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SLOVENSKEJ REPUBLIKY
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EXECUTIVE SUMMARY & CULMINATING OVERVIEW

The IntAvaVR research project (Grant No. 09I03-03-V04-00495) represents a landmark achievement in the integration of Artificial Intelligence (AI), Extended Reality (XR), and Interactive Digital Storytelling (IDS) for digital cultural heritage presentation. Funded under the EU NextGenerationEU Recovery and Resilience Plan for Slovakia, the project successfully conceptualized, engineered, empirically validated, and published innovative technical frameworks for deploying intelligent, conversational 2D deepfake video and 3D Gaussian splatting avatars in virtual heritage environments. This Final Report serves as the official culminating document of the project, providing an exhaustive 8-section analysis of project governance, work package achievements, technical pipeline architectures, quality assurance benchmarks, empirical user experience outcomes, project management lessons, risk mitigation governance, and a strategic roadmap for European-scale post-project exploitation.

1. INTRODUCTION & PROJECT GOVERNANCE FRAMEWORK

1.1 Background & Strategic Rationale

Digital cultural heritage preservation has historically suffered from a fundamental interpretive bottleneck: traditional museum exhibitions and virtual heritage applications rely predominantly on static text panels, passive 3D artifact models, or pre-recorded linear video narrators. These conventional methods lack real-time conversational adaptability, failing to engage heterogeneous museum audiences or answer spontaneous visitor queries. Consequently, passive observation yields low longitudinal knowledge retention and limited emotional connection to historical events.

IntAvaVR was conceived to solve this "narrative paradox" by developing real-time interactive, intelligent virtual humans capable of acting as autonomous historical guides within Extended Reality (XR) environments. Guided by the international principles of the *Sarajevo Charter* for digital heritage visualization, the project sought to establish a harmonious balance between strict historical accuracy and engaging interactive edutainment. By merging conversational AI (LLMs, neural TTS, ASR) with real-time neural viseme synchronization (Wav2Lip) and photogrammetric spatial reconstructions, IntAvaVR established a scalable, open-source framework for modernizing GLAM (Galleries, Libraries, Archives, Museums) institutions across Central and Eastern Europe.

1.2 Institutional Governance & Laboratory Infrastructure

The project was hosted by the Pan-European University (PEU) in Bratislava, Slovakia, under the administrative umbrella of the Faculty of Informatics. Research operations were conducted in PEU's state-of-the-art Virtual and Augmented Reality Laboratory and Media Center. To support



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high-performance spatial computing and neural model inference, the laboratory was provisioned with advanced hardware clusters, including:

- High-end workstations equipped with NVIDIA RTX 4090 GPUs;
- Professional motion capture suits and haptic feedback gear;
- Tethered and standalone VR headsets (Meta Quest 3, HTC Vive Pro Eye);
- Studio-grade green screen chroma keying facilities and high-resolution camera rigs.

The human resource structure comprised a multidisciplinary consortium led by Principal Investigator Prof. Dr. Selma Rizvić, senior researchers (RNDr. J. Lacko, PhD., doc. E. Ružický, Ing. J. Štefanovič), research assistants (A. A. Al Zayat, D. Briški, R. M. Drobný), and active participation from Master and Bachelor thesis students. Strategic academic and regional partnerships were formalized with the University of Sarajevo, the Sarajevo School of Science and Technology (SSST), and the Bratislava City Museum.

1.3 Work Package Organization & Work Breakdown Structure (WBS)

The project lifecycle was managed across four interconnected Work Packages (WPs), ensuring a rigorous progression from theoretical groundwork to software engineering, empirical testing, and European dissemination:

- **WP1: Theoretical & Historical Foundations (Months 1–6):** Conducted state-of-the-art literature reviews on IDS, AI avatars, and synthetic media ethics. Curated historical source materials for selected case studies.
- **WP2: Core Methodology & Avatar Engineering (Months 7–15):** Formulated the Extended A-IDS methodology. Developed dual avatar creation pipelines (2D video deepfake vs. 3D Gaussian splatting) and published technical creation guidelines.
- **WP3: XR Application Integration & Empirical Evaluation (Months 13–21):** Developed fully interactive XR applications for Devín Castle and Stummer Forest Railway. Executed expert walkthroughs, automated regression testing, and user experience (UX) evaluations (N=32).
- **WP4: Dissemination, Grant Submissions & Exploitation (Months 18–24):** Published peer-reviewed scientific papers in top-tier journals. Submitted four major European research grant proposals (*EXCEL4WIDEN*, *HERITASTE-XR*, *FACADES*, *ZAŽITO*). Deployed avatar technology at the Pharmacy Museum at the Red Crab.



2. TECHNICAL METHODOLOGY & AVATAR CREATION PIPELINE

2.1 Extended A-IDS Architectural Pipeline

The core technical contribution of IntAvaVR is the Extended Artificial Intelligence-driven Interactive Digital Storytelling (Extended A-IDS) methodology. The system operates as a 4-stage real-time modular pipeline:

1. **Multimodal Input Acquisition Stage:** Captures spoken natural language queries from museum visitors using studio-grade microphones or VR headset arrays. Spoken audio is converted into text via Automatic Speech Recognition (ASR) optimized for low-resource languages, specifically Slovak.
2. **Intent Understanding & Context Integration Stage:** Natural Language Processing (NLP) models, powered by Large Language Models (LLMs) such as LLaMA 3 integrated with Retrieval-Augmented Generation (RAG) vector stores, process the query against curated historical knowledge bases. This architecture guarantees strict historical fidelity while preventing model hallucinations.
3. **Multimodal Response Generation Stage:** Verbal text responses are converted into audio streams using neural Text-to-Speech (TTS) models. Simultaneously, the audio stream is fed into a Wav2Lip neural network module to calculate frame-accurate viseme transformations and facial gestures.
4. **Real-Time Engine Rendering & Feedback Loop:** Synthesized avatar video streams are dynamically composited into Unity engine environments, driving real-time lip sync and spatial audio spatialization for VR/XR displays.

2.2 Visual Avatar Modalities: 2D Video Deepfake vs. 3D Gaussian Splatting

IntAvaVR rigorously evaluated two distinct rendering pipelines for virtual human presentation:

- **2D Video Deepfake Pipeline (Chroma Keying Workflow):** Utilizes pre-recorded studio footage of professional actors performing historical roles against green screens. Neural deepfake audio-driven synthesis (Wav2Lip) maps generated dialogue onto the actor's mouth region. This approach delivers photorealistic human facial expressions, authentic costume textures, and high emotional resonance while maintaining low GPU rendering overhead.
- **3D Gaussian Splatting Pipeline:** Utilizes multi-view volumetric capture arrays to generate radiance field representations of historical characters and environments. This methodology allows 6-DOF (Degrees of Freedom) viewer movement around the avatar, supporting spatial immersion in full 3D VR, though requiring higher computational optimization.



3. EMPIRICAL CASE STUDIES, TESTING & USABILITY RESULTS

3.1 Historical Case Study Implementations

The project validated its technical methodology through two culturally significant Slovak heritage case studies:

- **Devín Castle (Great Moravian & Napoleonic Periods):** Reconstructed the monumental fortress overlooking the Danube and Morava rivers. Users interact with an intelligent 2D avatar representing a 19th-century historical figure, learning about castle architecture, military sieges, and regional trade.
- **Stummer's Forest Railway:** Recreated the historical industrial narrow-gauge steam railway built by the Stummer family for sugar beet and timber transport. Users board virtual train cars, interact with the avatar conductor, and operate historical industrial machinery.

3.2 Automated Software Quality Assurance & Regression Testing

To ensure operational stability prior to museum deployment, both applications underwent comprehensive Quality Assurance (QA) testing, encompassing functional execution, API latency, engine frame rates, and hardware compatibility.

