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Augmented and Virtual Reality Supported Mission Operations, Executive Summary Report

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Record of Changes

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	First Released Version	1.0	2022-11-29
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1 Introduction

1.1 Purpose

This document contains the Executive Summary Report (ESR) of the “Augmented and Virtual Reality Supported Mission Operations” study.

1.2 Scope

This document contains the summary of the accumulated output of the entire activity.

1.3 Application

The aim of this document is to provide a quick overview of the information accumulated about the activity in a single document.

1.4 References

Table 1 Table of References

Doc. No.	Title
ESA-DOPS-STU-SOW-0019	Augmented and Virtual Reality supported Mission Operations
TER/SPA/PRO/20/71867	AVRMO – Augmented and Virtual Reality supported Mission Operations; Detailed Proposal: Technical Proposal Part
AERG	Impact of Improved Ergonomics, Collaboration, and HCI in Ground Operations: The AERG Study at ESOC
AVRGST	Augmented and Virtual Reality Support Tool for Ground Station Equipment and Telescopes, Statement of Work, ESA-DOPS-STU-SOW-0022

1.5 Definitions

Table 2 Table of Terms and Definitions

Term	Definition
AR	Augmented Reality
EUD	EGOS User Desktop
MR	Mixed Reality
NEO	Near Earth Object
PoC	Proof of Concept
TC	Telecommand
TM	Telemetry

Term	**Definition**
UI	User Interface
VR	Virtual Reality

2 Study Context

The overall high-level context in which this activity is situated in is the incentive to improve ESAs space operations with the help of Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). VR/AR/MR offer promising features that appear to have the capability to improve space operations in various areas.

In the context of its precursor activities [GPGPU, AROPS], we consider the current activity as the next step in the direction of the practical application of AR, VR, and MR in real-life application scenarios for spacecraft operations etc. at ESOC. The focus is on ESOC application scenarios, more concrete applications, and going towards more practical solutions.

From our perspective, the most important high-level objectives of the activity are summarized in Table 2-1. We consider that the most important emphasize is that the work shall aim towards adding real value to day-to-day application scenarios.

Table 2-1 Activity Objectives

Id	**Objective**	**Summary/Analysis**
O-1	Find Meaningful Application Areas that Bring Value	"… find **meaningful application areas**, where AR or VR could **bring value** (**beyond the PR and nice to have**) to the way operations are planned, simulated, validated and eventually executed." [SoW, p. 10]
O-2	Operational Use	"… put AR/VR in **operational deployment** for satellite operations." [SoW, p. 10]
O-3	Add Real Value to Day-to-Day Tasks	"… identify use cases, where the adoption of AR/VR is seen as **adding real value** to the operational team, hence integrated in their **day-to-day tasks** execution." [SoW, p. 10]
O-4	Go Beyond "Eye Candy"	"… **surpass the "novelty" and "PR-effect"** …" [SoW, p. 10]

The activity is split into two high-level phases:

- Conceptual
  During the conceptual phase, the focus is on gaining conceptual insights and gathering information. Information that is gathered includes, e.g., collection and processing of use case ideas, survey of technologies, etc.
  Activities performed in the conceptual phase included:
  - Use Case Identification and Analysis
    Use case ideas were derived from, e.g., workshops with ESA staff, analysis of previous activities, and inputs to the activity such as the Statement of Work and the proposal. These inputs were further analysed and consolidated to

establish increasingly concrete and actionable use cases and derive requirements.

  - Technology Assessment
    The technology assessment considered AR/VR technologies and ESA systems. The capabilities of the available technologies had direct feedback on the feasibility of use case ideas and vice-versa use case ideas had a direct impact on what functionalities are required.

- Practical
  In the practical phase, a Proof-of-Concept (PoC) is implemented in an iterative process. For this phase, the first phase established the foundation. However, the practical phase itself is further executed in an agile-like approach such that new insights can also be included and considered.

During the study, the above sections were maintained in technical notes TN-001 to TN-003. This document combines the technical notes with the aim on providing a self-contained single document.

3 Use Case Ideas

In this section, the focus is on the use cases collected and discussed during the workshop, as during this activity is where we identified the most relevant use cases for our users. However, we also present here the use cases collected from the statement of work, during the writing of the proposal or in preparation for the workshop as these use cases have had a significant influence on what was presented and discussed at the workshop.

3.1 Use Case Input from the Activity etc.

As part of Task 1, further use case identification and ideation was to be performed. We collected use cases by establishing the following channels:

- In the “Kick Off” meeting, we invited all participants to send us any ideas, suggestions or feedback they might have.
- Use Case ideas collected in preparation for workshop
- We organised Workshop 1; 15 users attended, and their ideas were collected and further analysed.

Ideas are summarised in the following table:

Source	**Area**	**Ideas**
External Suggestions	Concurrent Design Facility (CDF)	- Mission Analysis (trajectory visualisation, eclipses, occultations, formations, etc.) - Structures and Spacecraft Configuration - Mission Timeline Planning Concept and Analysis
Preparation for Workshop Workshop 1	Remote support	- 360 Camera behind Spacon to look over the shoulder from remote (with your headset). Optional addition: If Spacon wears a HUD or HoloLens, he can see where observer is pointing. - A virtual meeting space for a team (i.e. for collaborative training).In training cases, show positions of subsystems, harness. Support operations procedures testing and AIT. - Virtual mission control room for remote work - AR remote access for experts
	Virtual Spacecraft	- AR/VR applications that interact with normal 2D applications. some users work on 2, others can use 3D - 3D twins to observe solar array wing and payload deployments for training and procedure validation. Also augment with real TM during online ops - enhance S/C safety in anomaly investigation (overlaying of anomalous TM on the SC) - Monitoring of collision avoidance, probabilities, manoeuvres - 3D model generation with mobile devices/iPads. real TM interface to models (that one was yours) - 3D MIMICS (display of complex data in the 3D environment)

Source	Area	Ideas
		- Observations planning (seeing the historic trail / ground track of the instruments on the surface in a 3d globe). - Observe the earth from the perspective of an instrument in a 3D environment (see planned paths, path that might cross from another object, magnetic fields, etc). - Execution assistant: 3D model of the effect the execution of a procedure will have on the S/C. - Satellite in orbit and interaction in VR/AR (zoomable to subsystem and unit level of the SC. anomalies can be marked or colour coded. Quick health overview, Out-of-Limits (OOL)). could also model entering into radiation zones, relative position to sun
	Other	- (HUD, like google glass) - Guided console procedures, augmented with additional information to the procedures (AR in the mission control room) - Virtual Engineering model during testing, augmented with injected or real parameters. - MPS data scheduling or re-scheduling - Mission specific animations (i.e. Rosetta approach to comet, project high res original images on model
	3D Planning	- Observe the earth from the perspective of an instrument in a 3D environment (see planned paths, path that might cross from another object, magnetic fields, etc). - 3D Planning: Seeing the historic trail / ground track of the instruments on the surface in a 3D globe - Sat Visibility on a ground track on the virtual globe
	3D Content	- Mission Specific Animations - Virtual Engineering model during testing, augmented with injected or real parameters - 3D modelling during Mission Review Boards (MRBs) - For critical operations (to help operators and for PR purposes): show overlay of critical activities (launcher ascend, solar array deployment, thruster firing,etc.) - "3D Twin", e.g.: observe solar array wing and payload deployments for training and procedure validation - Procedure Execution Assistant: 3D Model of the effect of the execution of a procedure will have on the s/c - "3D Mimics": Display TM on 3D Spacecraft Model - Visualisation of Spacecraft Orbit Information (Attitude, Orbit, Thrust/Force Vectors, etc.)

