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REMOTE-ACCESS EXPERIMENTS IN STRUCTURAL ENGINEERING University Handbook

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Preface

The sudden change in teaching from classroom to online because of the **COVID-19 pandemic** has shown that **digital teaching** is in general possible. However, difficulties in the rapid practical implementation of digital teaching coming from the lack of clear **digital teaching and evaluation concepts** have become apparent. Particularly, courses dealing with **laboratory experiments and practice** are among the most challenging aspects of **digitalization in teaching**. This is especially true for the university **research-oriented study of civil engineering**, where participation in laboratory experiments is a natural part of classroom teaching.

To overcome the issue with such courses, the use of **mixed and virtual reality** is foreseen as tools providing students the possibility to attend laboratories virtually and, thus, broaden digital teaching of civil engineering courses. In the case of digital learning, the student evidently cannot participate in laboratory experiments, and the real laboratory experience cannot be fully replaced by a video or online translation, whereas **virtual and augmented reality techniques** provide excellent opportunities to replicate real laboratory experience in a virtual environment.

Within the *PARFORCE project – an Erasmus+ Strategic Partnership 2020 for "Digital Education Readiness"* project (**grant no. 2020-1-DE01-KA226-HE-005783**) by **Ruhr University Bochum (Germany)**, **University of Aveiro (Portugal)**, **Josip Juraj Strossmayer University of Osijek (Croatia)**, **Ss. Cyril and Methodius University of Skopje i.e. Institute of Earthquake Engineering and Engineering Seismology (North Macedonia)** and **Bauhaus-Universität Weimar (Germany)** – significant contribution to establishing **virtual experimental setups** (which are not a part of standard education at each university but are carried out at specialized institutes), as different laboratory equipment (*shaking table, wind tunnel, and fire resistance laboratory*) are brought together and used by students of all partners.

The **virtual experimental setups** are accessible to **external interested parties** in order to broaden the reach of resources and foster a more inclusive and collaborative environment. The report presented herein constitutes the first in a series of three accomplished project reports:

- **Instructional Design Guide – Didactics of Media Learning Environments** – describing the derived methodological framework.
- **Methods and Algorithms for Digital Learning Tools Evaluation** - proposing a set of guidelines for evaluation, including measures and tools for quantitative analysis.
- **Remote-Access Experiments in Structural Engineering** – describing the elaboration of created virtual tours.

The results are an **added value for all partners and Europe**.

Project Principal Coordinator

Jun.-Prof. Dr.-Ing. Lars Abrahamczyk

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1. Introduction

Didactics of e-learning tools to be implemented in higher education studies and **evaluation methods suitable for e-learning platforms** have been thoroughly investigated in **intellectual outputs 1 and 2** [1,2], respectively. The focus has been set on assessing **electronic educational resources**, which have the outmost potential to be devised for conducting **remote-access experiments** within **civil engineering curricula**.

This report describes a framework that leverages **virtual reality (VR)** tools for presenting various experiments in form of *virtual tours (VT)*. Extended by the **strategic partnership**, the **VR-based framework** is devised for *pre-recorded experiment data* enabling students to audit laboratory experiments and to interact with *pre-defined virtual objects*.

The proposed framework is presented in detail in **Section 4**. The rest of the report is structured as follows:

- **Section 1** introduces the *report's objectives* and *context*, presenting a **VR-based framework** for *remote-access experiments* in **civil engineering education**. It outlines the rationale for using *virtual tours* as **learning tools** and summarizes the structure of the report.
- **Section 2** provides a short background and evaluation of *learning objects* for *virtual learning platforms* and respective characteristics, followed by few examples of implemented scenarios, hardware and software requirements.
- **Section 3** introduces *partner laboratories* and capabilities of the strategic partnership, from which contributions to the case studies have been made.
- The *case studies*, i.e. the *virtual tours*, are described in detail in **Section 5**.
- The *pilot course*, in which *virtual tours* have been employed as *learning objects*, as well as the *discussion and conclusions* on the framework implementation are presented in **Section 6**.
- In **Section 7**, the report concludes with an introduction on the *online platform*, where *virtual tours* as project deliverables are made available, and with a discussion on *potential further improvements* to project outcomes.

This report builds upon the outcomes of the first **PARFORCE intellectual output**, published as the *University Handbook* **Instructional Design Guide: Didactics of Media Learning**

Environments [1], which established the methodological and pedagogical foundations for designing and evaluating digitally assisted learning environments. The previous guide elaborated on *instructional design principles*, *learning models*, *evaluation of learning outcomes*, *inclusiveness for diverse learner groups*, and the *pedagogical preparation of teaching staff* for implementing *e-learning* and *virtual laboratories*.

The present report complements these didactic aspects by focusing on the **technical implementation** of *virtual and remote-access experiments* through **VR technologies**, thereby linking *educational design* with *practical application in civil engineering studies*.

As part of the project's recognition for excellence in **innovative higher education teaching practices**, the **PARFORCE framework** has been acknowledged through the *PROFFORMANCE+ International Higher Education Teacher Award 2024/25* (**Figure 1.1**).

__Figure 1.1__: Certificate of Recognition – PROFFORMANCE+ International Higher Education Teacher Award 2024/25.

2. Background on Remote-Access Experiments

2. 1. Didactic measures

Within the last two decades, researchers have implemented and tested **new teaching practices** in various **higher education fields**. While **conventional teaching methods** are still in practice to a certain extent, their **applicability and efficiency** may be questioned.

Educator-centered seminars and using a unified format (*one-fits-all*) for the majority of subjects have been proven **inefficient** in many disciplines [3]. Within *conventional teaching methods* it is often assumed that students have the same level of learning capabilities, hence, **learner-specific tools** are mostly neglected.

Students with *learning difficulties* such as **dyslexia**, **autism**, *different learning speeds*, and *diverse levels* of comprehension are all provided with **equal learning objects** [4]. Therefore, it should not be unforeseen that many students **struggle with course assignments or examinations**.

Electronic educational resources have been rapidly evolving and transforming in the recent years with the emergence of **new technologies** and **decentralized learning platforms**. E-*learning* and *hybrid learning methods* have **revolutionized the modern teaching practice** for various higher education disciplines [5,6].

New formats of learning objects have been developed suitable for **digital learning platforms**. The **main characteristics** of modern learning objects are **reusability**, **flexibility** and **interoperability**.

A reusable or adaptable learning object may be easily adjusted to the **teaching-learning process** and **course requirements or targets**. While *flexibility* offers educators **modification opportunities** to one learning object entity, *interoperability* (or *accessibility*) describes **platform (in-)dependency** and **different ways one learning object entity can be integrated** in the *learning environment* [7-9].

Moreover, **level of granularity** and **complexity** are commonly used to describe a *learning object entity*. *Level of granularity*, also referred as "*aggregation level*", represents the **fragments** of a learning object entity, if existing, while **complexity** refers to the **preparation workload** in terms of **time and skills required** [10].

A *learning object* may have the capability not only to be **modified by the educator(s)**, but also by the **students**, hence, in the last decade **interactive learning objects** have been integrated in *e-learning platforms*.

An **interactive learning object** may be used for **individual or group assignments**, **online examinations**, **live performance tracking**, and **adaptive learning scenarios** [11].

Today, in the **civil engineering field**, *decentralized learning platforms* commonly use **textual** and **audio-visual learning objects** as well as **computer-aided designs (CAD)**. The latter includes various formats of *computer-generated models*, such as **2D** or **3D reconstructions** of real environments and **parametric models of infrastructures** [12].

Similar to *conventional learning objects*, when searching for *learning objects* suitable for *e-learning platforms*, educators sometimes struggle with finding the **right tools** assuring that **course learning objectives** are met. For this purpose, it is important to review **main characteristics of learning objects** suitable for *e-learning* in the field of **civil engineering**.

Textual and **audio-visual learning objects** are normally prepared by the **educator** in advance and **lack reusability and flexibility parameters**. That means **adaptivity** and **modification opportunities** for above-mentioned learning objects are *limited*. Therefore, educators tend not to update **course material** over semesters and present the older versions with the minimum amount of modifications.

Meanwhile, **CAD learning objects** can be **modified easily** and can offer various ways of **integrating student contributions** into the *learning process* and opportunities to integrate **instructional methods** such as *inverted classrooms* [12,13].

For integrating **remote-access experiments** in the *teaching-learning process* within **civil engineering courses**, **data recording types**, **accessibility**, **interactive capability**, and **user's view** must be assessed (*see Figure 2.1*). The following **ontology** describes *main characteristic requirements* of **remote-access experiments**.

