A Multi-Device University XR Testbed for Immersive Learning, Training, and Human-in-the-Loop Research

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Abstract. Extended reality (XR) encompasses virtual reality (VR), augmented reality (AR), and mixed reality (MR) technologies. These technologies are increasingly used in education, training, and human-in-the-loop research. Their effective experimental use requires a structured environment that combines suitable XR modalities, interaction methods, and measurement capabilities. This paper presents the FRI Virtual Lab at the Faculty of Management Science and Informatics, University of Zilina, as a multi-device XR testbed. The testbed combines standalone and PC-based VR, video-see-through MR, optical-see-through MR, and external motion tracking. A common framework for XR experimentation is proposed based on five stages: Data or Model, XR Representation, Human Interaction, Measurement, and Evaluation. The framework separates domain-specific content from reusable experimental components. Its application is illustrated through scenarios in anatomy education, movement-oriented biomedical research, crisis and safety training, robotics, and AI-assisted industrial inspection. The proposed approach provides a methodological basis for comparative studies of XR modalities and interdisciplinary experiments involving human interaction with spatial digital information.

Keywords: extended reality; virtual reality; mixed reality; XR testbed; immersive learning; human-in-the-loop; university education

1 Introduction

Extended reality (XR) technologies can support spatial visualization, interactive simulation, training, and the study of human behaviour. Their use in higher education has grown rapidly, but access to immersive hardware alone does not guarantee effective learning or valid experimental results. Reviews of immersive VR in higher education report substantial variation in application design, learning outcomes, and evaluation methods [13, 6]. More recent work also points to a limited availability of standardized research frameworks and repeated comparative studies [16].

XR systems also differ in how digital content is related to the physical environment. Fully immersive virtual reality (VR) replaces the user's surroundings,

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while augmented reality (AR) and mixed reality (MR) combine digital information with the real world. Optical and video-based approaches differ in how the physical environment is perceived and how virtual content is registered [1]. These differences can become experimental variables when the same task is presented through different XR modalities.

The present work builds on previous activities at the Faculty of Management Science and Informatics, University of Zilina. The 3DBody platform established a basis for interactive anatomy education and medical terminology [2, 4], while later work investigated real-time anatomical AR and motion-aware overlays [5]. The Virtual Lab was also previously described from the perspective of digital motion processing and OptiTrack-based motion capture [9]. The current paper extends this foundation toward a broader multi-device XR testbed.

The FRI Virtual Lab combines three XR modalities with external motion tracking. Its purpose is to support a common workflow in which domain-specific data or models are transformed into an XR representation, presented to a human user, measured during interaction, and evaluated according to the research objective. This approach allows the research question to determine the required XR modality, interaction method, and measurement capabilities within a common experimental framework.

The contribution of the paper is threefold:

1. It presents a capability-oriented design of a heterogeneous university XR testbed that combines several XR modalities with external motion tracking.
2. It proposes a common experimental framework based on Data or Model, XR Representation, Human Interaction, Measurement, and Evaluation.
3. It maps this framework to representative scenarios in biomedical education, movement-oriented research, crisis and safety training, robotics, and AI-assisted industrial inspection.

Together, these contributions position the FRI Virtual Lab as a reusable environment for designing and evaluating XR experiments across different application domains. The proposed testbed and common framework provide a basis for comparative studies of XR modalities, interaction methods, and measurement approaches.

2 FRI Virtual Lab as a Multi-Device XR Testbed

The FRI Virtual Lab is operated within the Faculty of Management Science and Informatics at the University of Zilina and provides shared infrastructure for research, teaching, and student project activities. Its physical arrangement supports work with head-mounted displays, external motion tracking, and dedicated graphics workstations. Figure 1 illustrates three representative head-mounted displays used in the testbed and highlights the diversity of supported XR modalities.

Table 1 summarizes the core XR and tracking equipment together with characteristics that are relevant to experimental use. The devices provide complementary capabilities: Meta Quest 3 supports portable VR and video-see-through



Fig. 1. Representative head-mounted displays used in the FRI Virtual Lab: Meta Quest 3 (left), Magic Leap 2 (centre), and HTC Vive Pro 2 (right).

MR, HTC Vive Pro 2 provides PC-based immersive VR, Magic Leap 2 provides optical-see-through MR, and OptiTrack can serve as an external motion reference. This heterogeneous configuration supports experiments in which the selected modality and measurement method follow the requirements of the research task rather than the availability of a single device.

Table 1. Core XR and tracking hardware of the FRI Virtual Lab.