Source	**Area**	**Ideas**
		- Integrated Digital Twin in MCS and SIM: 3D CAD/CAE data being live updated by TM data, allowing ad-hoc predictions / simulations - 3D view of a spacecraft, with parameters aggregated to the current viewing level (overall system status, zoom in on specific subsystems, all the way down to individual parameters).
	Remote Support	- Virtual meeting space for a team, e.g., for collaborative training - Virtual mission control room for remote work - Training for hardware installation (e.g. NDIU). - Remote assistance of local operators from experts far apart - 360 camera on operator in a ground station for visualisation at ESOC - 360 Camera behind Spacon to look over the shoulder from remote - Augmented Control Room - wearables with relevant information shown to the operators (HUD, like google glass) - Remote Support "AR/VR Telepresence" - AR Maintenance: Telescope (at remote places) maintenance by non-trained staff - AR for remote support by, e.g., on-call engineers to people in control room, or station engineers to people installing equipment on-site
	Virtual Data Systems Assets	- Generic idea: display information as overlay that is currently hidden in documents or systems (e.g. during LEOP, which chain is a client connected to, which machines are affected by an outage, where do I have to go in case of outages) - Virtual Data Systems Assets. Monitor and navigate through networks, servers/clients and their status and performance. *somehow*
	Virtual Tours	- Not a 3D model but a 360 Virtual tour of buildings and sites (ground stations)
	Near-Earth Objects (NEOs)	- Collision Avoidance Analysis & Planning: Stereoscopic Display, e.g., see Collision Probabilities; What-if Analysis for Actions - Visual collision probability - NEO: impact probability; impact effects visualisation - Meteoroid streams visualisation - NEO, orbit visualisation - Near-Earth Object Visualisation & Analysis

Source	Area	Ideas
	3D Antenna Model	- create for example a 3D virtual model of an antenna so that we can better see the condition/situation of the various elements.
	Mission Planning System (MPS)	- MPS data scheduling or rescheduling
	3D graphs	- 2D schematics projected into 3D - e.g. redundant units appear "behind" prime units in a block diagram.
	Ground Station Mapping	- Planning of new cabling installation at remote sites

3.2 Other Sources of Use Case Ideas

3.2.1 Use Case Input from the Proposal

In this section, we present the first iteration of the analysis of use case scenarios for the adoption of AR/VR/MR which was first presented in the technical proposal for this project. For the sake of brevity, we focused on scenarios that we considered as most in line with the overall scheme of the activity to develop solutions that add value to real-world use cases:

- “3D Mimics”
  The idea is to provide 3D content “Mimics” similar to already existing 2D Mimics:

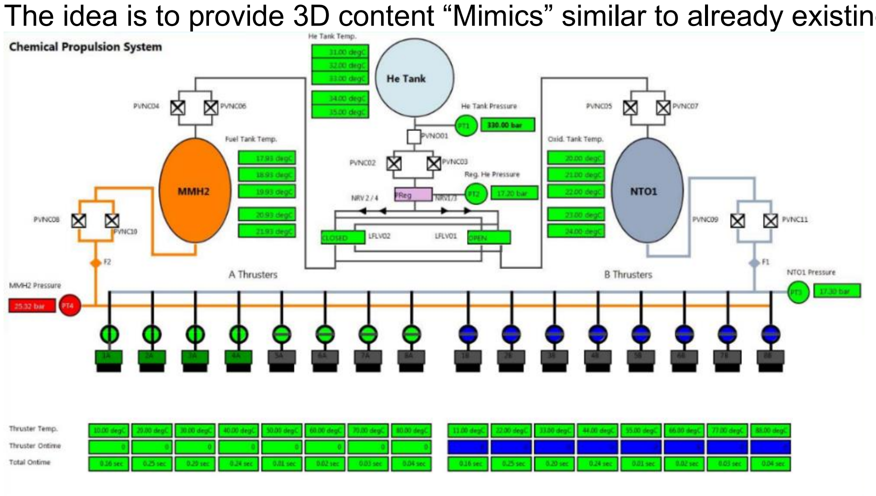


Figure 3-1 EUD 2D MIMIC Showing Internal Schematics of the Gaia Spacecraft[1]

[1] https://gsaw.org/wp-content/uploads/2014/03/2014s12b_schutz.pdf

- Remote Support

Figure 3-2 Remote maintenance procedures with linked experts.

- Collision Avoidance Analysis and Planning

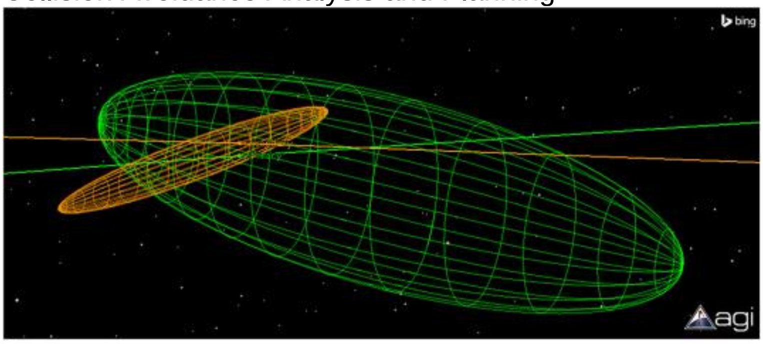


Figure 3-3 Spacecraft Collision Analysis with Ellipsoids to Indicate Probable Spacecraft Positions[2]

- Visualisation of Manoeuvres
- Near-Earth Objects (NEOs) Visualisation and Analysis

3.2.2 Related Activities at ESA

Preceding this activity, ESA has performed a number of AR/VR/MR studies that we have used in order to tailor our approach either by avoiding paths which have been previously taken and already concluded, avoiding use cases that have previously been shown as limited in any shape or form or exploring avenues which have previously been successful to a higher detail. These studies are mentioned here for reference purposes only:

- **Advanced Ergonomics on HCI for Satellite M&C (2013)**
  The [AERG] study examined ways in which Human Computer Interface (HCI) technology may evolve to support spacecraft operations in the following five to ten years.

[2] https://www.sciencedirect.com/science/article/pii/S0094576518304491

Figure 3-4 (Left) The demonstrator physical console; (Right) Visualization of a collaboration scenario with the UDC

- **GSTP - Application Domains for Virtual Reality in Ground Data Systems (2017)**
  "The aim of this study was to explore the potential of modern VR technologies, to identify and analyse application scenarios in the area of ESAs operations, and to investigate possibilities for integrating VR with ESAs ground system software, specifically a simulation system (SIMSAT) and the METERON surface operations mission control system (MOE). A PoC was implemented to gain hands-on experience and showcase the application of VR." [SoW]

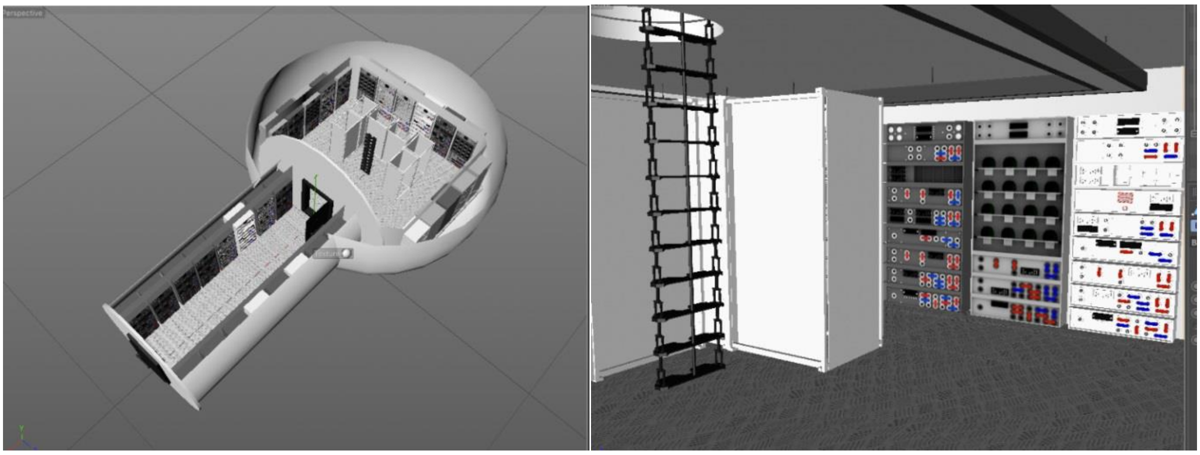


Figure 3-5 Example of the Exterior and Interior of the Virtual Lunar Base PoC

GSP - Augmented Reality Techniques to Enhance the execution of operational procedures (2018)
"The aim of this study was to explore the potential of modern AR technologies, to identify and analyse application scenarios in the area of ESAs operations, and to investigate possibilities for integrating AR with ESAs ground system software, specifically the METERON MOE surface operations mission control system. … The use cases chosen for the PoC were an interactive manual for ISS crew training and an AR/MR rover operations scenario." [SoW]