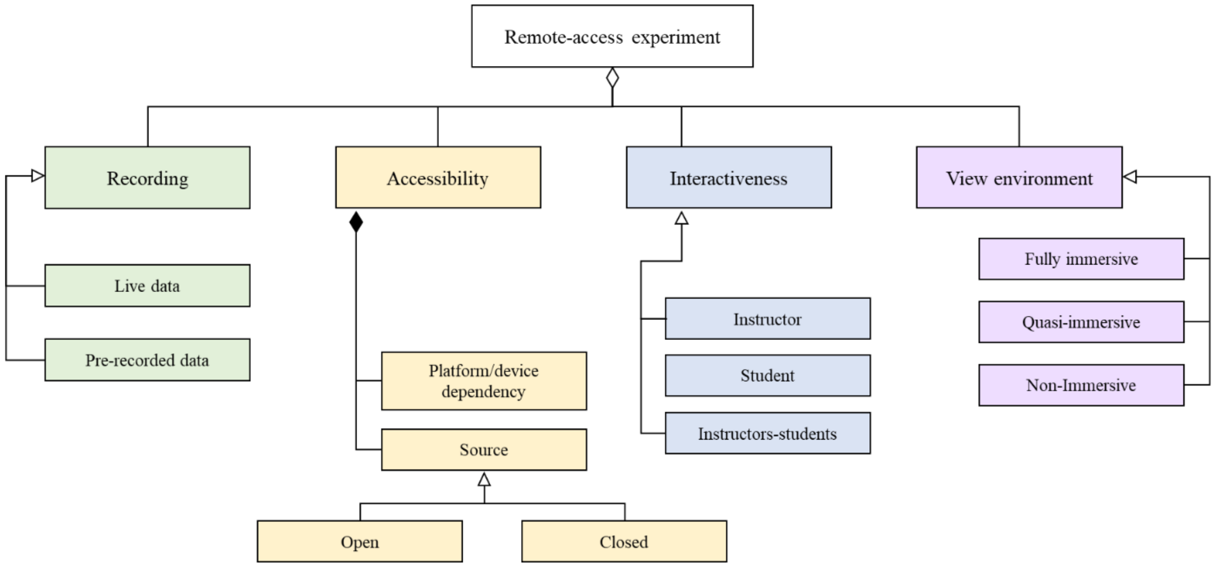


Figure 2.1*: Remote-access experiment characteristics*

A **remote-access experiment** may integrate **pre-recorded data** or **live streaming**. *Pre-recorded data* are believed to be **more reliable and stress-free**, since they can be viewed *offline* as well as *online* and have been thoroughly tested by **educators in advance** with respect to **platform compatibility** and **error-free presentations**.

Accessibility in terms of *platform* (*or device*) *dependency* and *availability* must be considered for using the **right tools** when designing *remote-access experiments*. For example, if an experiment can only be viewed *online* on the web browser and is only provided to *authorized users*, it is **less accessible** to students, who do not have **stable internet connections** or are not enrolled in the **virtual classroom**.

Remote-access experiments may provide **interactions from both sides**, i.e. **educators and students simultaneously may change the course of an experiment**. Interactions can be included as **pre-defined control parameters**, *drop-down menus* for different test approaches, or **sending and receiving commands** to *laboratory compliances* while running a **live experiment**.

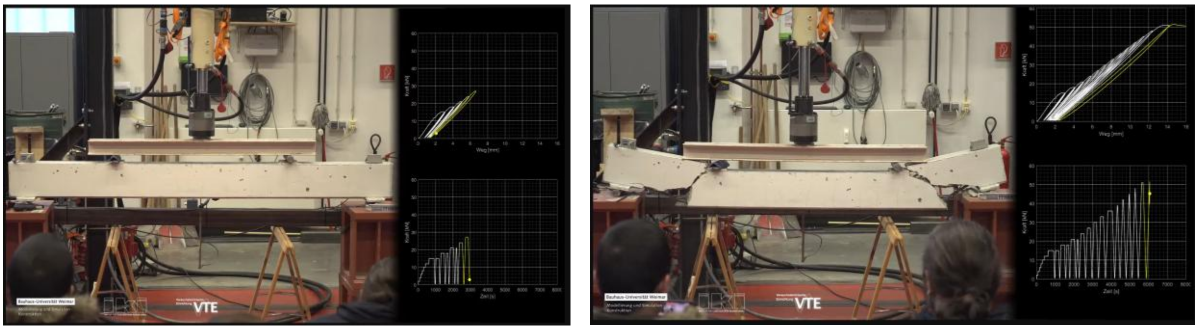
Lastly, the **environment**, in which *remote-access experiments* are depicted may be designed as an **immersive environment** using *virtual*, *augmented*, and *mixed reality* (*VAMR*) applications. The **immersive view** when combined with interactions has proven to be **more effective in teaching-learning process** in various disciplines [14-16].

In the following, few examples of **remote-access experiments** that have been developed for **civil engineering students** at the **Bauhaus-Universität Weimar** are depicted.

Figure 2.2 depicts screenshots of a **4-point beam experiment** conducted at the **experimental facility of the Institute of Structural Engineering**. The *remote-access experiment* is a **classical scenario**, where **pre-recorded (2D) footage** of the experiment is **synchronized with the sensor data (diagrams)** for the whole duration of the experiment.

Although this experiment is designed in a **non-immersive format** with **no interaction functions**, it has been **published online** and is **accessible for public**, making it with respect to **accessibility**, a **favorable option**.

It is worth noting that **students may revisit the experiment** at any given time and can **adjust it to their learning speed** [17].



(a) (b)

Figure 2.2*: 4-point beam experiment [17]: (a) before test; (b) after test*

Figure 2.3 shows a **screenshot of the 4-point bending test**, but in form of **rendered point clouds**. As the beam was being exposed to **various loads**, a **multi-camera setup** was used to take images of the beam over time to monitor **crack propagations**.

This **remote-access experiment** is using **pre-recorded database**, is provided *online* (*web-based*) but is only **accessible to authorized users**. Users can **choose load cases** and **view the respective results**, also **can change the rendering and classification parameters** from a *drop-down menu*.

Although the view is designed **non-immersive**, but users may have **interactions with the 3D beam model** and **change the point of view easily** [18].

***Figure 2.3**: Project "3D-RealityCapture-ScanLab", Bauhaus-Universität Weimar (source: Prof. V. Rodehorst)*

Another example is using **microcontrollers** for **remotely accessing experimental data**. *Figure 2.4* illustrates the "*shake table*" application developed for **Android-based smartphones** within a **student project**.

The **application** is used to **trigger the shake table** and **start experiments** with the **parameter set by the user**. Consequently, after vibrations and when the **test structure** is at rest, the **microcontroller on-site** collects **sensor data** (i.e. *structural responses*) and **sends them to the application**, reporting back to the user.

This **remote-access experiment** is conducted in **semi-live setup**, meaning that the data is **recorded live** but is **not transmitted instantly** or may **not be streamed** on the smartphone. The **application** is only developed for **Android phones** and is only accessible for **authorized users**; however, provides a **high level of interaction** to users [19].

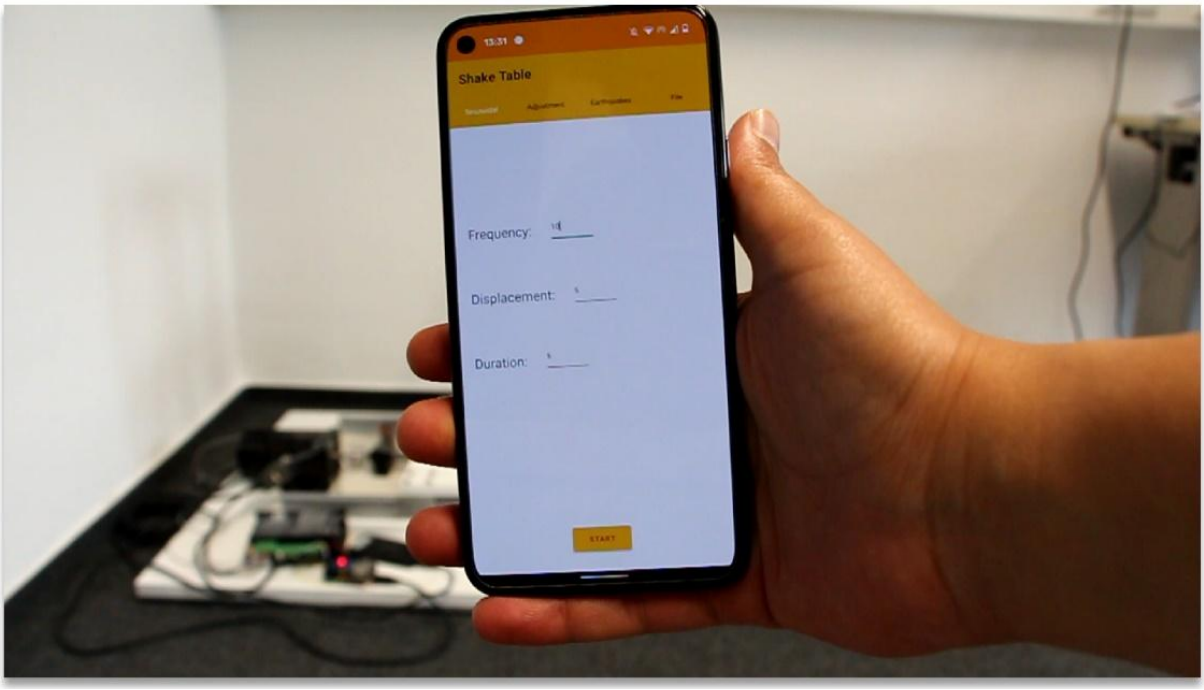


Figure 2.4*: Android-based smartphone application for shake table tests*

In the **research project *AuCity 2***, **virtual** and **mixed reality applications** have been developed as **learning objects** for **remote-access experiments**. *Figure 2.5* depicts the **virtual room**, in which users can **perform flexural tests** on a **beam element**.

