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Towards Leveraging Augmented and Virtual Reality for Spacecraft Mission Operations at ESOC

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Abstract

This paper presents the results of an activity at the European Space Operations Centre (ESOC) on moving towards leveraging Augmented and Virtual Reality (AR/VR) for Spacecraft Mission Operations. Previous activities aimed at assessing feature sets and surveying possible application scenarios on a broader range. This activity specifically targets towards real-world application scenarios in spacecraft mission operations. Experiences from precursor activities and results from this activity indicate that the applicability for day-to-day use depends more on content creation and less on the sophistication of the employed AR/VR devices. Consequently, the activity aimed at providing an end-to-end toolchain integrating AR/VR components where they offer the most utility. The paper presents the conceptual and practical results from the activity including the proof-of-concept implementation.

Keywords: Spacecraft Operations, Augmented Reality, Virtual Reality

1 Introduction

In this paper, we present the results of a study executed for ESA/ESOC on bringing Augmented and Virtual Reality (AR/VR) towards real-world application scenarios in spacecraft mission operations.

The overall high-level context in which this activity is situated is the study of the capabilities and application of AR/VR in the mission operations domains at ESAs Space Operations Centre (ESOC). AR/VR applications in industry show prospects for providing a clearer understanding of complex information by using the 3D space and by augmenting information on real and virtual assets, hence improving situation assessment, training, local and distributed communication, and engagement in activities.

Following several initiatives and technology assessments in the domain of extended reality in the Operations Centre, the targets of the activity presented in this paper were the core processes of the established, unmanned, space probe mission operations.

Aims were to:

- Find **meaningful application areas**, where AR or VR could **bring value** to the way operations are planned, simulated, validated, and eventually executed.
- 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 task** execution.
- Prototype key functionality to explore AR/VR for **operational deployment** for satellite operations.

The activity was split into two high-level phases, which will be detailed throughout this paper:

- Conceptual
  During the conceptual phase, the focus was on gaining conceptual insights and gathering information, especially from potential users of the systems. Activities performed in the conceptual phase included:
    - Use Case Identification and Analysis
    - Technology Assessment
- Practical
  In the practical phase, a Proof-of-Concept (PoC) was implemented.

Use cases were identified and refined, e.g., in workshops and interviews with ESOC staff. Five use-cases were defined and focused on throughout the project. Through further feedback of space operators, the use case focusing on the combination of 3D content with spacecraft-related data such as telemetry (TM) was of most immediate concern and hence selected for the prototyping stage.

1.1 AR/VR Spectrum

In the field of AR/VR, the terms Mixed Reality (MR) or eXtended Reality (XR) are also sometimes used. There is a spectrum in which AR/MR/XR/VR solutions can be located. Examples of distinguishing factors are, e.g.:

- Degree of Immersion: Immersion describes how "deep" a user is "enclosed" in a virtual environment. E.g., typical VR solutions provide an enclosed stereoscopic display such that a user can primarily see the virtual environment. AR, on the other hand, primarily shows the real world with additional virtual content overlayed on top. In this example, VR can be seen as having a higher degree of immersion than AR. The degree of immersion can vary and can also depend on which senses are considered, e.g., visual, audio, the perception of touching, force feedback, or how a user moves in a virtual environment. For visual perception, one metric that is related to the immersion is the Field of View (FOV) in which virtual content is shown to a user.
- Degree of Virtual Overlays: With AR, virtual content overlays are used for augmenting the real world. These overlays can provide, e.g., instructions like an interactive manual or important information in the field of view like a heads-up display. The degree to which overlays can be provided can be another distinguishing factor, e.g., in a simple case, only text can be displayed in the field of view or in a more complex case, items of the real-world can be identified, highlighted, and augmented with virtual content.
- Ways for Interacting with the Virtual Environment: AR/VR users can interact with virtual environments, e.g., via dedicated devices such as controllers or with means of tracking, e.g., hand tracking, finger tracking, movement tracking etc.

From the technology perspective, the selection of AR or VR defines how immersed the user is within the application. With AR devices such as Microsoft HoloLens 2, the user is still able to interact with real world objects in the room, while the longer established VR headsets such as HTCs Vive or Oculus Quest fully enclose the user within a virtual world, with the cost of removing any perception of the room and environment in which they are used.

2 Background

This activity was a continuation of previous precursor activities, which explored the use of AR/VR in scope of ESAs activities from more conceptual perspectives. Some selected examples this consortium had investigated are briefly introduced [1, 2]:

- Virtual Reality (VR)
  The proof-of-concept (PoC) developed in one precursor activity [1] investigated the combination of the high immersion offered by VR and the fidelity of data provided from operational simulators. To this end, a virtual astronaut training scenario in the context of a Virtual Lunar Base (VLB) was prototyped. This activity showed integration between VR, Operational Simulator, and Mission Control System (MCS).

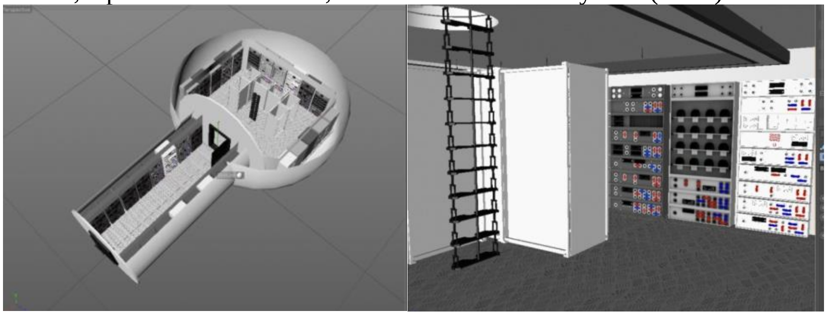


Figure 1 Virtual Lunar Base Models (Exterior and Interior)

- Augmented Reality (AR)
  The PoCs developed in another precursor activity [2] used AR capabilities for overlaying the real world with virtual content for exploring an interactive manual use case and an AR rover operation use case. The AR display provides a lower degree of immersion than VR but allowed to augment the real world with virtual content for providing additional information, e.g., virtual x-ray views or showing a reduced sized map of a rover operations situation on a planning table.