Device (quantity)	**XR modality**	**Selected characteristics**	**Experimental role**
Meta Quest 3 (2) [12]	Immersive VR, video-see-through MR	2064 × 2208 px per eye; standalone; inside-out tracking; controllers; hand tracking; color passthrough	Portable VR/MR and multi-user experiments
HTC Vive Pro 2 (2) [7]	Immersive VR	2448 × 2448 px per eye; 90/120 Hz; up to 120° horizontal FOV; SteamVR Tracking 2.0; PC rendering	Controlled high-fidelity VR experiments
Magic Leap 2 (1) [10]	Optical-see-through MR	1440 × 1760 px per eye; 45° H × 55° V FOV; head, controller, hand, and eye tracking; RGB and depth sensing	Spatial overlays and physical-digital interaction
OptiTrack (1 system) [9]	External optical tracking	PrimeX 13 cameras; up to 240 Hz; marker, rigid-body, and skeletal tracking	External motion reference and tracking validation

3 Design Objectives of the XR Testbed

The FRI Virtual Lab should support different application domains without requiring a separate technological concept for every research scenario. Its design therefore follows five objectives related to XR modality, device independence, measurement, extensibility, and university education.

Support for multiple XR modalities. The testbed supports immersive VR, video-see-through MR, and optical-see-through MR. Researchers can therefore select a modality according to the task and compare presentation conditions while preserving similar digital content.

Capability-oriented design. Research scenarios are defined by required capabilities, such as immersive visualization, spatial registration, controller or hand interaction, external motion measurement, and multi-user participation, rather than by a specific commercial headset. Task instructions, target information, interaction sequence, and evaluation criteria can remain consistent while the XR modality becomes an experimental variable, which improves comparability between conditions.

Measurability of human interaction. Experimental applications should provide objective measures such as task time, response time, errors, selections, decisions, navigation paths, or movement trajectories. Device tracking can add head, controller, hand, or gaze data where available, while subjective instruments can address workload, usability, presence, comfort, or confidence. This supports the need for systematic evaluation identified in immersive learning and training research [13, 16, 15].

Extensibility. The testbed should accept data produced outside the XR application, including anatomical models, simulations, motion trajectories, robot or sensor data, and outputs of intelligent algorithms. This keeps the XR representation independent from the method that generated the input and supports interdisciplinary integration.

Integration of research and education. The university setting allows the same infrastructure to support research and project-based education. Students can use immersive applications to study spatial content and can also develop 3D scenes, interaction methods, data interfaces, and experimental components that may later contribute to research prototypes.

4 A Common Framework for XR Experimentation

The representative application domains use different data and pursue different objectives, but they share a common experimental structure. We therefore propose a five-stage framework consisting of Data or Model, XR Representation, Human Interaction, Measurement, and Evaluation. Figure 2 summarizes the workflow and its relation to the capabilities of the FRI Virtual Lab.

The framework separates domain-specific information from reusable experimental functions and makes measurement and evaluation explicit parts of the

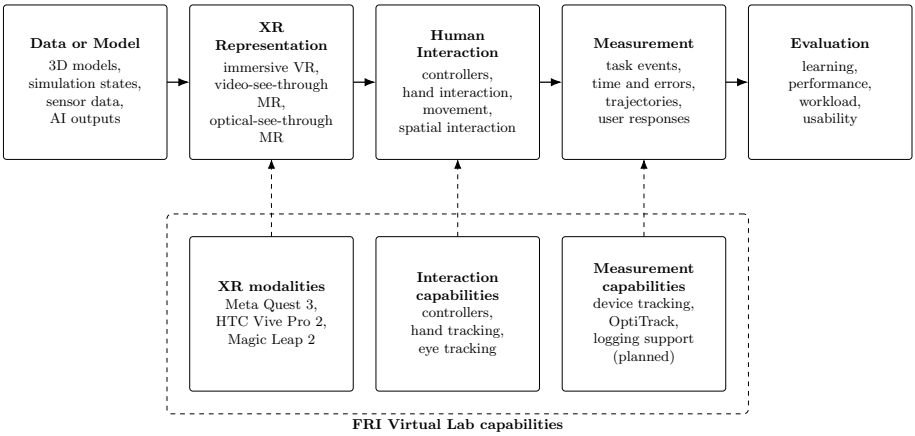


Fig. 2. Common framework for XR experimentation in the FRI Virtual Lab and its relation to the available testbed capabilities.

research process. This structure supports the systematic comparison of XR conditions while keeping the underlying task and research objective as consistent as possible [13, 16].

Data or Model. Every scenario begins with digital information that should be presented to the user. The input can include a 3D model, simulation state, sensor measurement, trajectory, image, educational task, or output of an intelligent algorithm, while the framework remains independent of how these data were created.