Users can have **interactions with the virtual objects** in this room, e.g. *placing weights on the beam and checking the deflections*, *moving around*, *selecting items*, and *answering questions*. This example of **remote unsupervised testing** grants users with **high interaction capability** and is **fully immersive** [20].

Another example from *AuCity 2* project is the **holographic structural analysis experiment** shown in *Figure 2.6*. Users can **define virtual objects** as an **overlay on real objects**, **assign structural parameters and load cases**, and **select the analysis type**. The **results are then visible as holograms**.

Although the **holograms** are not directly **interactive**, the **user can change pre-defined parameters** and the **holograms will be updated accordingly** [21].

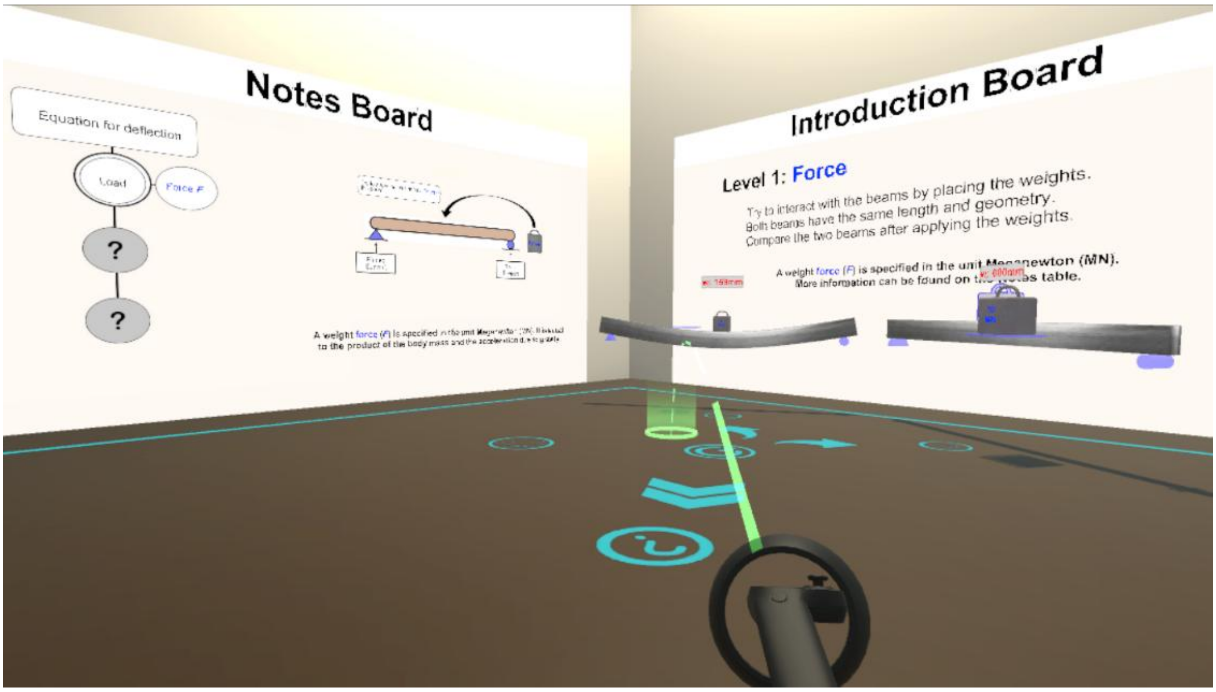


Figure 2.5*: VR learning scene for flexural beam and bending moment tests*

Each of the above-mentioned implementations of **VAMR** for **remote-access experiments** have **benefits and shortcomings**.

As an example of **VAMR applications**, a **virtual tour** as *learning object* offers many benefits:

1. In a *virtual tour* several formats of **learning objects** may be integrated, such as **textual**, **CAD**, and **audiovisual learning objects**.
2. A *virtual tour* can be viewed on **desktop PCs**, **tablets**, **smartphones**, as well as **virtual reality headsets**, therefore, a *virtual tour* is **not limited to type of device** and is **highly accessible**. Also, *virtual tours* may be integrated in any **virtual learning platform**.
3. In the case of **virtual reality**, users can experience a **fully immersive view**, which can give users a **feeling of being present at the laboratory**.
4. Last, but not least, the *virtual tour* has many **control points** or *hotspots* that can offer **greater interaction** with the **learning object** to the users. Educators can use **interactive virtual objects** as much as needed (*extendable*).

Therefore, within the framework of **PARFORCE project**, *virtual tours* have been considered as **the most suitable tool**, which can **deliver all purposes envisioned** for **remote-access experiments**.

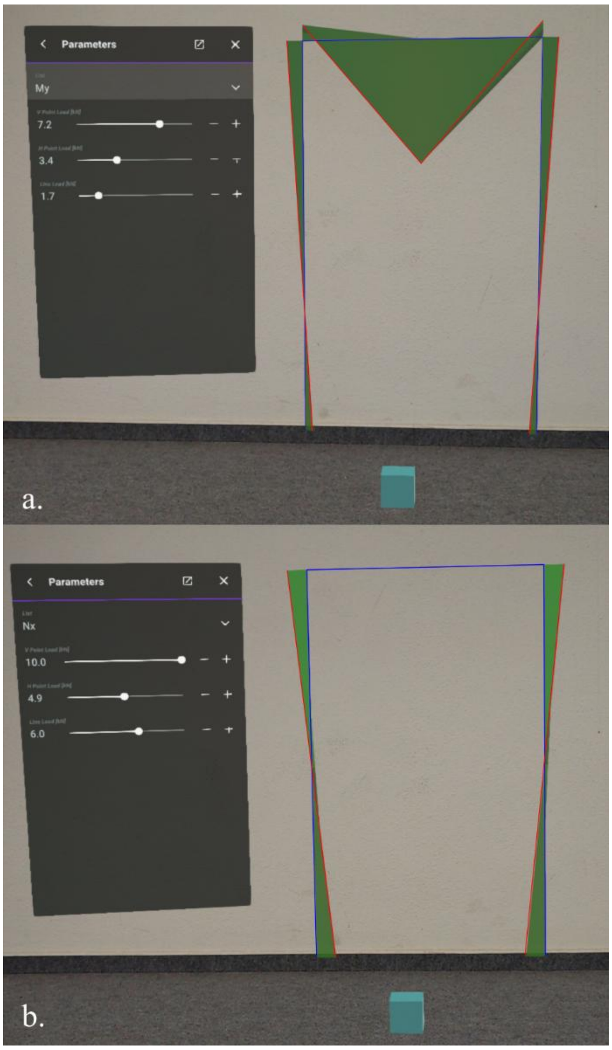


Figure 2.6*: Holograms of bending moments (a) and axial forces (b) obtained from the linear analysis*

2. 2. Virtual tours

Using **virtual tours** in **VAMR application** requires **preliminary knowledge** of suitable **data formats**, as well as **hardware tools**, which are addressed in the following.

Footage formats, in general, comprise **images** (*static frames*) and **videos** (*dynamic frames or more than one static frame*). **Field of view (FOV)** is a common parameter in **VR** that indicates how much of the footage in the **virtual environment** is seen through one eye or each **VR lens**.

For example, *Figure 2.7* depicts **FOVs of different VR glasses** in comparison to the **average field of view for human vision**.

The **angle of view** recorded in each *footage* depends on **camera lenses** in general. A **wide range of camera lenses** exist that based on use cases, one should choose from to match the required **FOVs**, ranging from **90° to 360°**.

Monoscopic and **stereoscopic 360° footage** (*images and videos*) are the **VR formats** which have been used in this project. In **monoscopic VR**, **one lens** records the intended *field of view*, which in case on **360° footage**, means that **a single lens** records **one footage with an FOV of 360°**, and projects the *footage* to both eyes on **VR devices**.

In contrast, in **stereoscopic VR**, **two footages** are recorded at the same time and are projected to the **left and right eyes** (*left and right VR lenses*) separately. The **two footages** (i.e. *camera lenses*) have **slightly different angles**, mimicking **human eye position** and **the interpupillary distance (IPD)**.

The **stereoscopic VR** is also known as **3D VR**, due to the fact that by projecting two footages to the *eyes*, **user's brain** can **calculate depth of field**, thus **creating 3D depth perception**. *Figure 2.8* shows an example of **stereoscopic VR** and **depth of field**.

Another common **VR format** is **VR180**, which can be described analogously as **stereoscopic VR** with **FOV of 180°**. *Figure 2.9* illustrates one instance for **monoscopic** and **stereoscopic 360°** vs. **VR180** footages.