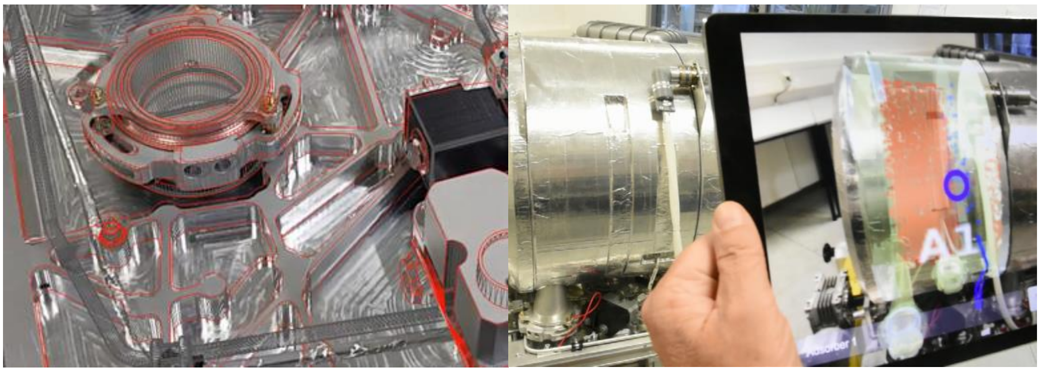


Figure 3-6 Model based tracking for ISS Crew Training and interactive visualization of processes

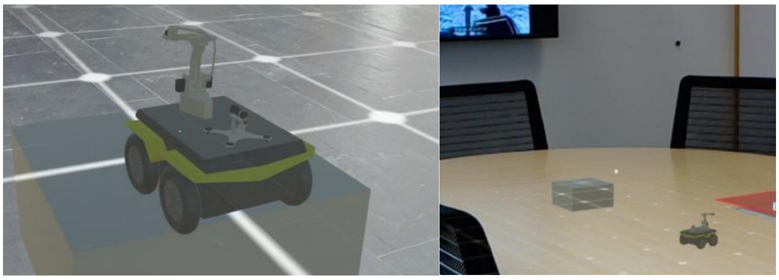


Figure 3-7 Virtual Rover in AR Full-size and downsized virtual Rover in "On-table" situation

- **Internal Study of Virtual Lunar landscape for Rover Operations (2018)**
  "As part of the ESOC Surface Operations framework and the METERON project, a Virtual Reality application was created to provide data and terrain visualization of a lunar landscape, rover, lander and surface crew…" [SoW]

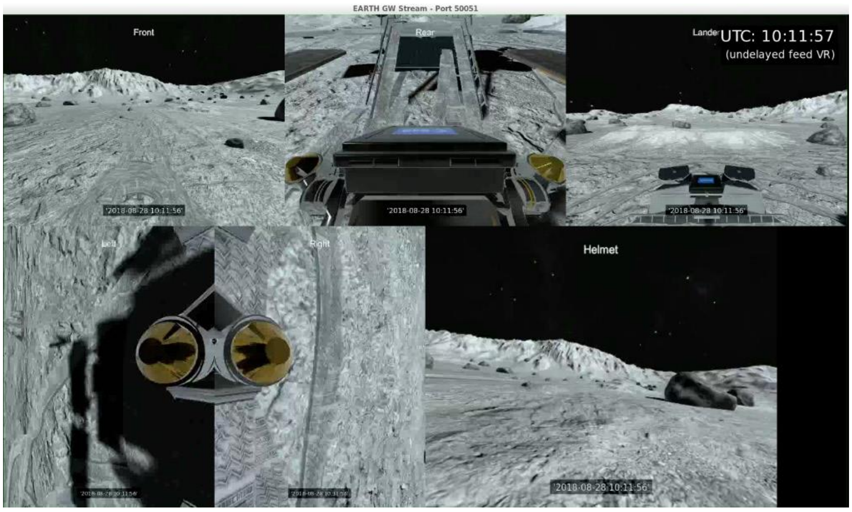


Figure 3-8 Rover on board video feeds streamed from VR to M&C system

- **Internal prototype of Google Glass for Mission Operations (2020)**
  "As described in the projects above, a set of AR and VR devices have been used in previous activities such as the HTC Vive VR headset and the Microsoft HoloLens (Gen 1) AR headset. In all those devices operators experienced certain eye fatigue and pressure marks after continuous usage of around 30-60 minutes. In order to experiment with less intrusive devices that might accompany operators more easily in control room environments, an ESOC internal assessment using Google Glass Enterprise Edition 2 is currently ongoing." [SoW]
- **Internal prototype of Virtual Reality in Support of Space Weather Forecasting (2020)**

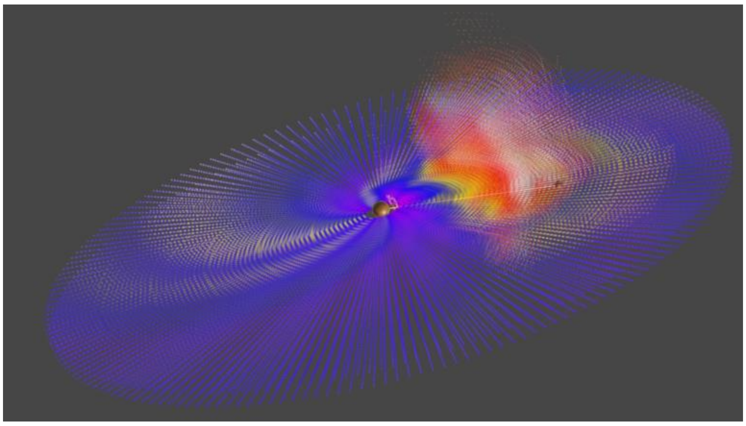


Figure 3-9 Visualization of Space Weather data in Virtual Reality

"A new approach for visualisation of Space Weather magnetohydrodynamic (MHD) model outputs is to use Virtual Reality (VR) (Figure 11). The aim is to be able to visualise the propagation of the plasma from a solar event as well as its interaction with background solar wind in a 3D environment, increasing knowledge about the propagation and unfolding of CMEs which pose a threat to human activities both on Earth and in space.

In an internal implementation, we aim at presenting 3D data in VR using a game engine." [SoW]

- **Ground Station Remote Maintenance (2022)**

Ground Stations and Telescopes are often in remote geographical locations. The local staff do often not possess the required specialization and/or knowledge to perform all tasks related to configuration, maintenance and operation of the hardware equipment. As a result, more experienced engineers must travel to the sites to perform the respective tasks.

4 Use Case Consolidation for Proof-of-Concept Development

Due to time constraints, a selection process needs to be executed on all the use-cases brought up in section 0, to be able to bring said use cases to a maturity in task 3 and 4 that would make them usable by the operators in their day-to-day work tasks.

4.1 Use Case Consolidation and Overview

From the use case ideas presented in section 2, we consolidate identifiable use cases. For each use case, we assign a unique id and a name. The name typically reflects the high-level use case area.

Table 2 Consolidated Use Case Overview

Id	Name	Comments
UC-01	3D Planning	Sub-cases: • Observe the earth from the perspective of an instrument in a 3D environment (see planned paths, path that might cross from another object, magnetic fields, etc). • 3D Planning: Seeing the historic trail / ground track of the instruments on the surface in a 3D globe • Sat Visibility on a ground track on the virtual globe
UC-02	3D Content	Sub-cases: • "3D Mimics": Display TM on 3D Model (S/C, Eng. Model) o Level-of-Detail (LoD) based on zoom, e.g., from system to sub-system levels. • "3D Twin", e.g.: observe solar array wing and payload deployments, thruster firing, etc. (e.g., for training, procedure execution & validation, PR) • Visualisation of Spacecraft Orbit Information (Attitude, Orbit, Thrust/Force Vectors, Instrument Pointing, ...) • Mission Specific Animations - Rosetta approach to comet, project high resolution original images on model • 3D modelling during MRBs • ~~Integrated Digital Twin in MCS and SIM: 3D CAD/CAE data being live updated by TM data, allowing ad-hoc predictions / simulations~~ (Note: this relates more to Model-based Engineering and its integration with MCS etc. instead of AR/VR. Because of this, this point is marked with strikethrough font to indicate that it is not applicable here.)