XR Representation. The input is transformed into a spatial representation suitable for the selected modality. Immersive VR can be used when the experiment requires full control of the environment, whereas video-see-through or optical-see-through MR can preserve a relationship between digital information and physical surroundings.

Human Interaction. The participant observes and acts on the presented information through navigation, selection, manipulation, movement, or decision making. The interaction technique should correspond to the research task and to the capabilities of the selected XR device so that device-specific interaction does not unnecessarily change the experimental objective.

Measurement. Interaction produces objective data such as task time, errors, selections, responses, navigation paths, or movement trajectories. Device tracking and OptiTrack can provide additional spatial measurements, while subjective instruments can address workload, usability, presence, confidence, or related constructs. Relevant events and experimental conditions should be defined before implementation and recorded through structured logging.

Evaluation. The recorded measurements are interpreted according to the research objective. Educational scenarios may focus on learning or spatial understanding, training scenarios on task performance and decision making, and

robotics or industrial scenarios on accuracy and interpretation of spatial information. Comparisons can then examine the suitability of particular XR modalities or interaction techniques without assuming that one device is universally preferable.

The same experimental structure can be reused across different application domains, while the input data, participant tasks, measurement variables, and evaluation criteria remain specific to each scenario. This separation provides a basis for developing reusable XR, interaction, and logging components without forcing different research questions into an identical experimental design. The framework therefore provides a shared methodological basis while preserving the flexibility required by individual application domains.

At the current stage, the operational testbed consists of the XR and tracking hardware summarized in Table 1, together with the device-level interaction and measurement capabilities provided by these systems. Existing 3DBody content [2], anatomical AR prototypes [5], and previous motion-processing work provide application-specific assets and experience for selected scenarios. The common five-stage framework proposed in this paper defines how these resources can be organized for future experiments. A unified cross-device layer for experiment configuration, structured logging, and data export has not yet been implemented and represents a planned extension of the testbed.

5 Representative Research and Educational Scenarios

Several representative scenarios demonstrate how the common framework can be applied across different research and educational domains.

Immersive anatomy and biomedical education. Existing 3DBody models and educational content provide a direct basis for immersive anatomy experiments [2]. Recent evidence supports the educational potential of VR and AR in anatomy while also showing that the effect depends on the selected modality and study design [3]. A future experiment could present comparable anatomical tasks through desktop 3D, immersive VR, video-see-through MR, and optical-see-through MR. Task time, identification accuracy, errors, pre-test and post-test results, workload, and usability could then be used to evaluate which representation is appropriate for a particular learning objective.

Movement-oriented biomedical research. Previous faculty work on real-time anatomical AR provides a starting point for connecting spatial visualization with human movement [5]. The XR testbed can present target positions, reference trajectories, or anatomical guidance while participants perform reaching or positioning tasks. Device tracking can capture interaction data and OptiTrack can provide an independent motion reference. Measures such as movement time, trajectory deviation, positioning accuracy, path characteristics, or range of motion are consistent with variables reported in reviews of immersive upper-limb assessment [8]. This scenario is intended for technical and experimental research, not as a clinically validated rehabilitation system.

Crisis and safety training. Immersive VR can reproduce hazardous situations that would be difficult, expensive, or unsafe to create physically. Safety-training research shows the importance of evaluating behaviour and task performance in addition to subjective reactions [15]. A scenario can contain a virtual environment, hazards, event sequences, and task objectives, while participants navigate, identify risks, and make decisions under time constraints. Response time, route selection, missed hazards, incorrect actions, workload, and situational awareness can provide measurable outcomes, and the availability of multiple headsets also creates a basis for collaborative scenarios.

Robotics and human-machine interaction. AR has been investigated in robot programming, motion planning, simulation, manipulation, and human-robot interaction [11]. The XR testbed can visualize a robot model, current pose, trajectory, target position, safety zone, or sensor information in VR or MR while the underlying control or simulation system remains independent of the representation. Participants can inspect trajectories, select targets, or identify unsafe movement, with decision time and accuracy used as evaluation measures. OptiTrack can provide an external reference when physical robot motion needs to be compared with planned or simulated data.

AI-assisted industrial inspection and training. In this scenario, the intelligent method performs defect detection or classification, while XR provides a spatial interface for human interpretation. Previous experimental work has shown that AR presentation of defect information can influence task performance and mental workload in industrial quality inspection [14]. A wind-turbine blade model can, for example, contain defect locations, classes, and confidence values that are displayed spatially in VR or MR. A future experiment could compare screen-based and XR presentation using the same inspection output and measure localization time, identification accuracy, decision time, confidence, and workload.