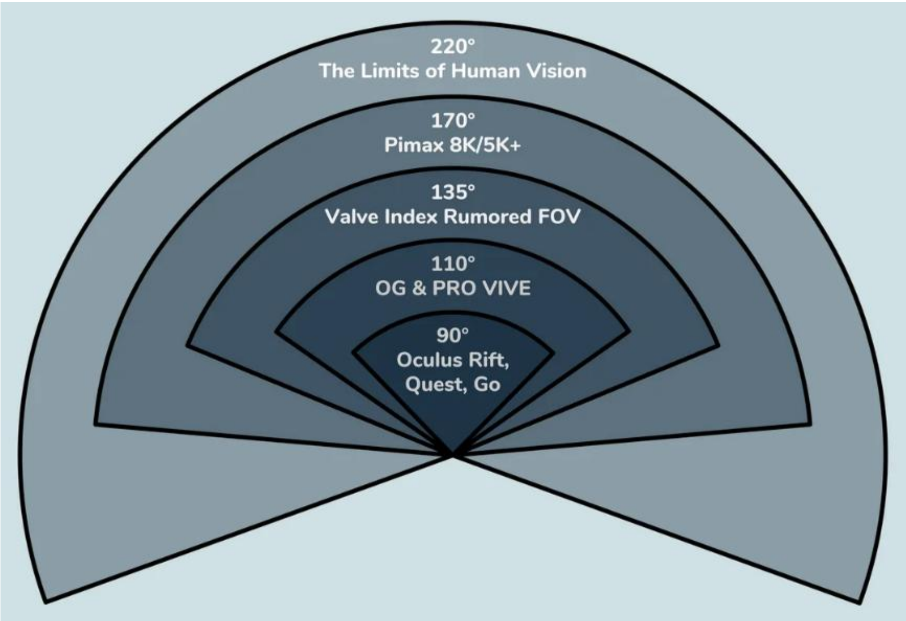


Figure 2.7*: Field of View (FOV) of selected VR glasses [22]*

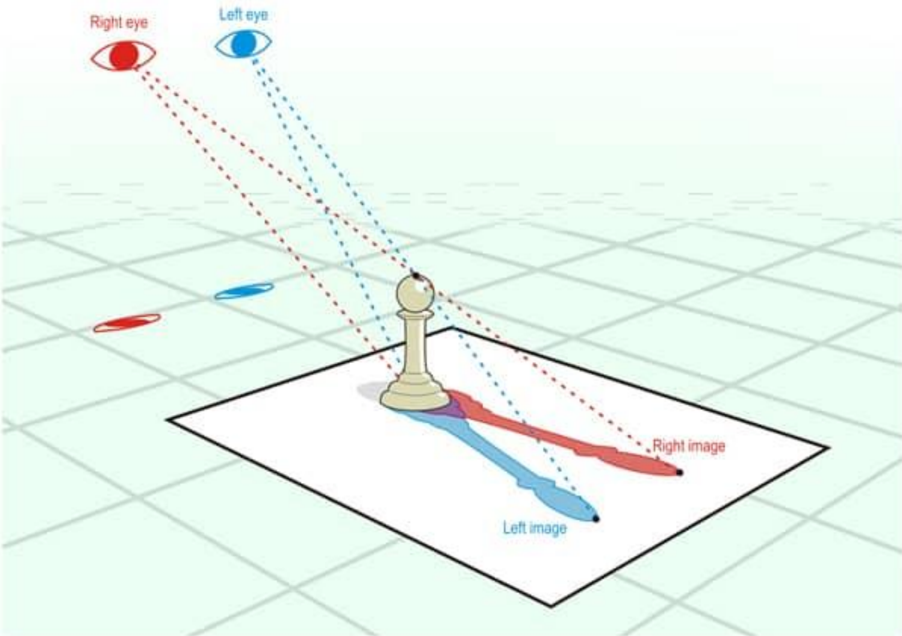


Figure 2.8: *Stereoscopic VR example [23]*

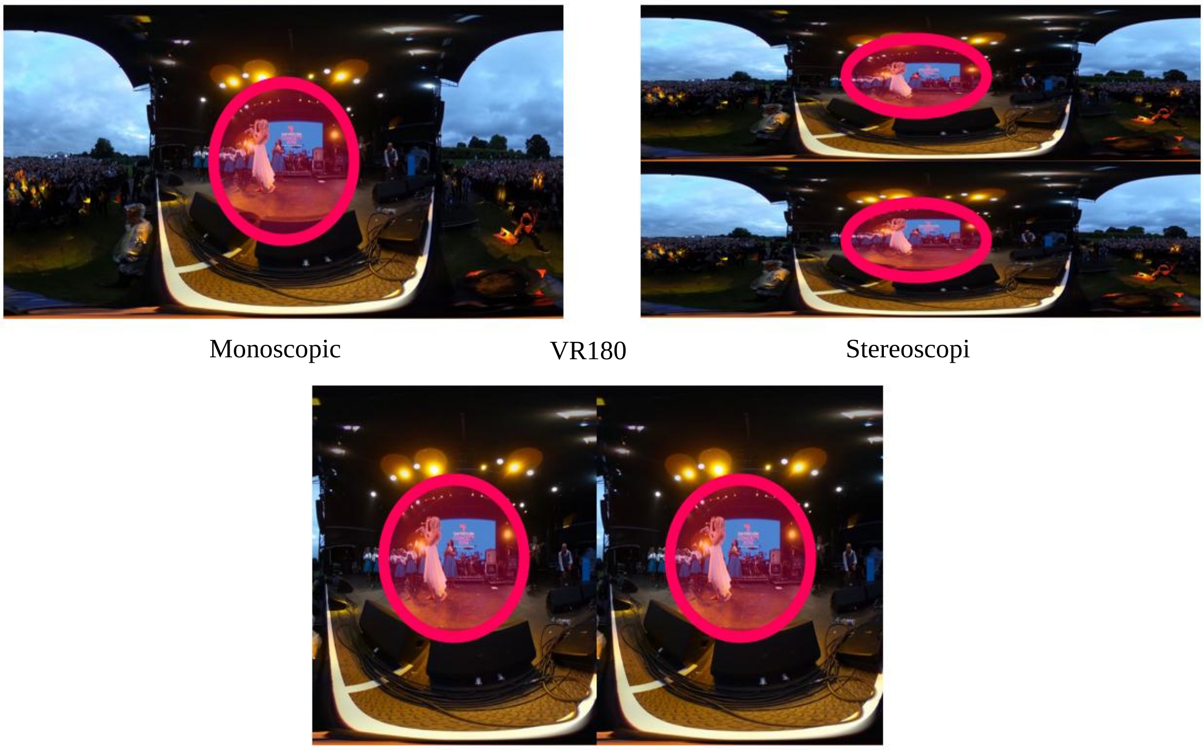


Figure 2.9: *Difference between monoscopic, stereoscopic 360° and VR180 [24]*

There are various **professional** and **consumer cameras** on the market for creating **VR-compatible images and videos**. Based on *use cases* and *ambient conditions*, one can **choose the appropriate camera** for shooting **experiments**.

For example, **professional stereoscopic 360° cameras** cost up to **25,000 €** and are **large in size**; however, they offer **more functionalities** and are, in general, **more resilient to harsh environmental conditions**. *Figure 2.10* depicts **Insta360 Pro 2.0 camera**, which is a **professional 360° camera** with **integrated GPS** that has been **used in the PARFORCE project**.

In contrast to **professional cameras**, **consumer cameras** offer **ample functionalities and controllers**, can also be **moved around the laboratory during recordings**, and cost up to **1,000 €**.

Figure 2.10*: Insta360 Pro 2.0 a professional camera used in this project [25]*

VR glasses are in general **three types**: **Standalone VR**, **PC VR**, and **smartphone VR glasses**.

Standalone VR glasses have a **built-in screen processor** (*graphics card*, *computing processor*), **cameras** and **motion sensors** for **position recognition**, as well as a **power source**; therefore, can **operate independently**, without the need to be connected to a PC.

On the other hand, **PC VR glasses** can operate only when **connected to the PC**, since they are use the **graphics card** and **computing processor** from the **computer** (*no built-in resources*).

Mobility (*degrees of freedom*), **image quality**, **means of communication**, **additional or required hardware** (such as **hand controllers** and **base stations**), **content variety**, and many more **parameters** should be considered when purchasing the **suitable VR glasses** for a given *use case*.

Smartphone VR glasses are the **simplest and cheapest** type of VR glasses comprising only **two lenses** that can **project the VR footage** from the **smartphone display** to **user's eyes**.

A hardware recommendation list for **360° cameras** and **VR glasses** is offered in *Annex A*.

3. Strategic partnership laboratories

This section provides an **overview of the strategic partnership facilities** and **common experiments** driven at each facility.

Laboratory settings, **detailed experiment procedures**, and **result evaluation** of experiments carried out at each facility are **beyond the scope** of this report.

For further information please visit the **website of each facility** cited at the **end of each subsection**.

3. 1. Ruhr University Bochum (RUB)

The **Boundary Layer Wind Tunnel facility** is replicated in **VR** within this project as the **first virtual laboratory strategy** developed by the project partner **RUB**. This virtual laboratory represents the **entire environment of a real wind tunnel**, including examples of **measurements carried out** and the **basic wind tunnel techniques** required to conduct experiments for the purpose of **wind engineering education and research**.