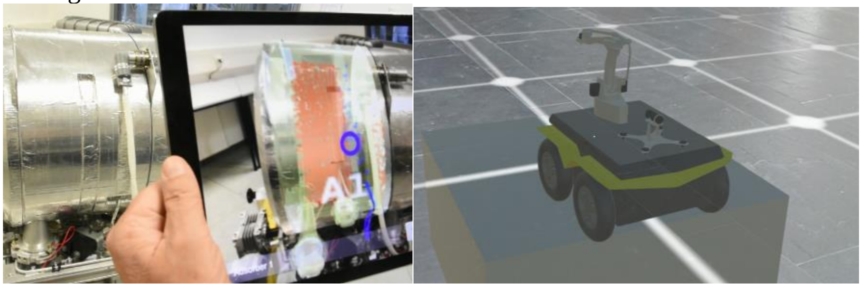


Figure 2 Precursor Augmented Reality, Interactive Manual and Virtual X-Ray, AR Rover

These activities were more in the scope of sounding activities looking for potential application areas of AR/VR and technology demonstrators exploring the integration of AR/VR with ESA systems, e.g., simulators or Mission Control Systems (MCS).

An important result from the previous activities is that AR/VR content creation was a major challenge, e.g., due to:

- Availability of 3D Models,
  The availability of 3D models is limited, e.g., because of Intellectual Property Rights (IPR) or high polygon counts of CAD models, which need to be reduced for enabling AR/VR applications. For AR/VR applications, 3D models can be seen as the basis for the content creation as most AR/VR content uses 3D models. Thus, the availability of 3D models or the possibility for creating custom 3D models is crucial for AR/VR content creation.
- Effort and Expertise for Preparing 3D Models for AR/VR Applications,
  In previous activities, the preparation of 3D content, e.g., 3D models, textures/materials for 3D models, annotations, etc. was done with established tools from the AR/VR domain. It showed that using these tools requires expert knowledge in the areas of 3D modelling and AR/VR content preparation. The need for in-depth expert knowledge makes it more difficult to roll-out AR/VR applications to a broader set of users and to keep them current with new content. Ideally, users should be enabled to perform at least basic content creation tasks themselves.
- Management of AR/VR Content Assets
  In previous activities, the AR/VR content was largely part of the PoCs that were developed. For these parts, the AR/VR content was a package produced during the activity and it was not needed to manage it. However, we also touched on some cases where content had to be organized as more dynamic assets and we observed that this part required considerable effort. For rolling out AR/VR to real-world applications and a wider group of users, we consider that it is needed that users can extend and manage AR/VR content more easily themselves.

These aspects were considered along the activity execution as guidelines in the overall context. They are, e.g., considered again during the detailed definition of the use case or the design of the PoC.

The present activity is explicitly aimed at going further and moving towards real-world application scenarios in mission operations at ESOC.

Following this scope, the use case identification and selection phase focused more on activities done at ESOC covering, e.g., mission operations. Likewise, the PoC selection and development aimed on covering aspects that have the potential to flow into real-world application scenarios.

3 Use Cases and Usability

Input for use cases was gathered from multiple sources:

- The statement of work provided results with use case ideas from previous activities and further additions.
- The proposal expanded on the ideas from the statement of work.
- Workshops with ESOC members were held for gathering and, later on, refining use case ideas.
- Further meetings in smaller groups also contributed to the use case identification.

For the sake of conciseness, in this paper, we only mention the workshops explicitly. Results from the other sources are included without explicitly detailing their source and process for defining them.

3.1 Workshop 1

The first workshop with 15 participants was held close to the start of the activity. Aims of the workshop were, e.g.:

- Identify potential contributors from the user perspective. For going towards real-world use cases, it is beneficial to get feedback from representatives from a potential user group.
- Get a general overview of the existing experience regarding AR/VR and how AR/VR are perceived.
- Identify use case ideas that may be implemented as proof-of-concept (PoC).

One take-away from conversations during the workshop is that AR/VR should not exclusively be considered for high-profile tasks, where AR/VR is the centre of the use case, but that they may also play supporting side-roles. The utility of 3D views in general was higher ranked than AR/VR by users.

We explicitly point this out because in the precursor activities, the AR/VR solutions had a central role in the envisaged use cases. For the precursor activities, this focus was deliberate to specifically showcase AR/VR features.

For the current activity, the aim was more to go towards utility applications. Thus, we also consider AR/VR along a broader workflow where they may add value.

3.2 Use Case Candidates

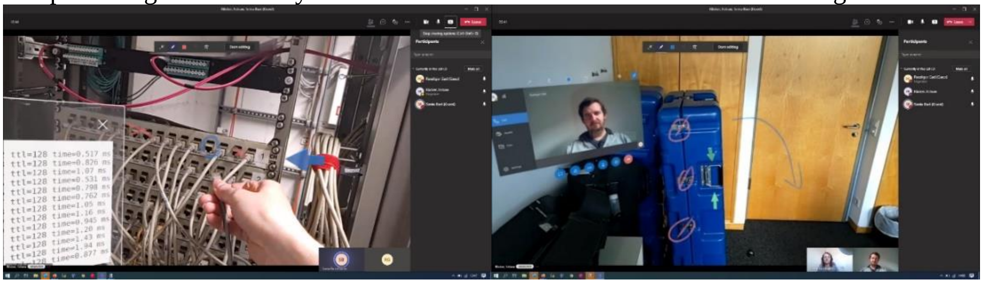
Below, an overview of the use case ideas is provided. The overview shows the accumulated use case ideas from all sources and with input from the workshops merged. The interest for the high-level use cases was determined with a poll among the participants. Some use case ideas could be grouped into logically related groups. For these, below, the group is given and excerpts of individual “sub-use cases” are shown as sub-items.