Across these scenarios, domain data and evaluation goals differ, while experiment configuration, interaction logging, task timing, and tracking can be reused. This shared structure is central to treating the FRI Virtual Lab as a research testbed rather than as a set of unrelated XR applications.

6 Discussion and Conclusion

This paper presented a capability-oriented design of the FRI Virtual Lab as a multi-device XR testbed. Its main methodological contribution is the common framework shown in Figure 2, which connects Data or Model, XR Representation, Human Interaction, Measurement, and Evaluation. The work is conceptual and design-oriented and therefore does not report results from a completed comparative user study.

The heterogeneous configuration creates research opportunities but also requires careful experimental design. The available devices differ in display, tracking, interaction, and computational architecture, so future comparisons should keep tasks and content as consistent as possible while documenting device-

specific conditions. Experimental applications should also support structured logging of relevant events and measurements, with OptiTrack used as an external reference where appropriate. Biomedical experiments involving clinical populations or claims of clinical effectiveness would additionally require suitable collaboration, validation, and ethical approval.

Further development will focus on reusable components for experiment configuration, logging, and data export, followed by benchmark experiments in selected domains. Anatomy education is a suitable starting point because existing 3DBody content can be reused, while robotics provides a complementary scenario with different spatial and interaction requirements. The objective is not to identify a universally preferable XR device, but to provide a testbed in which the research question determines the appropriate representation, interaction method, and measurement approach.

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References

1. Azuma, R.T.: A survey of augmented reality. Presence: Teleoperators and Virtual Environments 6(4), 355–385 (1997)
2. Bobak, D., Gabrisova, A., Juricek, M., Kulas, P., Listvan, A., Jelinek, A., Kardosova, K., Kvassay, M.: Development of online anatomical atlas for biomedical informatics. In: 2023 21st International Conference on Emerging eLearning Technologies and Applications (ICETA). pp. 68–75. IEEE (2023)
3. García-Robles, P., Cortés-Pérez, I., Nieto-Escámez, F.A., García-López, H., Obrero-Gaitán, E., Osuna-Pérez, M.C.: Immersive virtual reality and augmented reality in anatomy education: A systematic review and meta-analysis. Anatomical Sciences Education 17(3), 514–528 (2024)

4. Gorny, M., Chabada, M., Kvassay, M.: Development of universal administration module for online 3DBody anatomical atlas. In: 2024 International Conference on Emerging eLearning Technologies and Applications (ICETA). pp. 151–157. IEEE (2024)
5. Gorný, M., Kvaššay, M.: Toward real-time augmented reality in healthcare. Journal of Information, Control and Management Systems 23(2), 9–22 (2025)
6. Hamilton, D., McKechnie, J., Edgerton, E., Wilson, C.: Immersive virtual reality as a pedagogical tool in education: A systematic literature review of quantitative learning outcomes and experimental design. Journal of Computers in Education 8(1), 1–32 (2021)
7. HTC VIVE: VIVE Pro 2 Full Kit Specs. VIVE, https://www.vive.com/us/product/vive-pro2-full-kit/specs/, accessed August 24, 2026
8. Latif, U., Gong, Z., Nanjappan, V., Georgiev, G.: Kinematic upper limb assessment for rehabilitation in immersive virtual reality: A systematic review. Virtual Reality 30, 15 (2026)
9. Lekýr, M., Kvaššay, M.: Virtual lab for digital motion processing and virtual reality. In: Proceedings of OSSConf 2026 (2026), forthcoming
10. Magic Leap: Magic Leap 2 Hardware Specs. Magic Leap Developer Documentation, https://developer-docs.magicleap.cloud/docs/device/hardware/hardware-specs/, accessed August 24, 2026
11. Makhataeva, Z., Varol, H.A.: Augmented reality for robotics: A review. Robotics 9(2), 21 (2020)
12. Meta Platforms Technologies: Meta Quest 3 specifications. Meta Store, https://www.meta.com/quest/quest-3/, accessed August 24, 2026
13. Radianti, J., Majchrzak, T.A., Fromm, J., Wohlgenannt, I.: A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda. Computers & Education 147, 103778 (2020)
14. Seeliger, A., Cheng, L., Netland, T.: Augmented reality for industrial quality inspection: An experiment assessing task performance and human factors. Computers in Industry 151, 103985 (2023)
15. Stefan, H., Mortimer, M., Horan, B.: Evaluating the effectiveness of virtual reality for safety-relevant training: A systematic review. Virtual Reality 27, 2839–2869 (2023)
16. Stracke, C.M., Bothe, P., Adler, S., Heller, E.S., Deuchler, J., Pomino, J., Wölfel, M.: Immersive virtual reality in higher education: A systematic review of the scientific literature. Virtual Reality 29, 64 (2025)

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