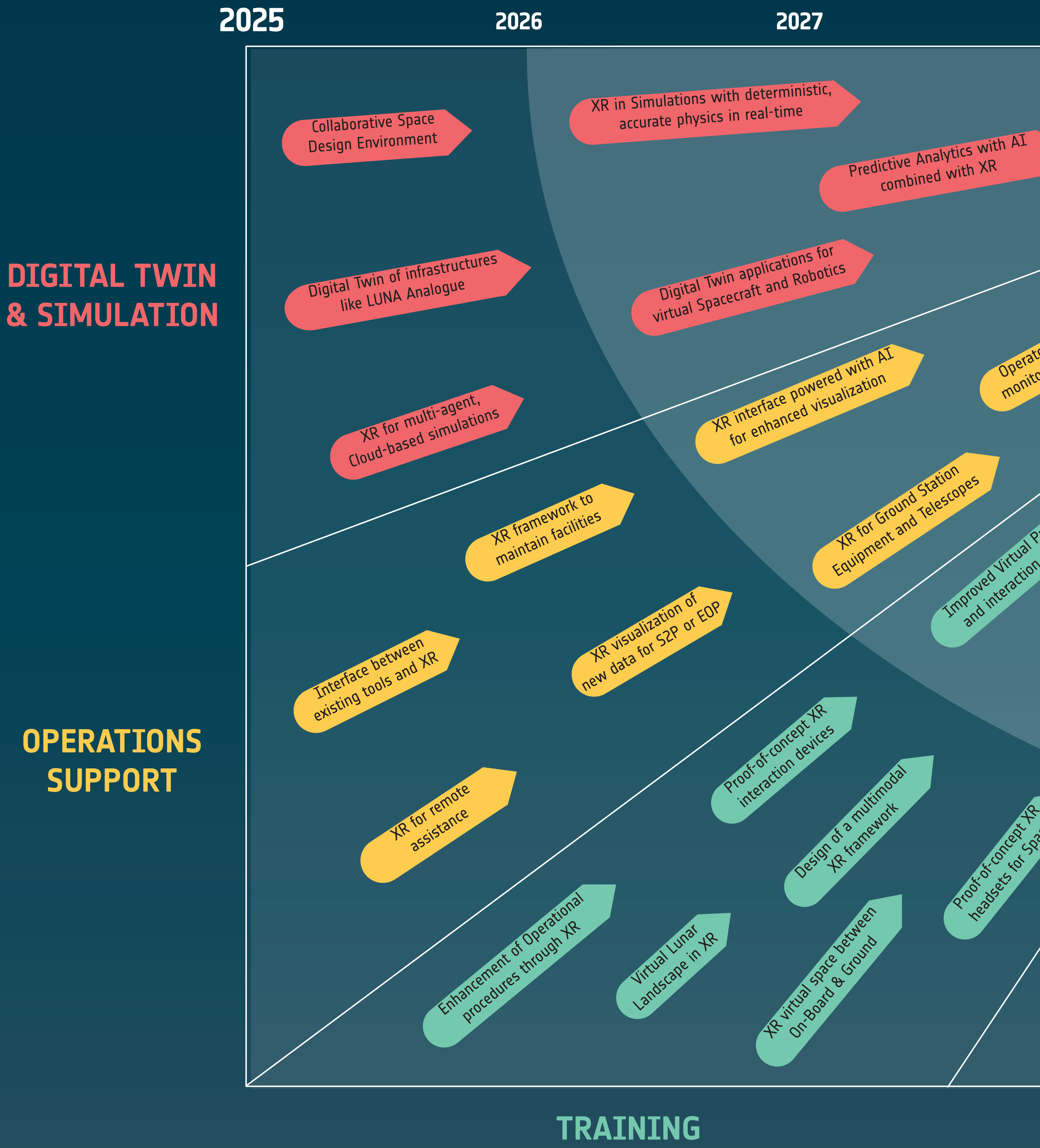
Any individual or organization wishing to contribute to XR for Space are invited to contribute to this package by creating components, submodules or plugins that inter-connect with it. Contributors will be able to publish these plugins in Fab[4] linked to the XR Lab Plugin, retaining their own Intellectual Property and commercialization rights.