Id	Name	Comments
UC-03	Remote Support	Sub-cases: • Virtual meeting space for a team • Virtual mission control room for remote work • Training for hardware installation (e.g., NDIU) • Remote Support "AR/VR Telepresence" • Live 360 camera on operator in a ground station for visualisation at ESOC • Live 360 Camera behind Spacon to look over the shoulder from remote • Augmented Control Room - wearables with relevant information shown to the operators (HUD, like google glass)
UC-04	Virtual Data Systems Assets	Sub-cases: • Generic idea: display information as overlay that is currently hidden in documents or systems (e.g. during LEOP, which chain is a client connected to, which machines are affected by an outage, where do I have to go in case of outages) • Virtual Data Systems Assets. Monitor and navigate through networks, servers/clients and their status and performance. *somehow*
UC-05	Virtual On-site	Sub-cases: • Not a 3D model but a 360 Virtual tour of buildings and sites (ground stations) • 3D video: the observer has no control over the space and is simply “walked through” a building • 3D 360° space: the observer can “look-around” a room in a building.
UC-06	NEOs	Sub cases: • Collision Avoidance Analysis & Planning: Stereoscopic Display, e.g., see Collision Probabilities; What-if Analysis for Actions, e.g., Delta-V • Visual collision probability • NEO: impact probability; impact effects visualisation • Meteoroid streams visualisation • NEO, orbit visualisation • Near-Earth Object Visualisation & Analysis

4.1.1 Workshop 2 Results

Workshop 2 was established to assess interest in the consolidated use cases.

Table 3 shows the results of a voting session done in the second workshop. For this vote, the workshop participants were asked to vote on what they consider the most important use cases. Multiple votes were allowed.

Table 3 Results of Use Case Voting

Use Case	**Votes**
UC-01 – 3D Planning	2
UC-02 – 3D Content	5
UC-03 – Remote Support (Will also be covered in AVRGST.)	4
UC-04 – Virtual Data Systems (May also be covered in AVRGST.)	2
UC-05 – Virtual On-site (Will also be covered in AVRGST.)	5
UC-06 – NEOs	2

The table also indicates which use cases will and may be covered in the parallel activity (AVRGST). This overlap is also considered for the selection to properly leverage synergies between both activities.

Based on the voting outcome and the relation to AVRGST, we consider that UC-02 3D Content is the highest priority use case as seen from the perspective of the user votes. As part of UC-02 3D Content, we also consider the Spacecraft Operations use case.

5 Mapping of Use Case Ideas to Technologies

In this section, we present a high-level mapping of use case ideas to technologies. The aim is to converge towards fusing the use case ideas with the available technologies.

With this mapping, we intend to achieve a better view on which use cases can be realistically implemented within the scope of this activity and which technologies are the best candidates for implementing the use cases. In addition, we consider that this view helps in optimizing the development efficiency, e.g., by optimizing re-use across use cases.

For the mapping, we start with the Use Cases identified during the use case identification. From the use cases, we derive “required functionalities” that are needed for addressing the use case. We then map the required functionalities to technologies that can be used for providing the respective functionality. Figure 5-1 shows an example for how we present this mapping in a graphical form.

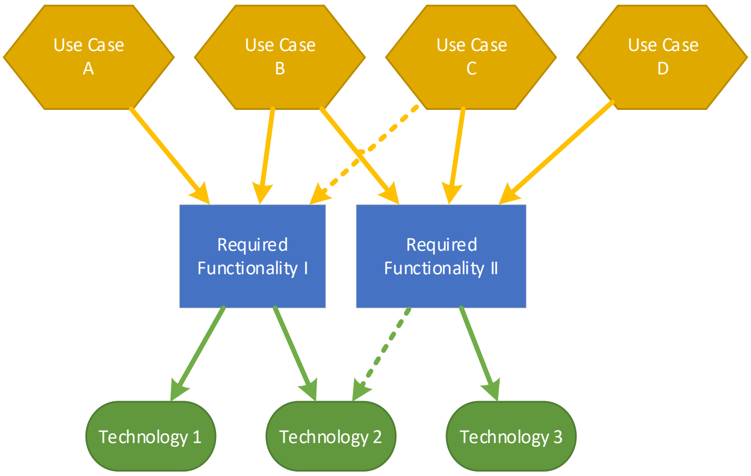


Figure 5-1 Use Case to Technologies Mapping Example

We performed these mappings for what we consider the core technological challenges in scope of this activity. Additional technologies etc. may be required. However, we limited the mapping to those aspects that we consider most critical to avoid unnecessary proliferation of this document.

5.1 3D/AR/VR Model/Content-related Aspects

To understand better how the use cases overlay in terms of AR/VR realisations, following diagrams have been created.

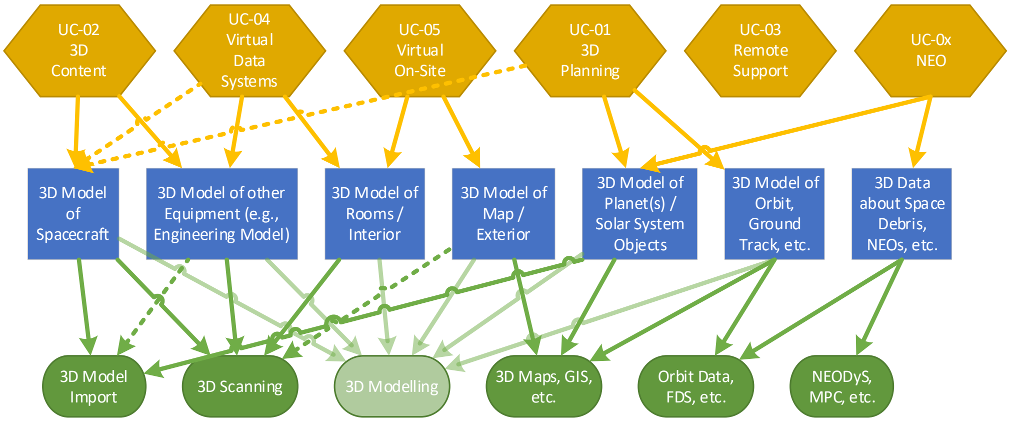


Figure 5-2 Mapping of Use Cases to 3D Models and 3D Activities.

5.2 3D/AR/VR Display-related Aspects

Figure 5-3 shows a mapping of use cases to 3D/AR/VR display technologies.

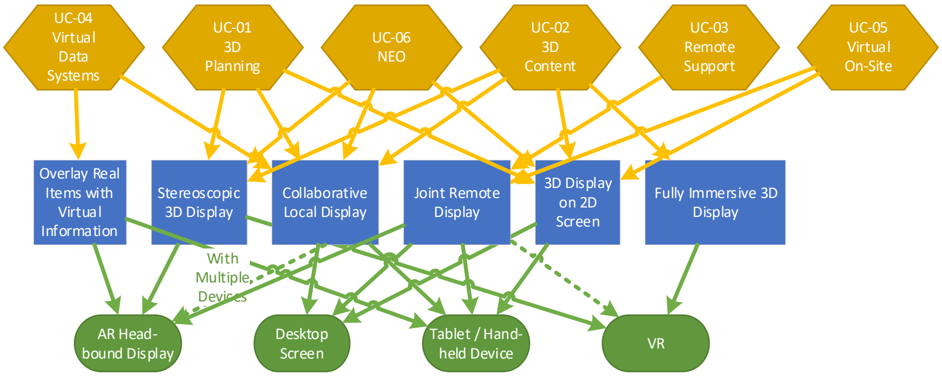


Figure 5-3 Mapping Use Cases to 3D/AR/VR Display Technologies

5.3 3D/AR/VR Interaction-related Aspects

Figure 5-4 shows an overview of mapping use cases to 3D/AR/VR interaction-related aspects. With interaction, we consider the user interactions with the 3D/AR/VR content or scene.