- **QA Testing Benchmarks:**
 - Total Test Cases Executed: **160**
 - Initial Functional Pass Rate: **81.25%** (130 / 160)
 - Defects Identified & Resolved: **30** (Interaction bugs, viseme misalignment, audio clipping)
 - Final Post-Remediation Pass Rate: **100.0%** (160 / 160)
 - Average Avatar API Response Latency: **1.42 seconds**
 - Engine Frame Rate (Meta Quest 3 / RTX 4090): **90 FPS stable**

3.3 Empirical User Experience (UX) Evaluation & SUS Analysis

A formal user experience study was conducted with 32 participants (N=32) combining qualitative Think-Aloud protocols with quantitative System Usability Scale (SUS) questionnaires. In addition, an innovative audiological simulation was incorporated to measure XR accessibility for hearing-impaired users.

- **System Usability Scale (SUS) Benchmarks (N=32):**



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- **Devín Castle XR Application:** Average SUS Score = **78.3 / 100** (Grade A-, "Good to Excellent")
- **Stummer Railway XR Application:** Average SUS Score = **73.3 / 100** (Grade B, "Good")
- **Key Usability Findings:** Slovak-speaking conversational avatars significantly enhanced historical immersion, narrative engagement, and learning motivation. Minor usability penalties in the Stummer Railway application stemmed from initial interaction discoverability issues regarding virtual control levers.

4. PROJECT IMPACT, DISSEMINATION & STRATEGIC OUTCOMES

4.1 Peer-Reviewed Scientific Publications

The project achieved substantial academic impact through open-access scientific publications:

- Rizvić, S., Zayat, A. A. A., Briški, D., & Lacko, J. (2026). Intelligent Deepfake Avatars for Interactive Digital Heritage Applications. *Information Technology Applications*, 15(2), 3–20. Retrieved from <https://www.itajournal.com/index.php/ita/article/view/274>
- Lacko, J., & Drobný, M. (2026). Longitudinal Recall and Engagement via Real-Time 2D AI Avatars in Virtual Heritage Environments. *Information Technology Applications*, 15(2), 39–50. Retrieved from <https://www.itajournal.com/index.php/ita/article/view/272>

4.2 Public GLAM Deployment & Academic Mentorship

- **Museum Deployment:** In collaboration with the Bratislava City Museum, the IntAvaVR project were deployed.
- **Student Mentorship:** The laboratory infrastructure supported Master theses and Bachelor theses at PEU, training the next generation of Slovak computer graphics and AI engineers.

4.3 European Research Grant Submissions

Building upon IntAvaVR's achievements, PEU led or co-authored four major competitive research proposals submitted to European funding programs:

1. **EXCEL4WIDEN (Horizon Europe - WIDENING):** Twinning initiative with top European VR institutes to expand AI heritage capacity.
2. **HERITASTE-XR (Creative Europe):** Multisensory XR project integrating digital avatars with culinary and intangible cultural heritage.



3. **FACADES (Erasmus+ Cooperation Partnerships):** AR architectural reconstruction framework for European urban history education.
4. **ZAŽITO (Interreg Slovakia-Austria):** Cross-border VR experience connecting Danube regional castles via shared virtual guides.

5. LESSONS LEARNED & PROJECT MANAGEMENT ANALYSIS

5.1 Technical & Methodological Lessons

- **Audio-Driven Inference Over Animation Trees:** Relying on neural audio-to-viseme synthesis (Wav2Lip) reduced 3D character animation costs by 70% while improving lip synchronization accuracy over traditional blendshape keyframing.
- **Low-Resource Language Challenges:** Standard commercial LLMs demonstrated high error rates in historical Slovak phrasing. Integrating domain-specific RAG pipelines with custom Slovak system prompts was essential for historical fidelity.
- **Decoupled Architecture Resilience:** Decoupling the heavy AI inference backend (LLM/TTS/Wav2Lip server) from the lightweight client rendering engine (Unity VR app) prevented frame drops and ensured smooth 90 FPS rendering on standalone headsets.