The **wind tunnel is 9.4 m long**, with a **test cross-section** of **1.6 m in height** and **1.8 m in width**. The **maximum flow velocity** is approximately **30 m/s**, corresponding to a **volume flow** of **86 m³/s**. The facility consists of two main rooms:

1. a **room with the wind tunnel chamber**, including a **large fan**, **motor** and **test section**;
2. an **electrical and instrumentation control room**.

A special feature of the facility is the **simulation of natural wind** in the atmosphere under **neutral thermal stratification**, achieved by means of an **array of castellated barriers**, **turbulence generators**, and **ground roughness elements**. The **Boundary Layer Wind Tunnel** is frequently used for **industrial projects**, **PhD and visiting researcher studies**, **advanced investigations of wind tunnel techniques**, and **educational tours for students**.

Notable experiments carried out in the wind tunnel investigate the **wind pressures**, **static and dynamic wind loads on buildings**, **aeroelasticity**, **vortex visualization** and **pollutant dispersion**.

The **second strategy** involves **remote monitoring of a full-scale wind turbine** and a **wiki-based digital teaching database**. Remote monitoring is integrated into a **web application** for the **AIRWIN DEW21 wind turbine** in **Dortmund**. The turbine type is **Enercon E40 – 500 kW series**, with a **hub height of 65 m**, and has been **monitored since 2010**.

The **web application** allows users to access the **monitoring database interface** via a **standard web browser**. Temporal and statistical measurements, such as **tower vibration acceleration** and **power generation**, can be observed through the application.

The application was developed using the **Eclipse Java EE IDE for Web Developers**, **Vaadin Eclipse Plugin 3.0.0**, and a **LAMP stack (XAMPP 7.0.8-0)** for the local database.

Additionally, a **joint Wiki-based digital teaching database (DigiDat)**, developed collaboratively by the **Chair of Continuum Mechanics** and the **Chair of Wind Engineering and Flow Mechanics (WISt)**, serves as an **open-access educational platform** for **students and teachers**. It provides **documentation and data** of example experiments.

DigiDat functions as an **online platform** offering **summarized case studies**, **analysis procedures**, and a **linked online database** for enhanced accessibility and learning.

3. 2. The Institute of Earthquake Engineering and Engineering Seismology (IZIIS)

The **Dynamic Testing Laboratory** of **IZIIS (Northa Mecedonia)** is one of the **strategic laboratories** in which **scientific and applied investigations** in the field of **structural dynamics** are continuously performed.

The essential equipment in the laboratory is a **3-DOF shaking table**, built in **1980**, with dimensions of **5.0 × 5.0 m** and a **payload capacity of 40 t**. When properly carried out and interpreted, **shake table experiments** provide valuable insight into **the structural behaviour under real earthquake conditions**.

Common types of **shake table tests** include:

- **Verification of existing mathematical models;**
- **Development of new models;**
- **Evaluation of new technological solutions;**
- **Qualification and proof testing.**

More than **400 reports** have been published related to experiments conducted on the **IZIIS shake table**. Although each experiment is unique, the **basic procedure** typically includes the following steps:

1. **Preliminary analysis;**
2. **Design of the model;**
3. **Construction of the model;**
4. **Mounting of the model on the shake table;**
5. **Selection and preparation of time histories for testing;**
6. **Instrumentation of the model;**
7. **Shake table testing;**
8. **Processing of the results;**
9. **De-mounting of the model;**

The experimental objectives are broad but can generally be summarised as **learning and understanding the seismic performance and safety of structures**, as well as their **damage and failure patterns**.

The **target groups** include both **external users** (companies and researchers) and **internal users** (master's and doctoral students), whose education in **earthquake engineering** significantly benefits from the experimental outcomes.

In **September 2020**, the **first remote-access experiment** was conducted at the IZIIS Laboratory, related to **dynamic testing using the forced vibration method** within the framework of the *INMAPSOL project* ("Dynamic testing of infills and masonry structures protected by deformable polyurethanes in seismic areas").

3. 3. University of Aveiro (UA)

Based at the **Department of Civil Engineering** of the **University of Aveiro (Portugal)**, the **Laboratory for Structures and Fire Resistance (LERF)** was established in 2007. The laboratory is equipped with a **vertical gas furnace** featuring a **3.10 m × 3.10 m free opening**, capable of carrying out **fire resistance tests** on **construction elements and products** in accordance with **European regulations**.

This enables the **experimental determination of fire resistance characteristics** according to the **functions performed by construction elements**, namely:

- **Load-bearing capacity** (*criterion R*);
- **Integrity to flames and hot gases** (*criterion E*);
- **Thermal insulation** (*criterion I*).

Fire resistance tests on **compartmentation elements** (such as **walls and doors**) and **post-fire behaviour evaluation** of **structural components and members** (such as **steel or concrete columns and beams**, and **timber connections**) have been conducted at **LERF**.

3. 4. University Osijek (UNIOS)

The **Faculty of Civil Engineering and Architecture Osijek (Croatia)** has been developing **virtual experiments** integrated into the **students' laboratory experience** and **course curriculum** addressing the **seismic behaviour of reinforced concrete (RC) frames** with and without **masonry infill walls** and **openings**.

The **large-scale experiments** conducted included **in-plane** and **out-of-plane behaviour tests** of **RC frames** with and without **masonry walls** and **openings**. The **test data** were collected using **hardware sensors** and **optical measurement techniques**. **Smaller-scale experiments** included **tests on masonry walls** and their **individual units**.

Based on these experiments, **3D micromodels** were developed. These models allow the **manipulation of various parameters**, providing the opportunity to **explore and understand** how changes in these parameters affect the **overall structural behaviour** of the micromodels. Using **calibrated micromodels**, **in-plane** and **out-of-plane loads** were combined into a **single simultaneous action**, enabling a more realistic representation of structural response (*see Figure 3.1*).

In addition to the aforementioned experiments and models, a **Python-based application** was developed that **generates graphs** and provides **load-bearing capacity estimations** for **RC frames with masonry infill walls**, with and without **openings of varying sizes and positions**. This application, available as an **executable (.exe) file**, allows students to **visualize** and **analyse** the effects of **infill walls**, **opening types**, and **positions** on the **load-bearing behaviour** of RC frames.

The application has proven invaluable in **bridging the gap between theoretical understanding and practical application**, empowering students **to analyse and evaluate civil engineering structures** more effectively.