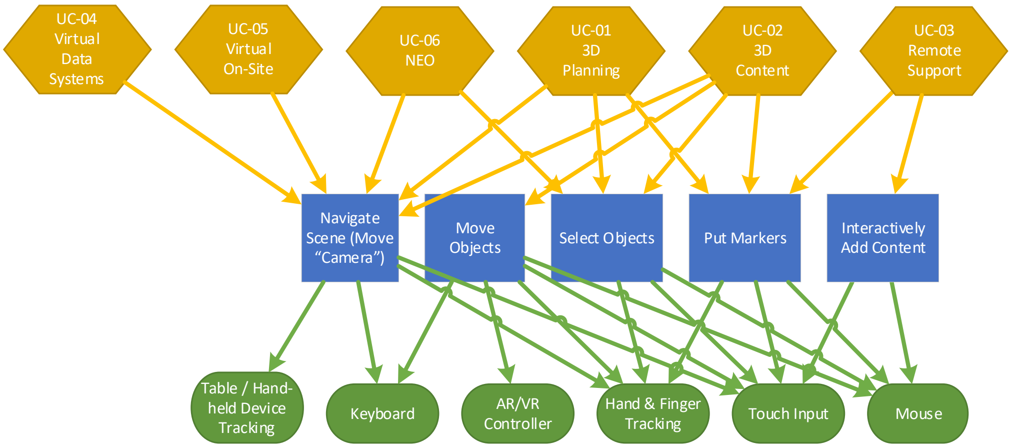


Figure 5-4 Mapping of Use Cases to 3D/AR/VR Interactions

5.4 Data Items / Data Source related Aspects

Figure 5-5 shows an overview of mapping use cases to data items and data sources related aspects.

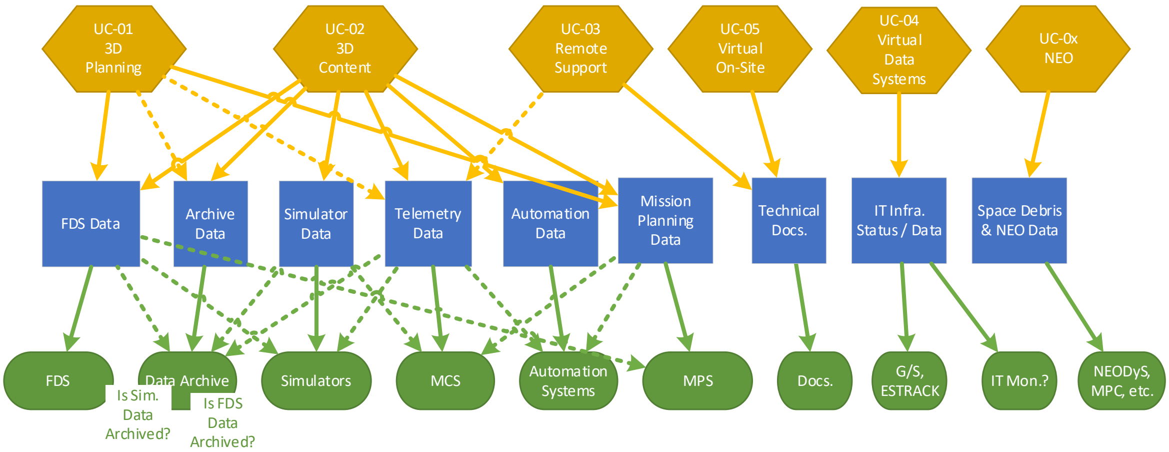


Figure 5-5 Mapping of Use Cases to Data Items and Data Sources

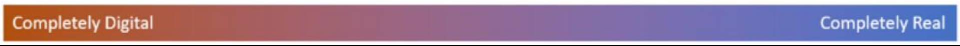
6 Virtual/Augmented/Mixed Reality

This section presents a technology assessment regarding Virtual/Augmented/Mixed Reality (AR/VR/MR) related hard- and software. In addition to directly related aspects such as 3D content creation, AR/VR/MR devices, or AR/VR/MR/3D run-times, this section also considers auxiliary or supporting aspects such as additional infrastructure that will be needed for deploying and using AR/VR/MR solutions in productive settings, e.g., repositories for content.

6.1 AR/VR/MR Devices

In this section, we present an overview of AR/VR/MR devices that we have considered for this activity.

Table 6-1 Device side-by-side comparison



Device	Vive Pro 2	Oculus Quest 2	HoloLens 2	Nreal light	Google Glass 2
Company	HTC	Facebook	Microsoft	Nreal	Google
Type	VR	VR/MR	MR	MR/AR	AR
Price	1260$	300$	~3500$	~1200$	999$
FOV	120°	90°	52°	52°	15°
Weight	850g	503g	566g	85g	46g
Hand tracking	x	x	x	x	

6.2 3D Content Creation

One important challenge we encountered in previous related activities was the AR/VR content creation. Aspects we found too complicated for day-to-day use were:

- Availability of 3D Models
- Annotating/Enriching/Linking 3D Models with Additional Data

6.2.1 Availability of 3D Models

Challenges we encountered regarding the availability of 3D models were, e.g.:

- IPR/License Limitations
- 3D Model Resolution
- 3D Model/File Formats
- Manual 3D Modelling
- 3D Model Structure

- Scaling
- Accuracy of 3D models

We encountered most of these aspects in different variations throughout our previous related activities. For this activity, we aim on providing solutions that help to mitigate these problems.

6.2.2 3D Scanning

The ease of coarse handheld scanning solutions enables users to create models in mere minutes. Often implemented as apps on mobile devices, or with the use of readily available sensors on PCs, these approaches provide usable results at moderate costs. Additionally, the applications are usually easy to use and therefore do not require special training or an exhaustive onboarding procedure.

Figure 6-1 shows raw 3D scan result from an iPad Pro scan. The left picture shows the untextured 3D model. The right picture shows the 3D model with the texture. The texture was also recorded and applied by the 3D scanning app as part of the scanning process.

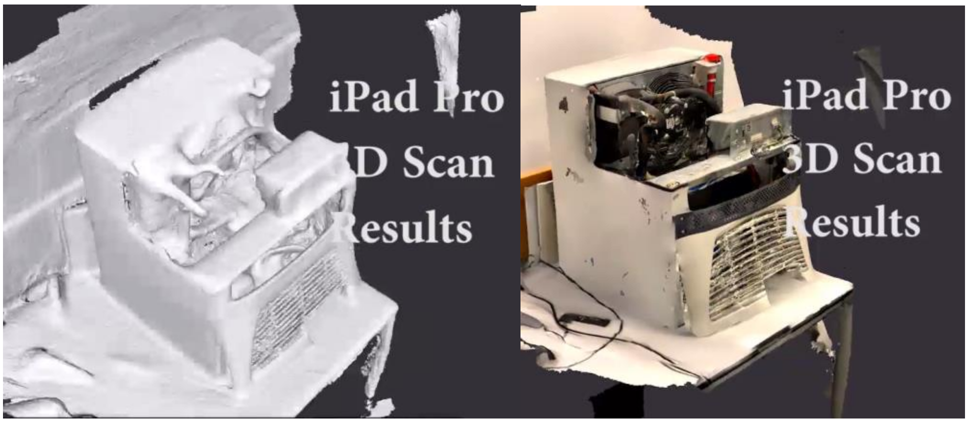


Figure 6-1 iPad Pro 3D Scan Results (Left: Untextured, Right: with Texture)

For this example, we used an industrial air conditioning device as object for 3D scanning. The object features various elements that can be considered to be posing challenges for a 3D scanning application such as internal details showing tubes, cables, etc. and something like a radiator cowling with a grating or grid-like structure.

6.2.3 Annotating/Enriching/Linking 3D Models with Additional Data

In addition to 3D models, it is important to annotate, enrich, or link 3D models with additional data, e.g.:

- For a 3D mimics (data display on top of a 3D model) use case, locations of data displays need to be defined.
- For manoeuvre planning use case the main axes of the spacecraft or its thruster need to be indicated in the 3D model.