- Support Mission Planning with 3D Views – (**high interest)**
  Examples of sub-use cases are:
    - 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.).
    - Sat Visibility on a ground track on the virtual globe
      Below mock-ups for potential use cases are shown.

Figure 3 Sat Visibility on Ground Track Mock-ups

- 3D Displays for Showing Spacecraft-related Information – (**high interest)**
  There were 11 sub-use cases. Examples of sub-use cases are:
    - 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)
    - Virtual Engineering model during testing, augmented with injected or real parameters
    - Integrated Digital Twin visualization in MCS and SIM
- AR/VR for Remote Support – (**high interest)**
  There were 10 sub-use cases. Examples of sub-use cases are:
    - Virtual meeting space for a team, e.g., for collaborative training
    - Virtual mission control room for remote work
    - Remote assistance of local operators from remote experts

  Below examples using Microsoft Dynamics 365 Remote Assist[1] with HoloLens 2 are given:



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ttl=128 time=1.20 ms
ttl=128 time=1.43 ms
ttl=128 time=1.94 ms
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Figure 4 Remote Support Scenario Examples

- Display Data Systems Information in AR – (**high interest)**
  A control room contains many computer systems that all need to jointly work properly. AR could be used to overlay otherwise not so easily visible key information onto the systems. This could aid in keeping an overview of the working system and in diagnosing misconfigurations.
- AR/VR Tours of Buildings and Sites – (**medium interest)**
  ESOC also operates infrastructure in remote locations. It can be helpful to have AR/VR counterparts of buildings, environments, and infrastructure, e.g., for planning of maintenance or for instructing remote personnel.
  Below, examples for creating AR/VR tour content with 3D scanning of exterior (garden) and interior (hall with pillars) locations are given:

Figure 5 3D Scanning for Room/Building Scale Example (Exterior, Interior)

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[1] https://dynamics.microsoft.com/de-de/mixed-reality/remote-assist/

- Near-Earth Objects (NEOs), Collision Avoidance, Analysis and Planning – (**low interest)**
    - 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 visualization
    - Meteoroid streams visualization

Below mock-ups for visualizing location probabilities, collision avoidance scenarios, and vectors are shown:

Figure 6 Location Probability Visualization Mock-ups

3.3 *Use Case Down-selection*

To determine which use case should be part of the proof-of-concept (PoC), the use case ideas were post-processed and consolidated. The post-processed use case ideas were presented and discussed in a 2nd workshop and a second poll was done to get feedback on the consolidated use case ideas for which the results are shown in Table 1.

Table 1 Poll on Consolidated Use Cases in 2nd Workshop

Use Case	**Interest**
UC-01 – 3D Planning	Low
UC-02 – 3D Content	High
UC-03 – Remote Support	Medium
UC-04 – Virtual Data Systems	Low
UC-05 – Virtual On-site	High
UC-06 – NEOs	Low

Based on the voting outcome, we considered UC-02 3D Content with the highest priority use case as seen from the perspective of the user votes. As part of UC-02 3D Content, we also considered the Spacecraft Operations use case. The other highly rated use case of Virtual On-Site which contains elements of remote presence was descoped, as it was covered in a separate study activity conducted by the Agency.

3.4 *Usability Considerations*

We considered that an easily usable solution helps improving adoption for real-world applications. The previous activities showed, e.g.:

- Some users were already familiar with AR/VR devices and could readily use them.
- User unfamiliar with AR/VR devices only needed relatively short familiarization periods.
- Head-bound devices were often considered uncomfortable after about 30 to 60 minutes of continuous use.
- Text-based input was considered complicated with head-bound devices.
- AR/VR interaction for navigating 3D worlds, e.g., changing the location or selecting and moving objects in 3D space, seemed to have been intuitive for most users.
- AR/VR content such as 3D models should be user maintainable. Even for the same generic use case, e.g., rover operations, updates to the 3D content, e.g., rover or environment 3D models, would have needed to eventually be done by users.
- AR/VR content handling required considerable effort, e.g., management, maintenance, and deployment of 3D files or metadata.

From this experience, we concluded that the usability of AR/VR devices was, in general, “good enough” given the restriction to usage in short time windows as part of larger workflows, except for isolated cases such as text input. In the further work, we aimed on considering these lessons learned, e.g., leveraging the intuitive 3D interaction offered by AR/VR devices while avoiding lengthy text input. Likewise, we considered 3D content creation as one important driving factor. Ideas for improving the usability are, e.g.:

- 3D Scanning for 3D Model Creation
  3D scanning software allows to create a digital 3D model from a real physical object. We considered that this may offer an intuitive way for creating 3D models for AR/VR content.
  Advancements in, e.g., photogrammetry software or the addition of LIDAR sensors to AR devices and software using them improved the availability of consumer 3D scanning software. In early test runs, it appeared that consumer 3D scanning applications may serve as intuitive way for creating 3D models.

