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XR Applications

As part of the project, test applications were implemented to confirm the correctness of the proposed methodology in the context of its further use for the presentation of historical places, areas, events and linking with museum exhibits. The created applications served to verify the results, therefore they were not optimized in terms of performance, use in non-standard conditions. Three applications were created for the needs of testing (one application for testing the fake avatar generation algorithm implemented in the Unity environment and two applications for linking storytelling events with generated intelligent avatars implemented in the Unreal Engine environment). The project output is two applications in the Unreal Engine environment. For testing purposes, an application using AR - augmented reality was also created, and as part of the final theses of students of the Faculty of Informatics of the Pan-European University, another 6 applications were created for testing partial tasks. All created applications use virtual reality as the basic means for displaying using Meta quest 3 headsets.

1. Testing app (UNITY)

A Unity project was created as a demonstration example, considering the capabilities it offers for the development of interactive 3D experiences. The Map Chamber from the game Hogwarts Legacy served as inspiration, where a character communicates with "pictures" on the walls. The interaction occurs by the player selecting one of the offered options/interactions, and based on this, receiving an adequate response that helps them continue the game. In this way, the player learns details they consider relevant for the continuation, and the visual segment is creatively connected with interactivity, creating a dynamic relationship between the player and the game.

In this project, the implementation of a similar mechanism is planned, where users will have the opportunity to interact with the displays on the walls, which will allow for space exploration and the discovery of new information should this module be integrated into a real game. This concept

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opens up the possibility of implementing a chatbot that could provide players with various information about the next steps or missions, depending on their in-game interactions. In this way, the chatbot would not be just a passive source of information, but could react based on the player's exploration approach. If a player explores a certain area, the chatbot could offer additional guidance on what they might discover or what steps might be important for further game progression. For the chatbot's correct response, it is necessary to forward information about the progress achieved so far or the player's current status. Based on this data, the next logical step in the game could be determined and relevant advice could be offered. This enables personalized interaction, as the chatbot can adapt its responses according to the current progress and the player's exploration approach.

Based on this simple Unity project, we demonstrated the operation of our deepfake chatbot, showing how user input can be converted into a personalized video response. This module is flexible and can be easily integrated into any other project, thereby allowing the addition of interactive video communication to various applications and systems. The appearance of the final project can be seen in the images below.

2. Testing applications – Devín castle and Stummer railway (Unreal engine)

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Both applications were implemented using the same basis of virtual camera movement when implemented through virtual reality. The Devín Castle testing application was developed as an immersive virtual reality experience using the Unreal Engine. The application was designed to evaluate the use of virtual reality, virtual camera movement, interactive historical scenarios, and artificial intelligence-based avatar narration in a reconstructed historical environment.

The application forms part of a broader set of VR applications implemented on a common technical basis. In particular, both applications used the same fundamental approach to virtual camera movement and user tracking when operating in virtual reality. The user's physical movement and head orientation were captured by the VR headset and transferred to the Unreal Engine application, where they controlled the position and orientation of the virtual camera.

The Devín Castle application was prepared for deployment on the Meta Quest 3 VR platform. An Android application package (.apk) was generated as part of the deployment process. Due to the computational requirements of the large language model (LLM) artificial intelligence components used within the project, the final testing configuration employed an external computer connected to the Meta Quest 3 headset via a high-speed cable link.

In this configuration, computationally demanding processes and rendering were performed on the external computer. The Meta Quest 3 headset was primarily used as a virtual reality display device and as a source of positional and rotational tracking data. This approach made it possible to combine the mobility and tracking capabilities of a standalone VR headset with the significantly higher computing performance available on an external workstation.

Within this application, we also present a script for avatar text when using the non-interactive part. This script was also used to generate the avatar. The script was in Slovak for testing with Slovak participants. We present a translation into English.

2.1 Scenario

To develop the application, we captured footage of an actress portraying the avatar. Based on the data obtained, data for the application's avatar was synthesized.

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Opening scene:

"Welcome to Devín Castle. You are standing at a place where rivers, roads and stories of people have met for centuries. This castle has witnessed trade routes, power struggles and the everyday life of those who lived here and protected its walls. Today, however, you will not be just a visitor - in virtual reality you can become a part of its past.

Perhaps you are interested in how the inhabitants of the castle managed life high on a rocky cliff. Without water, the castle would not have survived even a siege, so you can be transported to the period of the Garay dynasty and see with your own eyes how the deep castle well was created - from the demanding work of stonemasons to the techniques that provided water for the entire castle.

Or you can try a completely different role. Imagine that Ottoman troops appear on the horizon and the defenders have to stay alert. You will stand on the walls, observe the surroundings and experience what it was like to protect Devín from the impending danger.

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Where "Will you get married soon?"