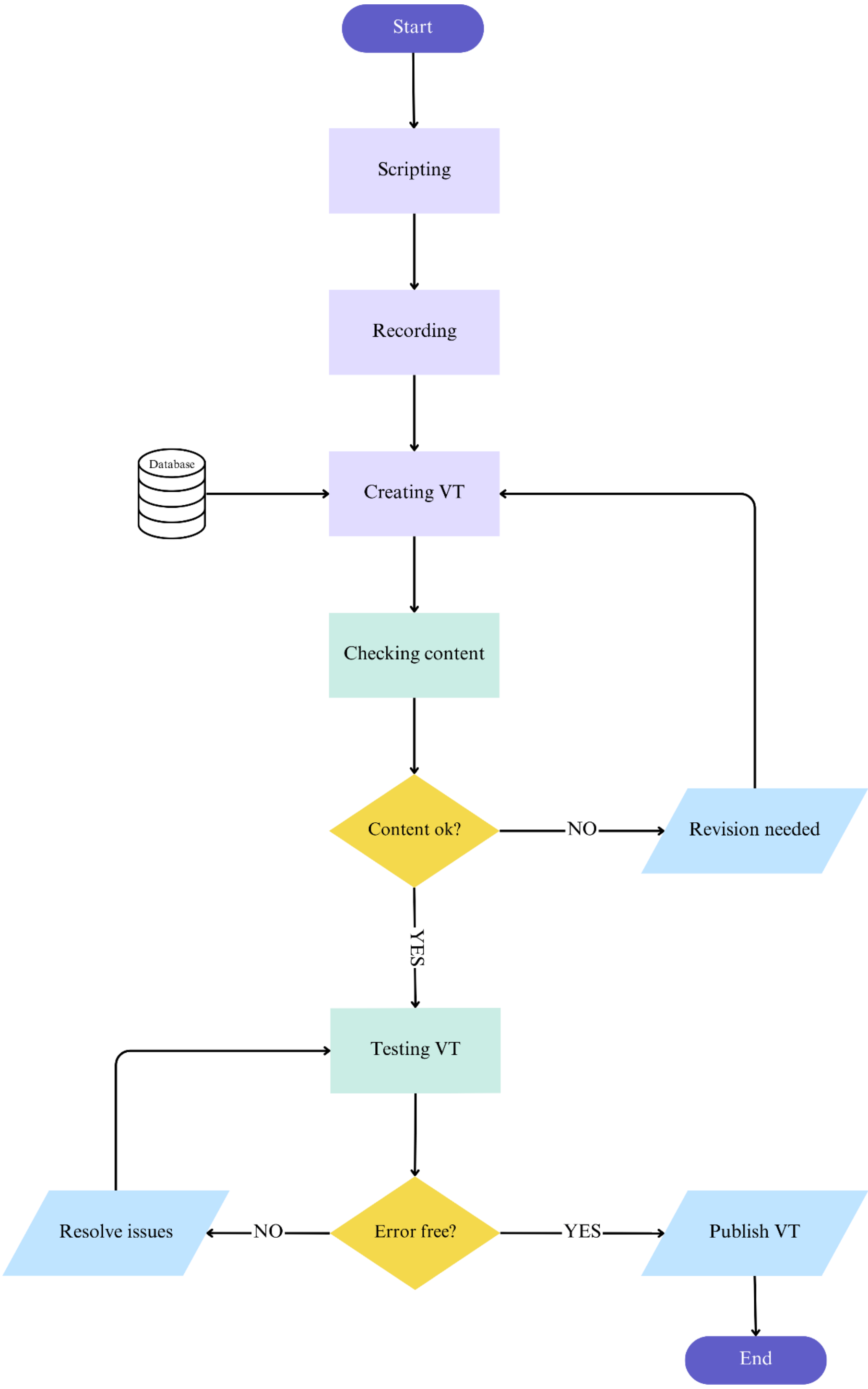


***Figure 3.1**: Flowchart of the proposed framework for creating virtual tours*

4. The Proposed Framework

The **strategic partnership** aims to **grant access to specialized laboratories** and **specific tests** listed in the previous section. **Students enrolled** at each university or institute can benefit from the **facilities and expertise** offered by the strategic partnership and can **extend their practical knowledge** using **experiments that are not locally available**.

For developing the **virtual laboratories** of the strategic partnership, **VTs** have been recognized as **the most suitable tool**, as described earlier in *Section 2*. To provide a **realistic view of laboratory environments** and enable **interaction with experiments**, **footage from laboratories and ongoing experiments** is recorded in **VR-compatible formats** and later **combined with supporting information and experiment data** using a *VT-maker software*.

The **framework for creating VTs** of laboratory experiments is depicted in *Figure 4.1* and is explained in detail in the following subsections.

Within the proposed framework, **three actors** are considered:

1. **Educators (and laboratory technicians)** – responsible for delivering the **scientific content** and **experiment data**;
2. **VT developers** – whose main task is **creating the virtual tour** and **integrating it into the virtual platform**;
3. **Users or viewers (students)** – who interact with the **virtual tours** and **gain experiential learning** from the laboratory simulations.

4. 1. Scripting

The **first and most important step** in creating a *virtual tour (VT)* is **to define the learning objectives** of the experiment and **describe the laboratory conditions**. To provide the **VT developer** with a clear overview of what is expected, the **educator** must identify **the experiment goals** and **learning outcomes**, including the **expected results**.

Moreover, the **experimental procedure**, **laboratory setup**, and **ambient conditions** should be thoroughly described. This process is referred to as "**scripting**" and is performed **iteratively** by the **educator** and the **developer** until a **mutual understanding** of the entire testing procedure is achieved.

Within the *script*, the educator can describe their expectations for the VT in detail — for instance, by addressing the following questions:

Laboratory and Ambient Conditions

- What is the **size of the test field**?
- How many **points of interest** exist for this experiment, and **where are they located**?
- Are there **objects moving** around in the test field? If yes, **how often** and **how fast**?
- Are there **any areas in the laboratory that must be avoided** due to **safety or confidentiality reasons**?
- Are **laboratory safety regulations** important for **remote viewers**? If yes, please specify them.
- What type of **equipment is present for hazard control**?
- Who is **present in the laboratory**, and what are their **responsibilities**?
- How are the **light exposure** and **ambient noise conditions** in the laboratory?
- What can be done to **eliminate distracting elements** from the environment during **test recording**?

Experiment Procedure

- What is the **goal** (or goals) of this experiment?
- What is the **procedure** of this test — i.e. *how is the goal of the experiment achieved*?
- What **parameters** are measured, and what **types of data** are to be collected or recorded?
- How is the **experiment data measured**? What **equipment** and **data acquisition systems** are available in the laboratory?
- What is the **process for preparing the test structure**? What **type of structure** is being tested, and **how long** does preparation take?
- **Educator's expectations** based on **theoretical knowledge** or **previous experience**: What results are **expected** according to the experiment goals?
- Are there **multiple tests** to be recorded? What is the **duration** of each test?
- Does the **experimental setup change** between test rounds? If yes, do the **points of interest** shift?
- Is it necessary to **record the entire duration** of the test, or are there **time intervals** that can be omitted from the VT (e.g. periods not relevant to remote viewers)?

- **Post-processing of experimental data**: What **data formats** should be used to present the results? What **types of data** will be integrated into the *VT*?
- **Interactions:** What **control points** or "*hotspots*" are envisioned for the *VT*? How can **students interact** with the VT content?
- **E-learning measures**: What are the **criteria for tracking student performance**? Are there **quizzes** included? How many **attempts** does each user have? Is there a **time limit**?

Any **supporting information** that is not included in the **first draft of the script** may be **added later**. However, **educators** and **VT developers** must invest **time and patience** in the scripting process, as the **script serves as the baseline** for determining the **software and hardware requirements**, as well as the **layout and structure** of the *VT*.

4. 2. Recording

Once the **script** is completed, the **VT developer** can choose the **appropriate tools** for **recording the experiment**. Within this project, **panoramas** and **videos** in **monoscopic** and **stereoscopic 360° formats** are employed for recording laboratory experiments.

Camera locations should be set so that the **points of interest** are clearly in focus and **ambient distractions** are minimized. If necessary, **studio lighting setups** (light sources, reflectors, and diffusers), **audio recording systems**, and **background curtains** can be used to improve the **ambient conditions** and enhance the **focus on the test area**.

The **script** helps educators and VT developers to **identify the key points of interest**. Although cameras can be moved as needed, **excessive movement** in a *VR view* may cause **motion sickness** for users. Therefore, it is **recommended to maintain at least one fixed point of view** in the laboratory during recording.

Although one recording setup does not fit all **experiments** and **laboratory conditions**, it is advisable to **keep one fixed point of view** throughout the entire experiment and to **record additional footage** from one or more cameras placed at **different angles and viewpoints**. This approach provides the **developer** with more data to choose from when preparing the *VT*. Since most experiments are **costly** and conducted in a **single round** (e.g. in the case of **destructive tests**), there is **no opportunity to retake footage** if the setup proves inefficient.

For this reason, it is **recommended to evaluate the laboratory conditions** and to **perform a full setup trial** before the actual experiment is conducted.

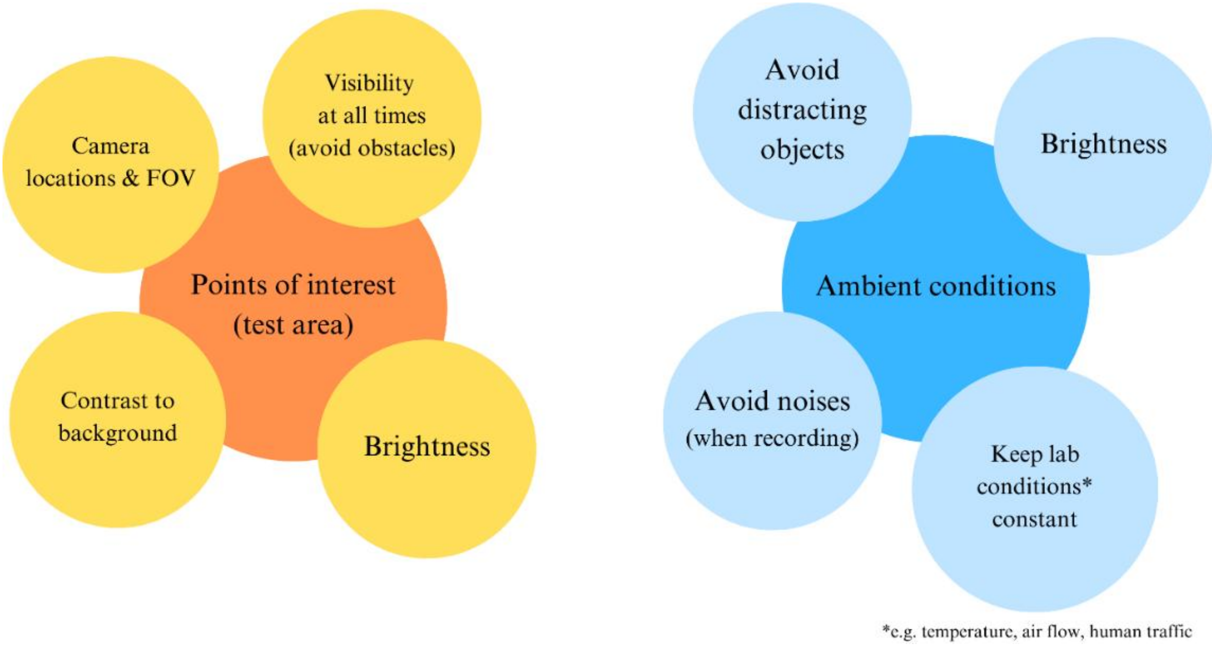


***Figure 4.1**: Important measures before you start recording*

4. 3. Creating the Virtual Tour (VT)

After conducting an experiment, the **VT developer** begins preparing the **recorded footage** for use in the *VT-maker* software. The **post-processing phase** includes stitching **360° panoramas and videos**, performing **colour corrections**, **reducing visual and/or audio noise**, **selecting video frames**, and, if necessary, **combining different viewpoints** into a single video.