6.3 Tracking Solutions for Augmented Reality

Tracking is the core technology for Augmented Reality as it registers position and orientation of the camera in real-time. In many AR-applications the following tracking approaches are used:

- Marker/image-based Tracking
- Sensor-based tracking
- SLAM (Simultaneous Localisation and Mapping)

6.4 Interaction within the AR Environment

The interactions for the trainer/trainee in an AR/VR/MR environment will depend on the selected scenarios. The interactions may be, e.g.:

- Grabbing objects of interests (OoI)
- Rotating, Moving, Releasing OoIs
- Displaying details of OoIs
- Displaying details of point of interests (PoI)
- Walkaround environments and inspection scenarios in order to detail other PoI/OoI and trigger additional information

6.5 AR/VR/MR/3D Runtime

Unity3D still is valid choice for this activity, since all of the hardware options in the closer selection are supported.

Another widely supported alternative is epics unreal engine, which by now also supports most of the relevant platforms. It bring’s a more favourable license model (free for internal use, royalties for successful of the shelf products), but requires the developers to train for the platform.

7 Implementation Building Blocks / Modularity

7.1 Concept

In order to maximize the output regarding how many or how deep use cases can be covered, we intend to apply a somewhat modular concept. The aim is to re-use whole or parts of implementations across multiple Proof-of-Concept (PoC) implementations.

With modularity, we do not mean a rigid system with strictly defined interfaces between components in the sense of strictly defined APIs or plug-ins etc. We rather aim on a loosely coupled architecture that eases the integration of heterogeneous components.

The aim is to leverage re-use quickly, efficiently, and rather informally and to avoid superfluous overhead that would be wasted by defining too strong interfaces/APIs.

7.2 Initial Set of Building Blocks Derived from the High-level Functional Analysis

Table 7-1 shows a matrix linking building blocks to use cases. The aim is to determine where and how building blocks can be used across use cases and to which degree building blocks need adaptation for use cases.

Table 7-1 Building Block/Use Case Matrix

Use Cases **Building Blocks**	**UC-01 Planning**	**UC-02 Content**	**UC-03 Remote**	**UC-04 Data Sys.**	**UC-05 Tours**
BB-01a 3D Scan (Small Scale)	Spacecraft (S/C) Models	Spacecraft Models, Engineering Models, etc.	Models of Equipment	Models of Equipment (Data Systems)	-
BB-01b 3D Scan (Room Scale)	-	-	Models of Remote Locations	Models of Data Centres etc.	Models of Tour Locations
BB-02 3D Import	Spacecraft Models, Celestial Body Models (Asteroids, Comets, …)	Spacecraft Models, Celestial Body Models (Asteroids, Comets, …)	Equipment Models	Equipment Models	-
BB-03 Custom 3D Model Development	As Above	As Above	As Above	As Above	
BB-04 3D Annotation	Place Points of Interest on S/C Models	Place TM on S/C Models	Annotate Equipment Models	Annotate Equipment Models	Annotate Locations w/ Tour Info

Use Cases	**UC-01 Planning**	**UC-02 Content**	**UC-03 Remote**	**UC-04 Data Sys.**	**UC-05 Tours**
BB-05a Immersive Display (VR Headset)	Possibly Used by Individual User	Possibly Used by Individual User	-	-	Remote VR Audience
BB-05b Augmented Display (AR Device like HoloLens or iPad)	Possibly Used by Individual User	Possibly Used by Individual User	Used by In-situ Operator	Operator In-situ	Audience In-place with Tour Augmentation
BB-05c Cooperative Display (Tablet, Projector, Screen)	Used by Team for Collaboration	Used by Team for Collaboration	-	Operator Team In-situ	Tour Guide Presenting to Audience
BB-05d Workplace Screen Display	Used by Individual User	Used by Individual User	Used by Remote Support Engineer	Monitoring Team, Planning Team	Remote Audience
BB-06 Meta Data Import	Possibly for Point-of-Interest Annotations	For TM Annotations	-	Possibly for Equipment Annotation	-
BB-07 ESA Data System Integration	Possibly for Displaying Data	For Displaying TM Data	-	Possibly for Displaying Data	-
BB-08 Content Management	For Models and Annotations	For Models and Annotations	-	For Models and Annotations	For Models and Annotations

7.3 Building Block Assessment and Selection

Table 7-2 shows the result of the building block assessment. The aim was to do the assessment at a reasonable level of detail to get a “good enough” result without excessively wasting effort and leaving enough effort for the actual Proof-of-Concept development.

The table indicates cost factors (Budget, Dependencies, and Complexity) with “x”s. The more “x”s, the more costly a building block is considered. Re-use potential is indicated with “+”s. The more “+”s, the more re-use potential is considered.

Table 7-2 Building Block Assessment Matrix

Assessment Criteria **Building Blocks**	**Budget**	**Dependencies**	**Re-use**	**Complexity**
BB-01a 3D Scan (Small Scale)	x Easily Usable 3D Scan Apps for Free	xx Suitable device, e.g., iPad needed.	++++ 3D Models Required for Many Use Cases	xx iPad Deployment and 3D Scan App Use
BB-01b 3D Scan (Room Scale)	x As Above	xx As Above	++ Less Use Cases w/ Room Scale	xx As Above
BB-02 3D Import	x Use Existing Models and Tools	xx Requires Special Tools	++++ 3D Models Required for Many UCs	xx Need to Install Tools and Get Models
BB-03 Custom 3D Model Development	xxxxx Requires Expert Knowledge	xxx Modelling Tools may be expensive.	++++ 3D Models Required for Many UCs	xx Need to Install Tools and Get Models
BB-04 3D Annotation	xxxx Custom Implementation Required	xx 3D App Development Environment Required	+++ Annotated Models Used in Multiple Use Cases	xx Need to Deploy Custom App.
BB-05a Immersive Display (VR Headset)	xxx Requires Content Preparation for VR	xxxx Requires VR Hardware	+ Usable for Few Use Cases	xxx VR Requires Space and Hardware Setup
BB-05b Augmented Display (AR Device)	xxx Requires Content Preparation for AR	xxxx Requires AR Hardware	+++ Usable for More Use Cases	xx AR can be easier usable than VR.
BB-05c Cooperative Display (Tablet, Projector, Screen)	xx Possibility to re-use display software from workplace screen.	xxx Requires extras hardware, e.g., tablet.	+++ Usable for More Use Cases	xx Tablets can be easily deployed.

Assessment Criteria	Budget	Dependencies	Re-use	Complexity
BB-05d Workplace Screen Display	xx Use standard frameworks.	x Only requires default workplace setup.	++++ Can be used in multiple use cases.	x Workplace setups already exist.
BB-06 Meta Data Import	xx Required metadata is simple.	x Uses standard software libraries.	+++ Usable for More Use Cases	xx Need to deploy custom software.
BB-07 ESA Data System Integration	xxx Access to ESA software may be complex.	xx May require ESA custom software integration	++ Can be used in few Use Cases	xxx Need to deploy custom software and integrate with ESA software
BB-08 Content Management	xxx Requires more complex setup.	xxx Requires integration of multiple systems.	++++ Can be used in multiple use cases.	xxx Need to deploy a more complex system.

8 Architecture Definition

For displaying the architecture overview concisely, the presentation uses some simplifications, such as:

- 3D scanning, optional post-processing, and 3D annotation are done on the same iPad Pro device. In principle, these steps could also be done on different devices.
- The interaction with the 3D Content Repository is shown in a simplified way without details regarding file system structures or protocols etc. This applies to both the iPad Pro for the content creation and the devices for display.
- The MCS integration does not consider details about the MCS. The integration is demonstrated with data generators for online and offline data.

Figure 8-1 shows the architecture of the Proof-of-Concept (PoC) implementation. Software items are indicated with ellipses. For these software items, green colour shows new development that was done as part of this activity, blue shows re-use of Commercial Off-the-shelf Software (COTS) and Open Source Software (OSS), and pink shows re-use from a previous activity. One exception for the software items is the 3D Content Repository, which is indicated with a cylindrical database symbol. The 3D Content Repository is also provided via OSS. Squares indicate data items. Hexagons indicate physical models.