Scene – well:

“Welcome to the reign of the Garay family, when Devín Castle was turning into a powerful and representative seat of the Hungarian nobility. It is the 15th century and the new lord of the castle, Palatine Nicholas II. Garay — one of the most powerful men in Hungary — is rebuilding Devín according to his own ideas. The castle is growing, new palaces, fortifications and farm buildings are being added. But one thing is more important for life in the castle than high walls or defensive bastions — water.

Imagine everyday life high on a rocky cliff. Dozens of residents, soldiers and craftsmen need water for cooking or survival during a siege. Carrying it from the river deep below the castle would be dangerous and almost impossible during an attack. That is why the decision was made to build a castle well.

Masons, carpenters and workers are working high above the Danube. The well they are building will reach a depth of approximately fifty-five meters. It is a huge challenge — both the upper and lower parts are reinforced with worked stone blocks, on which the stonemasons leave their marks, as if they were a signature of their work. However, the middle part must be cut directly into the hard bedrock.

And why such a depth? The water gets here through cracks in the rock and is naturally filtered by layers of river sand. Thanks to this, the well can supply the castle with clean water even in times of danger.

Now you can look around the courtyard and help build a place without which Devín would not be able to survive.

Scene – Castle Defense 1:

“Night has fallen on Devín Castle. You are standing above the confluence of the Danube and Morava rivers on the Maiden’s Tower, one of the castle’s best watchtowers. Your task is clear — to observe the surroundings and spot danger in time.

The story is set during a time when the borders of Hungary are threatened by Ottoman troops. News of raids are spreading across the country, and the garrison at Devín remains on constant alert. Although the castle is one of the strong fortresses guarding an important route along the Danube, the defenders know that even high walls do not guarantee safety without watchful eyes on the ramparts.

Look around in the darkness. Do you see flashes of fire? Do you hear distant voices or movement at the foot of the cliff? Every shadow could mean an incoming attack. If the enemy tries to approach the walls, you must act quickly.

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A crossbow and arrows lie ready next to you. No ordinary — their tips can be ignited to illuminate enemy movement or strike attackers and their equipment. Grab your crossbow, aim into the darkness, and watch the movement beneath the castle. When a target appears, light an arrow and fire.

Today you are not just a visitor to history. On this tower, you are part of the castle guard — and Devín is counting on your courage and attentiveness."

Scene – Castle Defense 2:

"Excellent, you've handled your guard duty at the Maiden's Tower. But the castle defense continues. You're moving to the next defensive position — the cannon bastion.

The defenders know that if the enemy gets too close to the walls, it won't just be their courage, but also the power of the castle's weapons that will decide.

You see a cannon ready in front of you, aimed at the other bank of the Danube. Your task is clear — to load and fire at the right moment. One precise shot can stop the attackers' advance and buy the defenders precious time.

Take over the cannon operator. Devín Castle is still under attack — and now its defense depends on you."

2.2 Technical deployment

The technical deployment architecture consisted of three main components:

- an Unreal Engine application,
- an external high-performance computer,
- a Meta Quest 3 virtual reality headset.

The Unreal Engine application was responsible for managing the virtual environment, user interaction, scenario logic, avatar presentation, and communication with external artificial intelligence components.

The external computer served as the primary computational platform. Its responsibilities included:

- real-time rendering of the virtual environment,
- execution of the Unreal Engine application,
- processing of computationally demanding application components,
- communication with the LLM-based artificial intelligence system,

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- generation and management of avatar-related content where applicable.

The Meta Quest 3 headset was connected to the external computer through a cable-based connection. This configuration enabled the rendered image to be transmitted from the computer to the headset while simultaneously providing the application with tracking information.

The headset supplied information concerning:

- the position of the user's head,
- the orientation of the user's head,
- movement within the available tracking area,
- controller-based interaction, where applicable.

These data were used to update the virtual camera within the Unreal Engine environment in real time.

The deployment architecture can therefore be described as a PC-rendered VR configuration with the Meta Quest 3 functioning as the immersive display and tracking interface.

Virtual camera and user movement

A common virtual camera movement system was used as the technical basis for both VR applications developed within the project.

The movement system was designed to map the physical movement of the participant to the movement of the virtual camera. The orientation of the user's head directly influenced the direction in which the virtual camera was facing. This provided a natural first-person perspective and enabled participants to observe the virtual reconstruction of Devín Castle by physically turning their heads.

Depending on the available interaction space and scenario requirements, user movement could be implemented using a combination of:

- physical movement within the tracked area,
- controller-based locomotion,
- scenario-based repositioning or teleportation.

The selected movement approach was intended to provide an immersive experience while maintaining a stable and predictable interaction model for testing participants. The same fundamental camera architecture was retained across all scenes to ensure consistency. As a

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result, users did not need to learn a new navigation method when transitioning between scenarios.

Meta Quest 3 Integration

The Meta Quest 3 headset was selected as the primary virtual reality interface for testing the application.

The headset provided stereoscopic visualization of the virtual environment and real-time tracking of the participant's head position and orientation. The tracking information was integrated into the Unreal Engine VR framework and used to control the application's virtual camera.