The **developer** collects all **experiment data** and **supporting materials** from the **educator**. At this stage, the developer follows the **script step-by-step** to organise the **360° footage** in sequence and to assign the **logical order of appearance** and **functionalities** to the *hotspots*.

In general, **hotspots** can be divided into **two categories**:

1. **Hotspots that change the point of view**;
2. **Hotspots with e-learning functionalities**.

The latter includes:

- **Pop-up information windows** (*including images, videos, and text*);
- **Albums** (*sliding image or text sequences*);
- **Quiz cards**;
- **Download buttons** for **experiment documentation**.

Changing the point of view can be defined as **switching between panoramas and videos**, or as **moving from one point to another** within the laboratory panorama.

Various data formats—such as **CAD models**, **2D/3D footage**, **PDF files**, **Excel sheets**, and others—can be **integrated into virtual tours**. If an **internet connection** is available, **websites** and **links to online learning platforms** or **external e-learning materials** can also be embedded within the virtual tour.

It is important to note that the **available functionalities** depend on the *VT-maker* software in use. Therefore, it is **recommended to consider all required functionalities when selecting or purchasing** the *VT-maker software*.

Figure 4.2 depicts the **functionalities (or actions)** offered by the *3DVista Virtual Tour Pro* software, which was used in this project to prepare virtual tours.

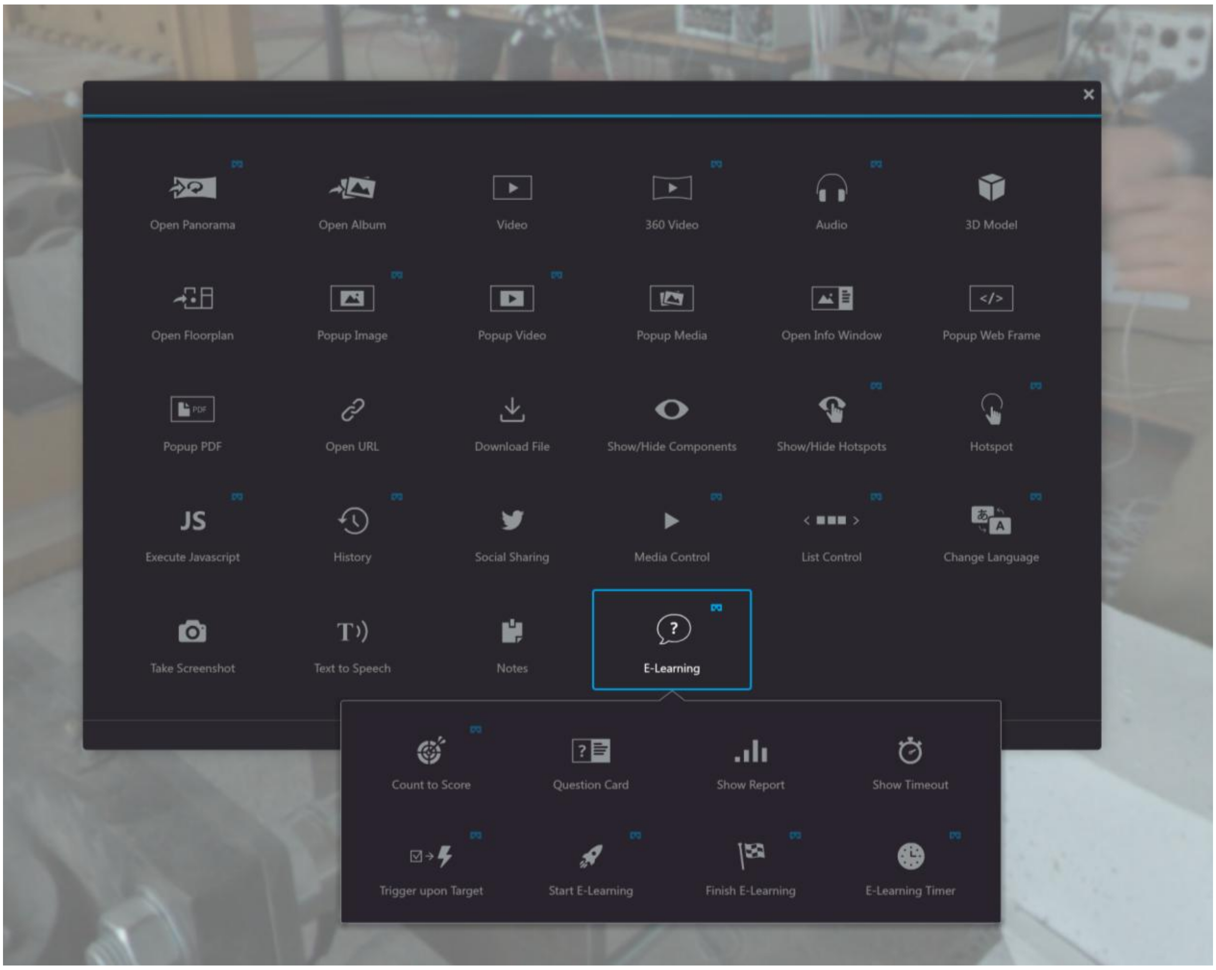


Figure 4.2: *Screenshot of hotspot actions from 3DVista Virtual Tour Pro* [24]

4. 4. Checking the Content

Before publication, the **VT** must be **reviewed and confirmed** with respect to its **content accuracy** and **educational alignment**. Even though the **VT developer** follows the **script** step-by-step, the **educator** must **approve the virtual tour** at least once to ensure that the **content corresponds to the predefined learning objectives**.

In many cases, **additional data** may need to be **added or replaced**, requiring **minor revisions**. This validation process can be **repeated even after publication**, for example, when **new course assignments** are to be integrated or when **temporary e-learning functionalities** are to be **activated or deactivated** within the virtual tour.

4. 5. Testing VT Functionalities

The **final step** before publishing a *VT* is to **ensure that it is fully accessible and functions without technical issues** on the intended display devices. Whether designed for **desktop computers** or **VR headsets**, the **device compatibility** of virtual tours must be **thoroughly tested** to verify **content integrity**, **hotspot functionality**, and **audiovisual quality**.

For this purpose, the **VT developer** tests each virtual tour **multiple times** across **different devices** and **platforms**. In some cases, a **hotspot** that appears correctly in the **desktop version** may **not appear** in the **VR version** or may be misaligned due to differences in **scaling parameters** predefined in the *VT-maker software*.

Another potential issue arises when the **projected ray** from a **VR hand controller** (or **hand gesture recognition**) cannot activate a **hotspot** because of a **mismatch between the depth of field** of the hotspot and the **projected ray**.

4. 6. Publishing

After **checking the content** and **testing accessibility**, the *virtual tour (VT)* can be **published and shared with users**. Depending on the *VT-maker* software, a virtual tour can be published for **desktop computers**, **smartphones**, and **tablets**; as a **web-based application** (*accessible online and/or offline*); or as a **VR application** compatible with **virtual reality (VR) headsets**.

To **reduce device and platform dependencies** and to **increase accessibility**, it is **recommended to publish the virtual tour in multiple formats**. Although **VR headsets** are often **not readily available to users** due to their **high cost**, the **VR format** provides a **fully immersive view** of the **real laboratory environment** and is therefore **highly recommended** as one of the available formats when creating virtual tours.

5. Virtual Tours as PARFORCE Products: Case Studies

This section presents the **virtual tours** developed as **remote-access experiments** within the framework of the **PARFORCE project**. These virtual tours are published on the "*360-degree.education*" platform [27], a **publicly accessible**, **web-based educational platform** designed to host and share **interactive learning environments**.

Links to the virtual tours are provided in reference [28].

5. 1. Wind Tunnel Experiments

The **virtual tour** of the **Wind Tunnel Facility** at the *Ruhr University Bochum (Germany)*, **Institute of Wind Engineering and Fluid Mechanics (WiSt)**, comprises a total of **14 scenes** (*panoramas*) that visualize the entire facility — from the **exterior of the building** to the **interior of the wind tunnel chamber**.

Two **laboratories experiments** are introduced in this virtual tour:

1. The **boundary layer test** of grouped cylinders;
2. The **free-vibration** and **forced-vibration tests** of a horizontal cylinder.

The tour includes **interactive hotspots** that provide students with information such as:

- **Viewing course materials and slideshows;**
- **Description boxes** over real laboratory objects;
- **Technical data sheets** of the laboratory equipment;
- **Video guides** around the wind tunnel hall;
- **Video footage** of ongoing tests from different angles;
- **Theoretical background** related to the laboratory tests.

In addition to informational hotspots, **two scenes** are equipped with **quiz hotspots** designed to assess the **interim knowledge** of users regarding the presented VT content. Users can attempt the quizzes **as many times as needed**, since they are **not graded assignments**. The **timer** and **score display** are included solely for **self-assessment** purposes.