A typical workflow with this architecture can be as follows:

- Create a new 3D model, e.g., via:
    - 3D scanning a physical model
    - or importing an existing 3D model.
- Upload the model to the 3D Content Repository.
- Import S2K metadata and upload the imported metadata to the 3D Content Repository.
- Download a model from the 3D Content Repository to the annotation iPad.
- Annotate the 3D model with the 3D annotation application.
- Upload the annotation file to the 3D Content Repository.
- Display the annotated 3D model via
    - the native 3D display application, e.g., on iPad or Desktop
    - or the hybrid web application.

For the hybrid web application, the software item ellipse is indicated on the browser as this is the GUI that displays the software. Of course, the hybrid web application is served from a web server. For the hybrid web application, the 3D model and annotation data are served from the 3D Content Repository.

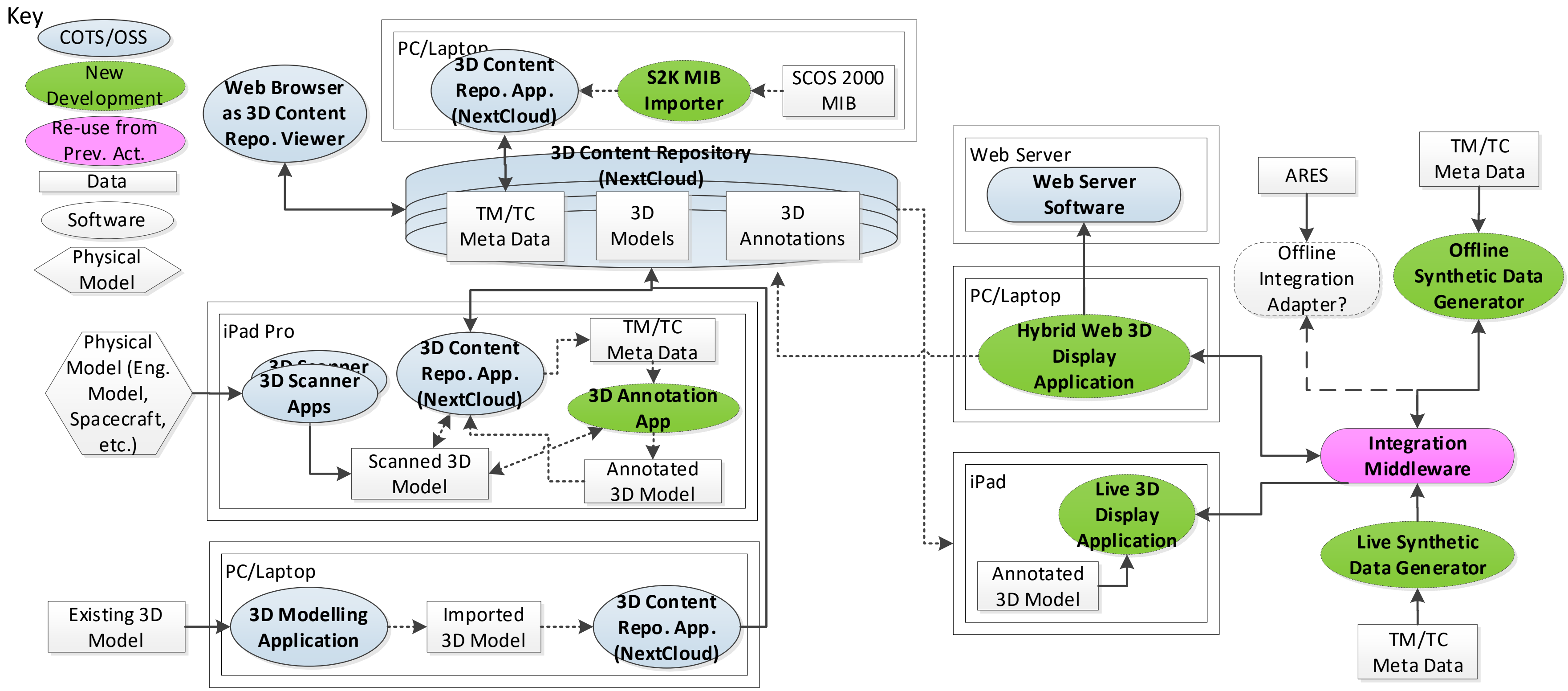


Figure 8-1 Proof-of-Concept Architecture

9 Summary

One central goal of this activity was to move the application of AR/VR/MR further towards providing value to real-world use cases. For achieving this, the activity was split into:

- a conceptual phase
  In the conceptual phase, input on use cases was gathered, e.g., in scope of workshops and interviews. Furthermore, technologies were analyzed.
- and a practical phase
  In the practical phase, selected use case ideas were refined and implemented in a proof-of-concept (PoC).

In this study, use cases of operations workflows have been analysed and extended to benefit from the recent advances in AR technologies. Five main use-cases were defined:

- UC-01 3D Planning
- UC-02 3D Content
- UC-03 Remote Support
- UC-04 Virtual Data System Assets
- UC-05 Virtual on site.

The feedback has shown that for space operators, solutions for use cases UC-02 and UC-03 are of most immediate concern. Due to a dedicated sister project that focuses solely on UC-03, this use case has not been developed further under this study. Hence, content creation and manipulation has been determined as the main focus point which can solve the content bottleneck that many real-life AR/VR applications in the operations field are facing. The use case selected as the main driver for the PoC is:

UC-02	3D Content	Sub-cases: • "3D Mimics": Display TM on 3D Model (S/C, Eng. Model) ○ Level-of-Detail (LoD) based on zoom, e.g., from system to sub-system levels. • "3D Twin", e.g.: observe solar array wing and payload deployments, thruster firing, etc. (e.g., for training, procedure execution & validation, PR) • Visualisation of Spacecraft Orbit Information (Attitude, Orbit, Thrust/Force Vectors, Instrument Pointing, ...) • Mission Specific Animations - Rosetta approach to comet, project high resolution original images on model • 3D modelling during MRBs

A central property of this use case is that it links 3D-models with spacecraft-related data. In the PoC context, spacecraft-related data is telemetry (TM).

This required the combination of 3D and spacecraft data for content creation and display. During content creation, TM metadata had to be linked with 3D models to annotate 3D models. In the data display part, real TM data had to be displayed together with 3D data.

For enabling real-world applications, we considered that AR/VR/MR content creation and ease of use were central elements. The idea is that easily creatable and maintainable content and easily usable solutions lower the entrance barrier and increase user acceptance. Thus, an important aspect during the PoC design and implementation was to enable an easily content creation pipeline.

On the premises explained above, a workflow was developed which was demonstrated at ESOC. The workflow had the following objectives:

1- To reduce the complexity of creating 3D content

2- To store the 3D content in an easily accessible repository

3- To be able to display on the 3D content relevant operational live data

4- To be able to visualize the 3D content and operational data on regular everyday mobile devices.

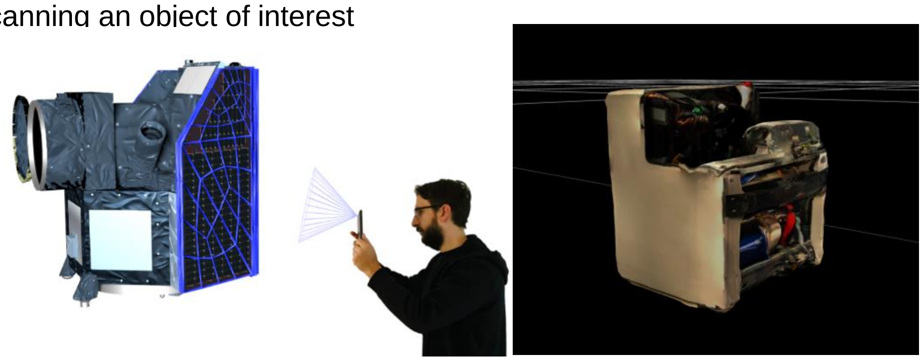
For each objective, solutions were identified either by identifying COTS or by developing an internal software application solution. Some conclusions could be drawn:

1. There are off-the-shelf applications available ready to produce 3D scans of any object. Currently these applications are limited to the Apple environment, and specifically the iPad Pro, due to the tablet's integrated LIDAR sensor. The applications can produce reasonably clear scans within a short amount of time (under 10 minutes) in widely used formats.
   The applications more thoroughly analysed were 3D Scanner App and Scaniverse, the former working well with large scale objects (e.g., a room, a real scale satellite model), and the later with small scale objects (e.g. a backpack, a table)
2. Nextcloud was identified as an accessible repository for 3D content and as such adopted as part of the workflow.
3. Manipulation of 3D content is still a somewhat developing area and as such, in this study, two applications have been developed: an annotation application and a hybrid visualization application.
   The annotation application has the role of correlating the 3D content with live data for the purpose of better understanding the functioning of a system e.g. display power generated measurements on solar panels of a satellite 3D model.
   The hybrid web visualization application takes the 3D annotated content from the previous app and expands the data shown on the 3D model to 2D plots.
   The 2 developed applications show some potential for further development in the are of 3D content manipulation.
4. All applications used in this study had to be easily accessible (used on common hardware) and have and quick learning process.