- AR Interaction for 3D Model Annotation
  In the previous activities, linking 3D content, such as 3D models, to domain-specific content, like spacecraft telemetry, showed to be another important task. To better support this, we envisaged leveraging the capability of AR/VR devices in providing intuitive 3D interaction. Here, we consider adding annotations to a 3D model, e.g., placing markers regarding where spacecraft-related data shall be displayed as one example where AR/VR can help in easing content creation.
- Using a Central 3D Content Repository for Content Storage, Management, and Retrieval
  In previous activities, the focus was more on explorative prototypes regarding use case ideas. For these, the 3D content was bespoke development, and no user-drive extension was foreseen. However, it started to become apparent that handling of content will become important once solutions shall be rolled out to real applications and when users need to maintain their own content. Thus, for supporting the move towards real-world use cases, we consider that users shall be supported in, e.g., storing, managing, and retrieving content. For this, we foresee a “3D Content Repository” that shall serve as central hub for managing AR/VR content.

Figure 7 Conceptual Depiction of 3D Scanning and AR-based 3D Model Annotation

4 Technology Assessment

4.1 Use Case/Technology Mapping

One important idea for the proof-of-concept (PoC) implementation is to leverage re-usable building blocks. To assess which technologies are required for the PoC and their re-use potential, we mapped use cases to technologies in a three-step process.

We performed these mappings for:

- 3D/AR/VR Model Content
- 3D/AR/VR Model Display
- 3D/AR/VR Interaction
- Data Items and Data Sources

In Figure 8, the mapping for 3D/AR/VR Content is shown as example. At the top, the down-selected use cases are shown in yellow. In the middle, the required functionality is shown in blue. At the bottom, technologies with which the required functionality can be achieved are shown in green. Arrows indicate which functionality is required by which use cases and which functionality can be provided with which technology.

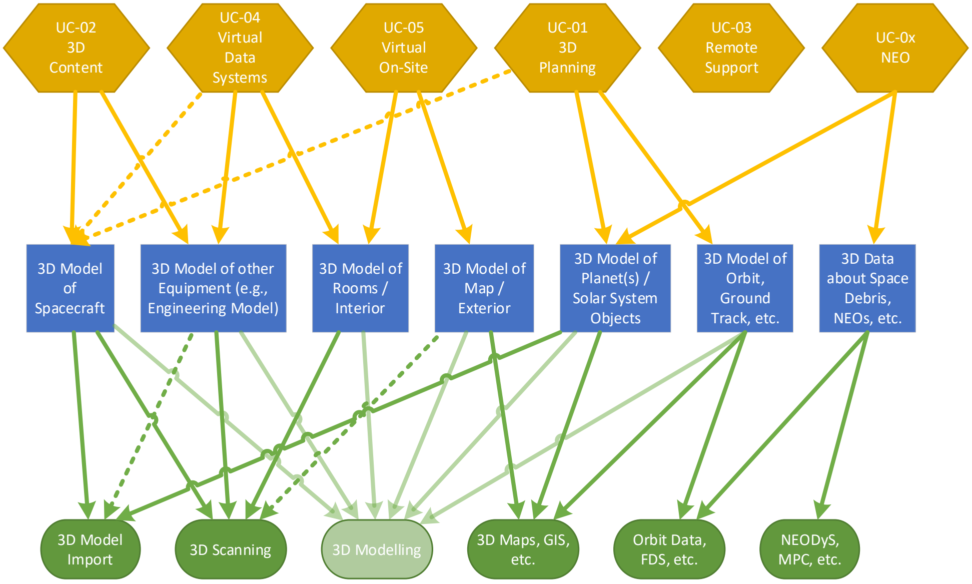

Figure 8 Mapping of Use Cases to 3D Models and 3D Activities

We included “3D Modelling” for the sake of completeness. However, as defined in the overarching goals of focusing on solutions that should be easily usable, we consider that 3D modelling will likely not fit and thus we show it shaded.

For UC-02 (3D Content), it can be seen that 3D model import and 3D scanning represent important technologies. Furthermore, 3D model import and 3D scanning can also be used for multiple other use cases, which indicates good re-use potential.

4.2 3D Scanning Assessment

For assessing 3D scanning, we considered the following devices:

- iPhone 11
- iPad Pro (2020)
- Artec Eva

Figure 9 shows the results of the 3D scan process using an iPhone 11. The left picture shows an overview and the right picture shows a close-up perspective that allows a more detailed view on the scan results.

Figure 9 iPhone 11 3D Scan Results (Left: Overview, Right: Details)

Aspects we consider noteworthy regarding the scan results are:

- Colour information is preserved.
- The resulting 3D data is a point cloud.
  This can especially be seen in the close-up detailed view. This is important as this may impact the usability of the 3D object, e.g., when it is required to closely zoom in on details of the scanned object.

Figure 10 shows the raw 3D scan results from the 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. Furthermore, the 3D scanning app allowed post-processing for removing background objects etc., which we do not explicitly show here.

Figure 10 Scan Results with iPad Pro

Figure 11 shows a close-up view on a part of the 3D model with the aim on illustrating geometric detail versus texturing. The two orange circles mark terminals to which electric cabling is connected on the 3D scanned device. In these pictures, the terminals and cables are recognizable mostly because of the applied texture. In the left view, it can be somewhat seen that the geometric model is comparably flat and that the geometric detail does not fully capture the wires and wire terminals. On the right-hand picture, the model looks more natural due to the perspective from which the texture applied to the model was captured.

Figure 11 iPad 3D Scanning, Geometric Detail vs. Texturing

For comparison, we also included a dedicated 3D scanning device. The Artec Eva uses structured light to reconstruct the 3D geometry of the captured object. With multiple light flashes per second it reaches a precision of up to 0.1mm and can scan objects as small as 10cm.

The 3D model processing for the Artec Eva is done with a dedicated specialized software.

The 3D model acquired with the Artec Eva, as shown in Figure 12, is more detailed and even small bumps and elevations (e.g., plugs and connectors) are visible and represented in the model. Nevertheless, this improvement in quality comes along with a more time-consuming and a more complex scanning process.