During deployment, particular attention was given to the communication between the headset and the external computer. A cable-based connection was selected to provide a stable connection suitable for the transmission of high-resolution rendered data and real-time interaction information.

The deployment procedure included the following steps:

1. installation and configuration of the required Meta Quest development environment;
2. installation of the appropriate Unreal Engine VR integration;
3. connection of the Meta Quest 3 headset to the external computer;
4. verification of headset detection by the operating system and VR runtime;
5. configuration of the Unreal Engine project for the selected VR runtime;
6. testing of head tracking and controller input;
7. execution of the application in virtual reality mode;
8. verification of rendering performance and interaction latency.

An Android .apk package was also generated for the application. This package represented a deployable version of the application for the Android-based Meta Quest environment. The APK build was used for testing and deployment purposes where standalone installation was required.

Rendering and Computational Infrastructure

The Devín Castle application contained computationally demanding components associated with the integration of artificial intelligence. In particular, the use of a large language model

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required substantially greater computational resources than those available directly within a standalone VR headset.

For this reason, an external computer was used as the primary computational platform.

Rendering was performed externally rather than exclusively on the mobile hardware of the headset. This approach provided several advantages:

- higher available CPU and GPU performance;
- the ability to render more complex virtual environments;
- increased flexibility for integrating external software components;
- support for computationally demanding LLM processing;
- simplified debugging and monitoring during testing.

The separation of rendering and display functionality allowed the VR headset to focus primarily on immersive visualization and tracking.

The application architecture was therefore divided conceptually into the following layers:

Presentation layer

The Meta Quest 3 headset displayed the stereoscopic virtual environment to the participant and captured tracking information.

Rendering layer

The external computer executed the Unreal Engine rendering pipeline and generated the frames displayed in the headset.

Application logic layer

Unreal Engine managed scenario transitions, interaction logic, object behavior, user input, and the overall progression of the application.

Artificial intelligence layer

LLM-based functionality was executed using the available external computational infrastructure. This layer was responsible for the artificial intelligence functionality required by the application and associated avatar interaction or content generation.

Application Packaging and APK Deployment

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An Android application package (.apk) was generated as part of the application deployment process.

The APK packaging procedure involved configuring the Unreal Engine project for the Android platform and preparing all required application assets. The generated package contained the executable application components and associated resources required for installation on a compatible Meta Quest device.

The general deployment workflow consisted of:

1. configuring Android platform settings in Unreal Engine;
2. configuring the required Android SDK and related development tools;
3. preparing application assets for packaging;
4. defining the application identifier and deployment settings;
5. building the project for the Android platform;
6. generating the .apk application package;
7. transferring the package to the Meta Quest device;
8. installing and testing the application.

The APK deployment enabled the project to be evaluated in a headset-oriented configuration independently of the development environment where appropriate.

However, because the LLM component required substantial computational resources, the external computer configuration remained important for the complete testing environment.

Deployment Limitations

Several technical limitations were identified during the deployment of the application.

The primary limitation was the computational performance required by the LLM artificial intelligence component. A standalone Meta Quest 3 configuration does not provide the same level of computing resources as a dedicated external workstation. For this reason, external processing infrastructure was required for the complete experimental configuration.

A second limitation concerned the dependency on the cable connection between the headset and the external computer. Although this configuration provided reliable data transmission and access to external computing power, it reduced the physical mobility of the participant compared with a fully standalone or wireless VR deployment.

The complexity of the historical environment also influenced rendering requirements. High-quality geometry, lighting, visual effects, and interactive objects can significantly increase GPU

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requirements. Performance optimization was therefore an important part of the deployment process.

Potential optimization techniques include:

- level-of-detail systems;
- optimized texture resolution;
- occlusion culling;
- simplified collision geometry;
- efficient lighting;
- selective loading of scene assets;
- optimization of AI communication frequency.

3. Conclusion

The Devín Castle and Stummer railway applications were successfully designed as a virtual reality testing environment combining historical reconstruction, interactive scenarios, avatar-based narration, and artificial intelligence functionality.

The technical deployment was based on Unreal Engine and the Meta Quest 3 VR headset. An Android APK package was created for the application, while the complete testing environment also used an external computer connected to the headset through a cable link.

The external computer was responsible for computationally demanding operations, including application rendering and support for the LLM artificial intelligence functionality. The Meta Quest 3 headset provided immersive stereoscopic visualization and real-time information about the position and orientation of the participant.

The application was divided into four scenes: an introductory scene, a scenario focused on the historical castle well, and two scenarios dedicated to the defense of Devín Castle.

This deployment architecture demonstrated a practical approach to combining standalone virtual reality hardware with external high-performance computing resources. The resulting system enabled the implementation and testing of a complex VR application that combined immersive historical education, interactive gameplay elements, virtual camera movement, avatar narration, and artificial intelligence-based functionality.

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