To give an overview of the PoC, a simplified example of a typical workflow is presented below:

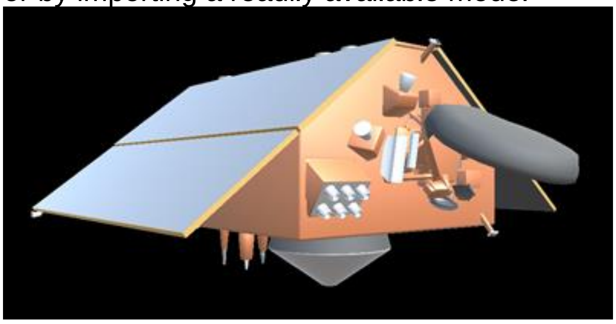
- Import a 3D model, e.g.,

- by scanning an object of interest



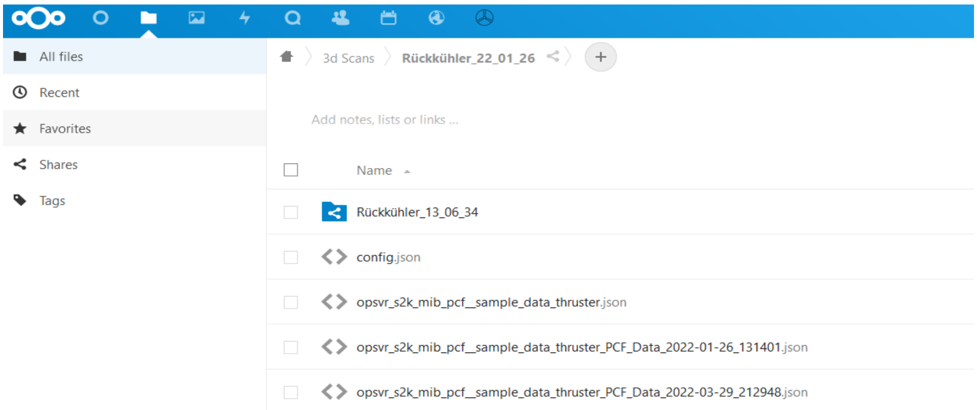
3D scanning with off-the-shelf applications was identified as one major tool to increase the usability by making 3D content creation more approachable. With this, arbitrary objects such as spacecraft models, engineering models, or rooms can be quickly digitized and made available as 3D content.

- or by importing a readily available model

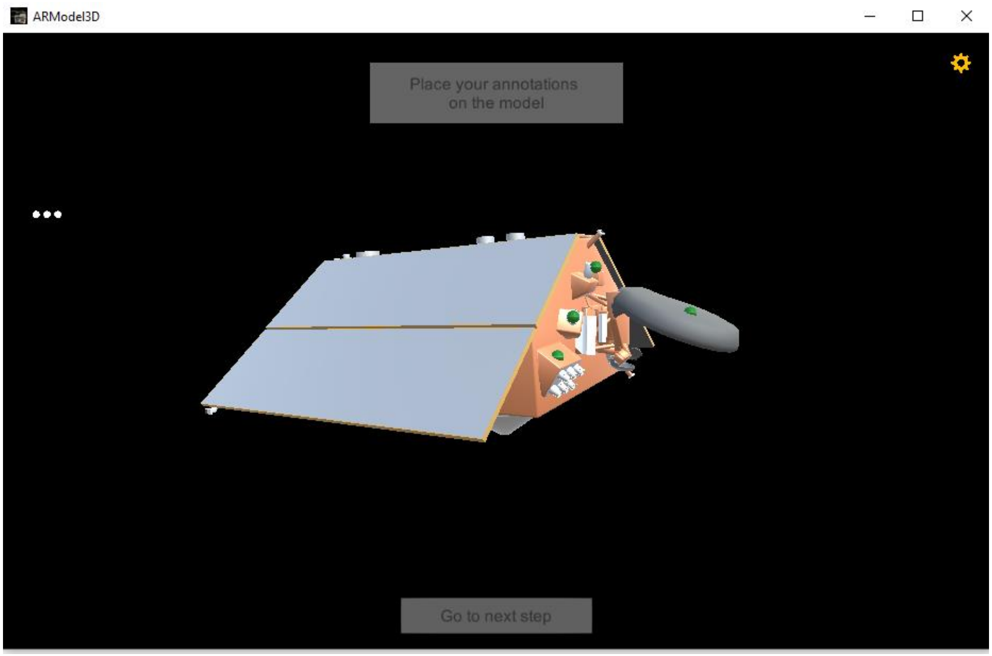


Using readily available 3D models is another way for accelerating content creation.

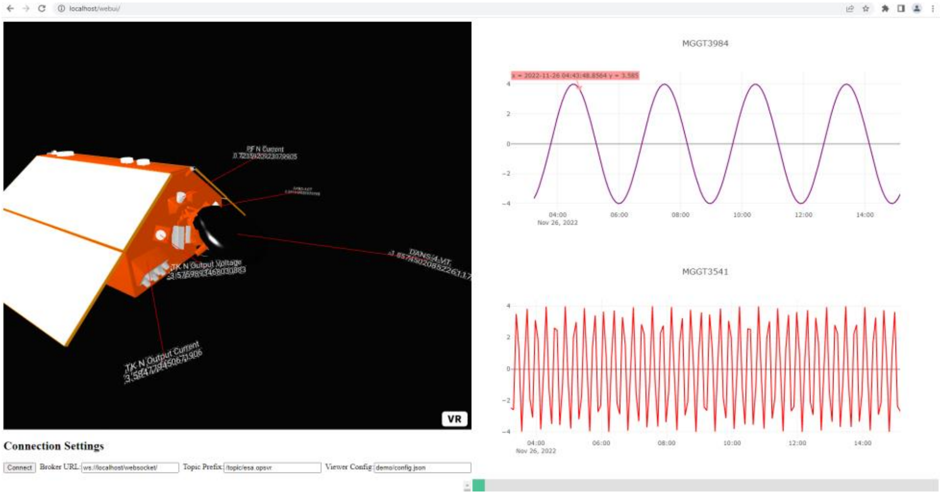
- Using an integrated content creation and management pipeline for managing and distributing content was identified as another important driver for bringing AR/VR/MR tools closer to real-world application scenarios. As one example for this, here we show NextCloud, which was used as central hub for managing content.



- For easing the integration of 3D content with spacecraft-related data, an AR annotation application was developed. The aim was to reduce the need for specialized 3D application knowledge and to provide an intuitive solution for enhancing 3D models with annotations about what data to display where. This way, e.g., a spacecraft can be annotated with the locations from where TM values originate.



- A data integration backend was developed for linking operational ESOC data with the annotated 3D model.
- For displaying annotated 3D model and associated data a hybrid web app was developed. The aim was to provide different viewpoints on spacecraft data:
    - Spatial Relations
      A 3D view allows to analyze the spatial relation between TM values from different locations. It can help, e.g., to show when TM relate because of spatial proximity.
    - Time Relations
      For indicating time relations, timeseries charts are provided that allow analysis of the behavior of selected parameters over time.
    - Interactive Link between View Points
      3D and timeseries view are linked interactively, e.g., the TM parameters to be shown in the timeseries plots can be selected from the 3D view. Similarly, the timestamp for which TM values are shown in the 3D view can be selected via the timeseries views.


MGGT3984
MGGT3541
Connection Settings
Connect
Broker URL
Topic Prefix
Viewer Config
VR