Figure 12 3D Reconstruction precision

For the needs of the use cases and for the proof-of-concept, we selected the iPad pro with off-the-shelf 3D scanning applications as “3D scanning device”. Reasons for this are:

- The focus is on usability and ease of use and our impression is that the off-the-shelf 3D scanning applications for iPad are easily usable and do not require other specialized software.
- The iPad pro offers a LIDAR sensor such that photogrammetric and LIDAR-based approaches can be used.
- The Apple app store offers multiple 3D scanning apps. This avoids vendor lock-in and enables to select the best app for a certain purpose. E.g., we noticed differences regarding spatial resolution or the suitability to scan exterior locations.
- The 3D scanning apps typically also provide post-processing capabilities such as cropping of objects to remove background etc. This way, the output of the 3D scanning apps is often directly usable as 3D model without further post-processing.

4.3 ESOC Systems

For including spacecraft-related information, it is required to consider integrating corresponding data systems. For this activity, we selected a novel REST Data Access API. The ESA REST Data Access API provides a bridge to different ESA systems. This way, by supporting the REST API, it will be easily possible to include more data systems. The REST API fits well to the envisaged technology stack as anticipated for the PoC implementation. Furthermore, it showed that thanks to the rich REST ecosystem, e.g., JSON, Swagger/OpenAPI [3], and Mockserver [4], it was easily possible to provide a mock deployment of the REST API for development purposes. This allowed to do most of the development against the mock without the need to replicate more complex systems. Only the final integration had to be done against the original system and this integration only required comparably small adjustments.

4.4 Orbit Visualization

Visualizing information about orbits, trajectories, location/collision probabilities etc. was identified as a potentially relevant functionality for use case ideas. Thus, we performed a brief survey on publicly and freely available solutions for visualizing this kind of information.

The functionality and clarity of 3D models could be enhanced by the ability to place them on a simulated orbit (e.g., a satellite on an orbit around Earth). For this purpose, some tools have been analyzed for the possibility to integrate with the 3D content created.

- Cosmoscout VR [5]

Cosmoscout VR is a DLR application which allows the user to visualise the universe in a modular way. Orbits of the planets around the Sun can be easily identified and differentiated by their colour, but also modified via the available plugins. Figure 13, left, shows a screenshot of CosmoScout VR.

- NASA "Eyes" [6]
  Under https://eyes.nasa.gov NASA provides multiple web-based applications for displaying space-related data in 3D. Figure 13, centre, shows a screenshot of NASA Eyes.
- CesiumJS [7]
  CesiumJS is a JavaScript library for displaying information in form of 3D globes and maps. The CesiumJS library is available as Open Source Software. In addition to the library, there is a commercial offering (Ion) of a service which provides related data. In the work presented in this paper, we consider CesiumJS primarily as library. Figure 13, right, shows a screenshot of CesiumJS.

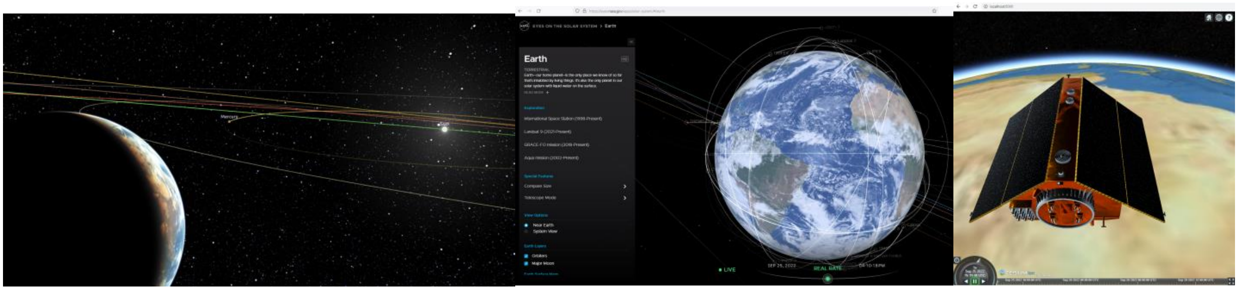

Figure 13 Screenshots of CosmoScout VR, NASA Eyes, and CesiumJS

In our analysis, we considered a desktop application (CosmoScout VR), a web-based application (NASA "Eyes"), and a library (CesiumJS). Based on our analysis, we consider that a wide range of options for displaying orbit information and related data is available for a wide range of platforms. Some applications can be extended via plug-in mechanism and frameworks enable the development of bespoke custom applications. Consequently, we consider that for this activity, it is better to focus on the content creation itself as we observed this as the major obstacle when moving towards day-to-day use cases.

5 Design and Implementation

For the current activity, we took the lessons learned from previous activities as important input.

We defined support for content creation as one main goal. Our idea is that reducing the cost, e.g., in terms of time spent, price of assets, or required expertise, of AR/VR content will help in bringing AR/VR closer to day-to-day use cases. To ease the application at ESOC, we defined re-usability of sub-components as another main goal.

For addressing these two goals, we defined what we call "AR/VR content creation pipeline". The pipeline tries to support the entire AR/VR content creation and application process.

The proof-of-concept (PoC) that was designed and implemented in this activity is an implementation of one end-to-end pipeline. In this section, the design and implementation of the PoC are presented.

5.1 Building Block Concept

For facilitating re-use, we aimed on developing a "building block" concept. The content creation pipeline is built of building blocks that can, in perspective, be used in further use cases.

From the use case down-selection, we selected the display of spacecraft telemetry data on top of a 3D model of the spacecraft as Proof-of-Concept (PoC) use case. We also refer to this as "3D Content" or "3D Mimics" use case. This 3D display enables to better identify spatial relations between different telemetry values during the analysis of telemetry data. In principle, the use case can be extended to any situation in which spatial location and overlay of data may be helpful, e.g., overlaying other hardware such as racks or engineering models with data.