1 https://www.khronos.org/openxr/
2 https://github.com/mordentral/VRExpansionPlugin
3 https://jakeplayable.gumroad.com/l/MimicPro
4 https://www.fab.com/

Representation of AXIOM model (credit: Albin)

ROADMAP

The following roadmap describes the vision of ESA towards the use of Extended Realities in the European Space secto



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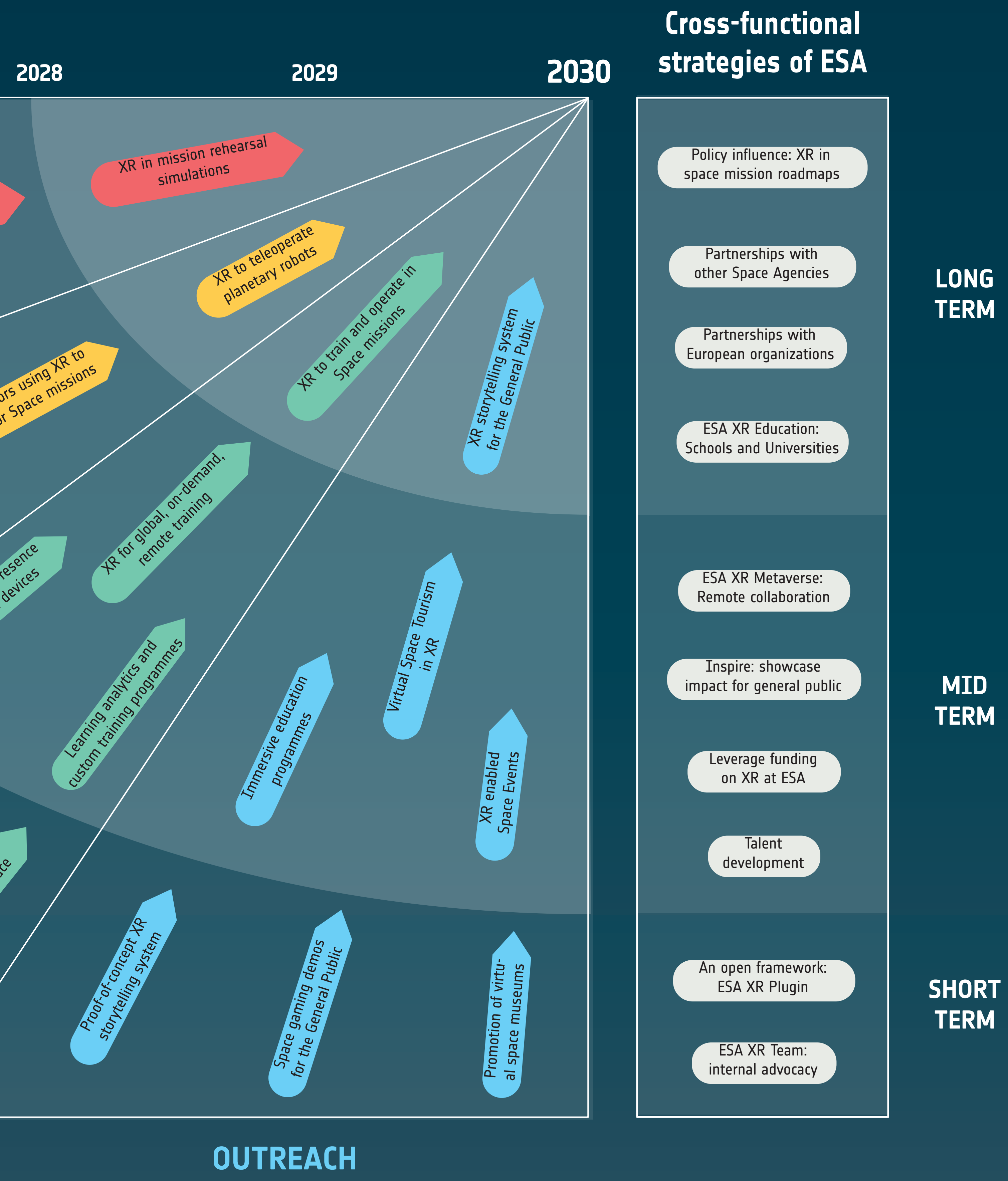

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