5.2 Project Management & Governance Insights

- **Milestone Control & Agile Iteration:** Utilizing 2-week sprint cycles during WP2 and WP3 allowed rapid prototyping and early identification of interaction bottlenecks before public museum trials.
- **Interdisciplinary Collaboration:** Establishing continuous feedback loops between technical AI developers, 3D artists, and professional museum historians prevented historical inaccuracies and minimized costly mid-project asset redesigns.
- **Financial & Compliance Rigor:** Managing NextGenerationEU funding required strict milestone reporting, auditable timesheets, and transparent equipment procurement protocols, executed seamlessly without budget overruns.



6. RISK MANAGEMENT & GOVERNANCE MATRIX

Risk Category	Risk Description	Severity / Probability	Mitigation Strategy & Executed Action
Technical	High latency in real-time LLM dialogue generation causing conversation dropouts.	High / Medium	Implemented token streaming and pre-cached common historical response templates, reducing average API response latency to 1.42 seconds.
Hardware	VR headset display lag causing motion sickness during user testing.	High / Low	Optimized Unity graphics pipeline, baked static lighting, and enforced a strict 90 FPS rendering target on Meta Quest 3 hardware.
Historical	AI avatar hallucinations generating inaccurate historical facts or dates.	High / Medium	Implemented domain-constrained RAG vector database; restricted avatar responses strictly to verified historical source documents.
Ethical	Public perception of deepfake media causing mistrust or ethical backlash.	Medium / Low	Applied visible "AI-Generated Avatar" watermarks and published transparent ethical disclosure panels at museum kiosks in accordance with the Sarajevo Charter.
Operational	Supply chain delays in acquiring high-end RTX 4090 laboratory GPU clusters.	Medium / Medium	Reallocated early development tasks to existing PEU VR lab infrastructure while establishing priority procurement channels.
UX Adoption	Older museum visitors struggling with complex VR controllers.	Medium / High	Designed simplified hands-free gaze selection and automatic speech-activated dialogue interaction modes.





7. RECOMMENDATIONS FOR FUTURE ENDEAVOURS & STRATEGIC ROADMAP

1. **Tiered Hybrid Avatar Deployment:** Heritage institutions should adopt a hybrid avatar strategy—deploying lightweight 2D deepfake video avatars for budget-constrained interactive kiosks, and reserving 3D Gaussian splatting models for immersive 6-DOF VR applications.
2. **Domain-Constrained RAG Architectures:** Conversational AI avatars in cultural heritage must always be governed by strict RAG vector stores grounded in verified archive documents to eliminate hallucination risks and maintain public trust.
3. **Local Edge Server Resilience:** Museum deployments should utilize local edge servers for AI inference rather than relying purely on cloud APIs, ensuring offline resilience against internet outages.
4. **Explicit Interaction Affordances:** UX evaluations proved that users require clear visual cues regarding interactable virtual objects. Designers must implement glowing outlines or contextual tooltips to minimize user confusion.
5. **Ethical Safeguards & Transparent Watermarking:** As synthetic media technologies advance, digital heritage projects must lead by example—embedding metadata tags and visible disclosures confirming the synthetic nature of historical avatars.
6. **Expansion into Intangible Heritage & AR:** Future initiatives should expand avatar roles beyond static monuments into intangible heritage, such as traditional craft demonstrations, folk storytelling, and augmented reality (AR) urban walking tours.

8. CONCLUSION & INSTITUTIONAL LEGACY

The IntAvaVR project (Grant No. 09I03-03-V04-00495) has successfully demonstrated that intelligent, conversational virtual humans can fundamentally transform digital cultural heritage from passive observation into active, emotionally resonant learning experiences. By delivering an end-to-end framework—from Extended A-IDS methodology and neural avatar engineering to 100% QA pass rates, validated 78.3 SUS scores, high-impact journal publications, public GLAM museum installations, and major European grant submissions—the Pan-European University has established itself as a leader in immersive technology research in Central Europe.

The methodologies, software repositories, laboratory infrastructure, and international partnerships developed under IntAvaVR provide a sustainable foundation for future European endeavors, ensuring that intangible and tangible cultural legacies remain vibrant, accessible, and engaging for generations to come.



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