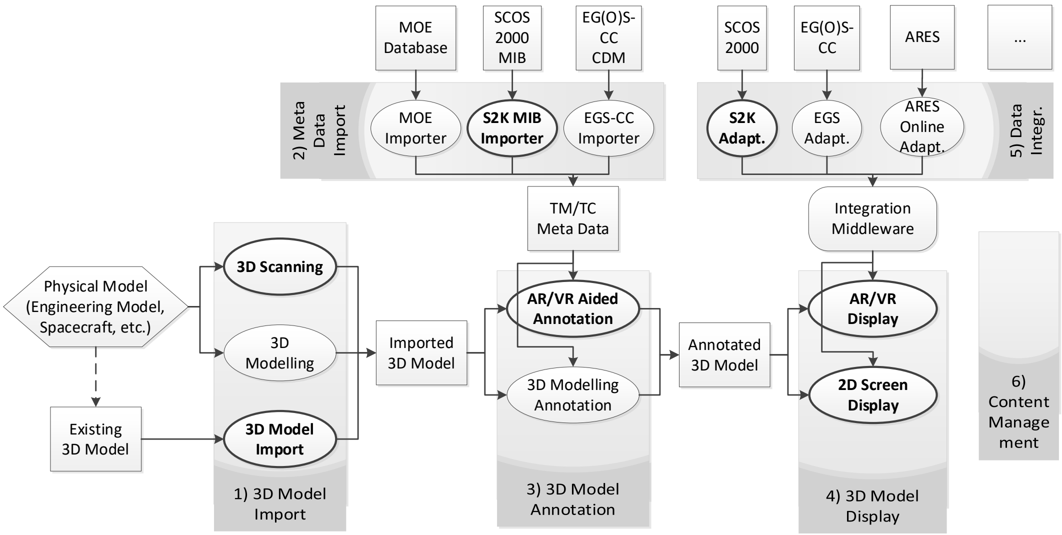

Figure 14 Building Blocks Concept Overview

Figure 14 shows a conceptual overview of building blocks for the PoC use case. Key building blocks are:

1) 3D Model Import
   - 3D Scanning
     3D Models are created with Commercial Off-the Shelf (COTS) 3D scanning applications on commodity tablets with LIDAR sensors. The scanned 3D models also provide textures that resemble the colors of the scanned real-world objects.
   - 3D Model Import
     As second option for this building block, we added the import of existing 3D models. The import step converts the existing 3D model into the format that is used by the remainder of the content pipeline.
2) Metadata Import from ESA MCS
   Metadata from ESA MCS is used, e.g., for annotating 3D objects with locations for displaying data on them.
3) 3D Model Annotation via AR-based Annotation of 3D Models
   Annotations on 3D models are used to define locations for displaying selected telemetry values. We developed an AR-based annotation application for easing the placement of these annotations.
4) 3D Model Display
   - 3D Display Application
     The 3D display application provides simple 3D display of data.
   - Web-based Hybrid 3D Display Application
     A web-based hybrid 3D display application enables to view the 3D overlay in context of x/y timeseries data plots. This allows seeing spatial relations together with time relations for selected telemetry parameters.
5) Integration Middleware and Backend
   Telemetry data is provided via an integration middleware and a backend. The integration middleware provides message-based data exchange that allows multiple participants to join a data analysis session. The backend provides access to telemetry data and handles the processing of requests sent from the frontends. We use a test backend providing synthetic data for testing and one example backend for connecting to a telemetry data store at ESOC for providing real telemetry data.
6) 3D Content Repository
   A web-based file repository is used for storing AR/VR content assets such as 3D models, metadata files, or annotation files. This repository is used during different steps of the process, e.g., 3D scanning, annotation, or deployment of AR/VR content.

The repository connects with most other items. For the sake of simplicity, these connections are not explicitly shown in the figure.

5.2 Architecture

Figure 15 shows a simplified architecture of the Proof-of-Concept (PoC) implementation. Software items are indicated with ellipses. For these software items, green color 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). 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.

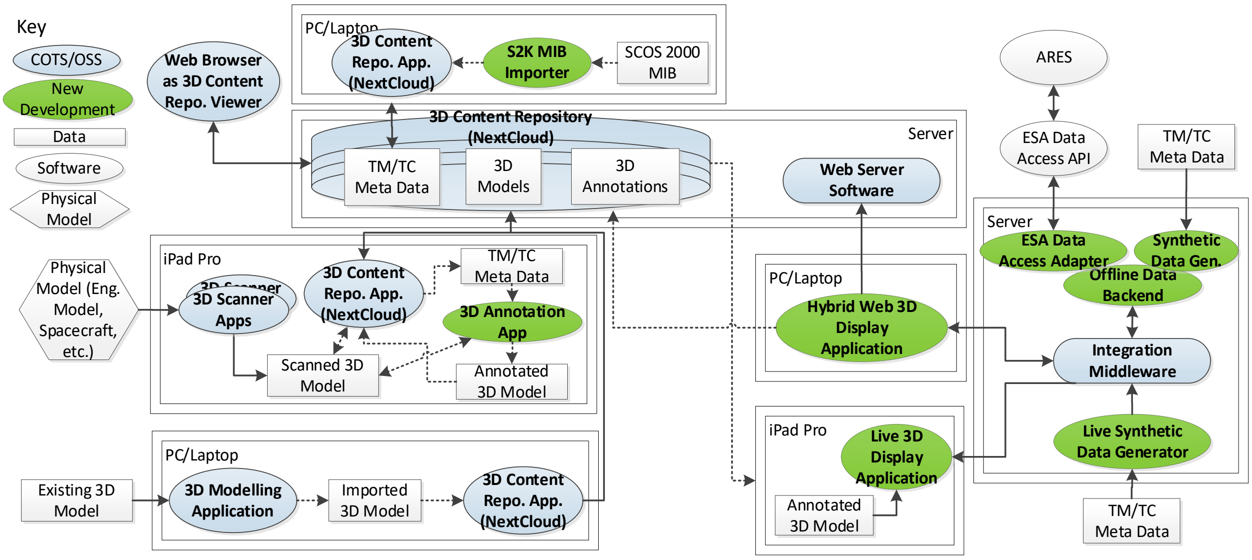

Figure 15 Proof-of-Concept Architecture

Following the rough order of a typical workflow, the elements in the Proof-of-Concept are:

- 3D Model Import
    - 3D Scanner Apps [8, 9] (from App Store) Multiple apps are available and supported in the workflow.
    - Import via 3D Modelling Application (Blender [10])
- Metadata Import (Custom Implementation)
- Content Repository (NextCloud [11])
- 3D Model Annotation (Custom Implementation using Unity [12] game engine)
- Data Backend (Open-Source Message-oriented Middleware [13] and Custom Implementations for Data Sources)
- 3D Display Applications
    - Live 3D Display Application (Custom Implementation using the Unity game engine)
    - Hybrid Web 3D Display Application (Custom Implementation using A-Frame [14] and Plotly [15])

5.3 Implementation

5.3.1 Main Data Items and Data Integration

For enabling a sound building block concept, the data items to be exchanged between the building blocks need to be well-defined. In this section, we give an overview of what we consider the main data items involved in the Proof-of-Concept (PoC). We considered the following main data items:

- 3D Models
  For 3D models, we use the established OBJ format as internal data format. As this is a widely supported and used format, we do not provide further details here.
- Metadata
  Metadata describes the domain-specific data to be handled by the system. For the PoC, this is spacecraft telemetry.
- Telemetry Values Data
  This is the telemetry data to be displayed in the AR/VR content.

To provide well-defined interfaces between building blocks, the format of the internal data items is defined using JSON Schema. We use JSON Schema because we already made good experiences with using JSON for the integration in the precursor activities. JSON Schema allows, e.g., to auto-generate code for data classes ("beans") and data schema verification.

Spacecraft TM data is provided via the data backend. The data exchange integration is done via a multi-protocol Message-oriented Middleware broker that supports MQTT (used for the annotation application), STOMP (used for backend tools), and STOMP via WebSockets (used for the hybrid web application) as protocols. The exchanged data uses JSON for serialization.

- Synthetic Data
  For development and testing, synthetic data is used. The synthetic data generation uses the imported TM metadata information to produce data matching the TM parameters that are used.

    - Synthetic Live Data
      Synthetic live data produces a continuous stream of artificial values.
    - Synthetic Offline Data
      Synthetic offline data produces a 1 year sample of artificial data that can be queried like real data.
- Offline Data Integration
  Offline data integration retrieves offline data from an ESA REST-based data access bridge. This bridge fetches data from the actual ESA data systems and returns it through a unified REST API.

When multiple instances of an application, e.g., the simple data display or the hybrid web application, connect to the same set of topics, a multi-user scenario can be realized. For this, the same state will be shown in all application instances. This can be useful, e.g., for scenarios where the team members are in different locations.

5.3.2 3D Annotation and Live Data Display App

The main use case of the 3D annotation application is to place annotations on a 3D model. Input files to the annotation application are:

- the 3D model to be annotated
- the imported metadata JSON file with the metadata for which annotations shall be placed.

The annotation application is implemented as a Unity AR application. It can be built for iOS and Windows:

- On suitable iOS devices, it supports AR interaction. A user can use the iOS device, e.g., an iPad tablet to load and view the 3D model to be annotated in an AR view such that the model floats in the real environment. For placing annotations, the user can use the AR interaction with the device to navigate around the 3D model and to intuitively place the annotations.

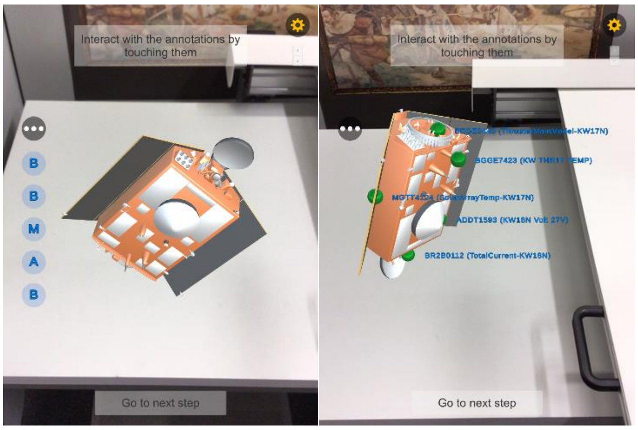

Figure 16 AR Annotation App on iOS

- On Windows with non-AR devices, the display can be loaded and annotated with mouse interaction:

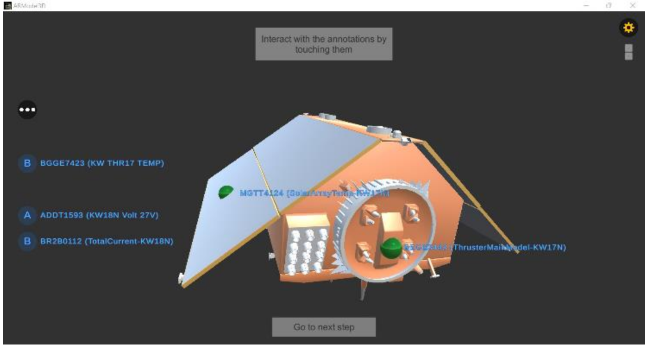

Figure 17 AR Annotation App on Windows

The second use case for the annotation application is to serve as simple 3D display application that can show an annotated 3D model and single set of telemetry data values. The single telemetry data values can be either from a live telemetry data stream or from a joint session with the hybrid web 3D display application. In the latter case, the displayed values will match the data shown in the 3D view in the hybrid web application as described below.

Covering the annotation and simple display use case, the annotation application enabled testing a simple case for an end-to-end content creation pipeline.

5.3.3 Hybrid Web 3D Display Application

Based on further feedback from ESOC stakeholders during the Proof-of-Concept (PoC) development, a use case for combined display and interaction with common data visualization and 3D models was added. The rationale is that spacecraft telemetry is typically treated as timeseries data for which the progression over time is one crucial aspect during analysis.

The hybrid web 3D display application combines timeseries plots with a 3D plot showing the same telemetry overlayed on top of a 3D model. The aim is to combine the capabilities of analyzing spacecraft telemetry with respect to its behavior over time and with respect to its spatial relation. Figure 18 shows a screenshot of the hybrid application.

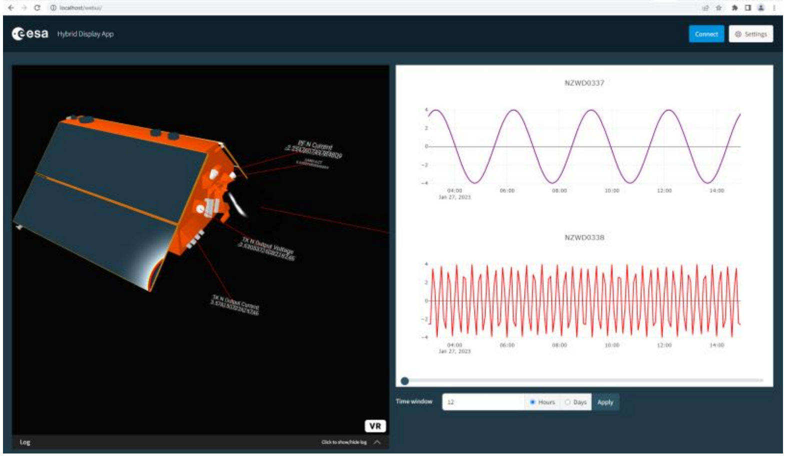

Figure 18 Hybrid Web 3D Display Application Screenshot

Figure 19 shows an overview of the different parts of the web application and their interaction with each other via the backend. The most important interactions are:

- On start-up, when the web UI is in its initial (empty) state, a reset message is sent to the backend. The backend replies to this with the default selection.
- Selecting a TM parameter in the 3D view cycles through the TM parameters that are shown in the x/y timeseries plots. The newly selected TM parameter is set to be displayed in the timeseries plots and the previously oldest shown parameter is removed.
- When the time range selection is changed, the x/y timeseries plots are updated to show the new time range.
- When a single timestamp is selected in the timeseries plots, the 3D display is updated to show the TM parameter values for the displayed parameters at the newly selected timestamp.

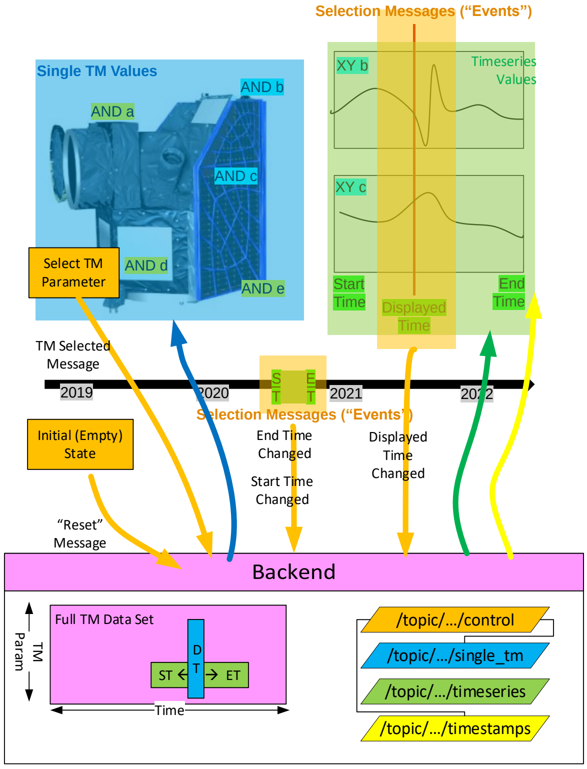

Figure 19 Web Application Interaction

6 Summary and Conclusion

In this paper, we presented the results of an activity at ESA/ESOC on bringing AR/VR closer towards the application in spacecraft mission operations. The aim of this activity was to move into the direction of identifying and prototyping, where AR/VR can provide value to real-world day-to-day applications.

One central aspect we identified for enabling day-to-day applications is to empower users to create their own content when it is needed. This is in-line with experience from previous activities during which content was typically created by dedicated AR/VR experts, which showed to limit the re-usability of results among a broader range of end users, who typically are not AR/VR experts.

To enable users for creating 3D content, we aimed for a solution that should be easily usable and be generic enough to be re-usable in more than one context. For providing this, we defined the concept of a content creation pipeline that supports the end-to-end process starting from creating 3D models to using them in an application scenario. A proof-of-concept end-to-end use case was selected and implemented. It covers the whole process of creating 3D models, annotating them, linking spacecraft data to 3D models, managing the content via a repository, and displaying the 3D/AR/VR content in display views.

We consider that this 3D content creation pipeline significantly eases the AR/VR content creation and reduces the cost of AR/VR assets. Furthermore, we consider that the module building block concept helps in re-using and customizing the content creation pipeline in full or in parts. For future work, our aim is to further lower the barrier of leveraging AR/VR in day-to-day scenarios.

Acknowledgements

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