As users cannot physically move around the real environment, **navigation hotspots** (arrows on the ground and doors on the walls) are implemented to allow **movement between scenes**.

The *virtual tour* has been **published in both desktop and VR versions** and made available to students.

Screenshots from the desktop version of the tour are shown in **Figures 5.1–5.4**.

For further information about this virtual tour, please visit the **PARFORCE project website** [28].

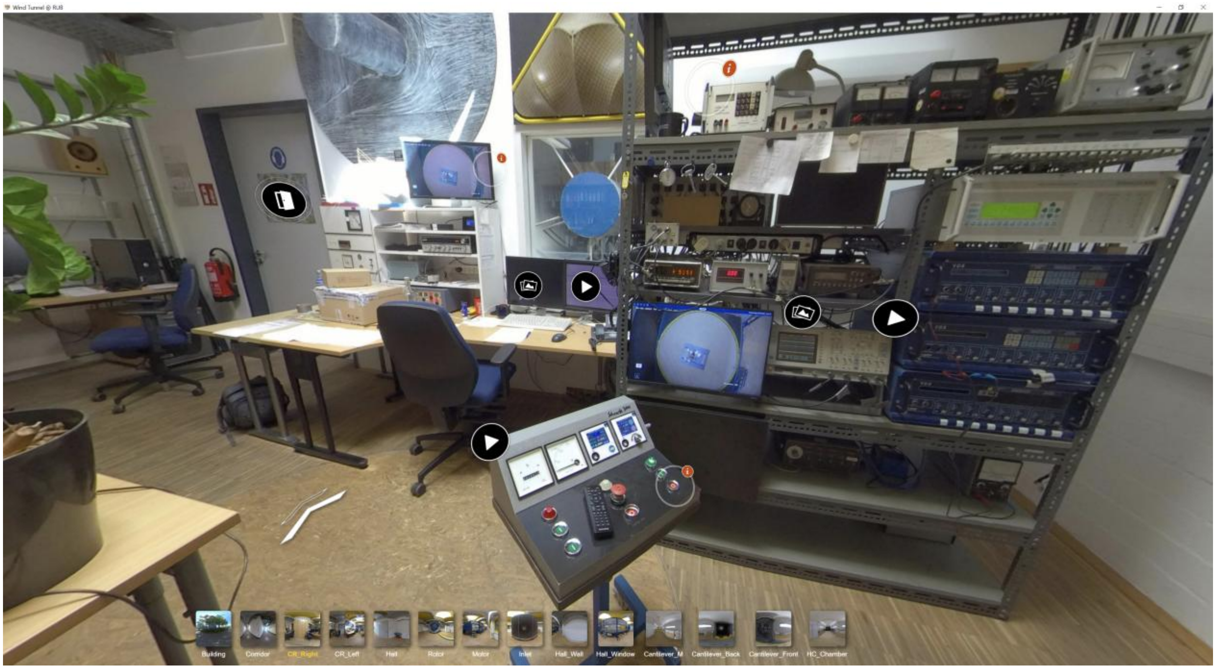


Figure 5.1: *Control room scene of the VT from the wind tunnel facility at RUB, WiSt*

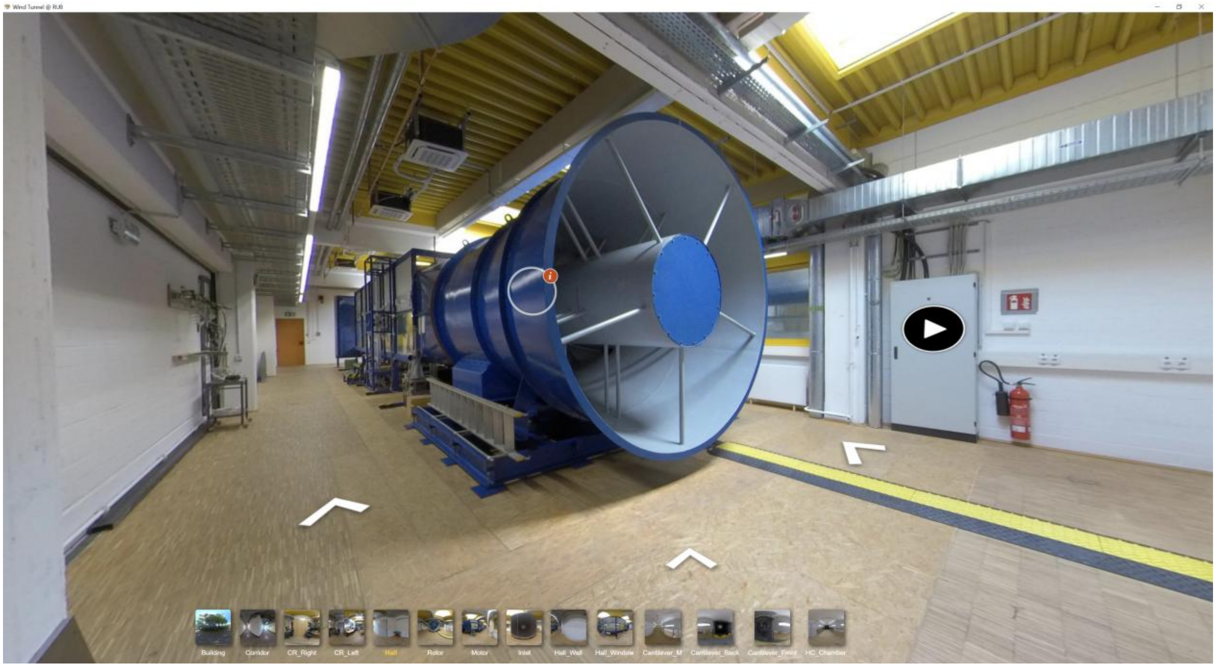


Figure 5.2: *Rotor scene of the VT from the wind tunnel facility at RUB, WiSt*

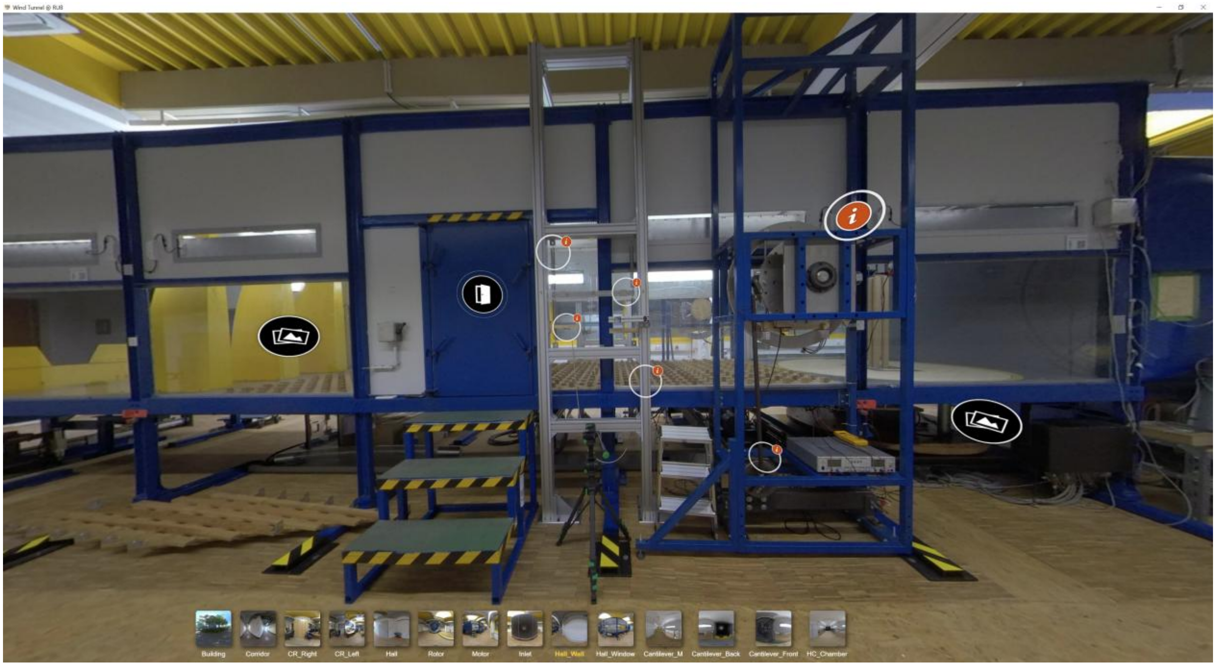


Figure 5.3: *Chamber entrance scene of the VT from the wind tunnel facility at RUB, WiSt*

Figure 5.4: *Inside chamber scene of the VT from the wind tunnel facility at RUB, WiSt*

5. 2. Gypsum Board Fire Resistance Test

The **VT** of the **Fire Resistance Test Facility** at the *University of Aveiro*, *Department of Civil Engineering*, depicts a **fire resistance test** conducted on a **gypsum plate wall**. The objective of this test was to **evaluate the integrity to flames**, **hot gases**, **and thermal insulation** in accordance with the **criteria of standard fire resistance classification**.

It is important to note that the **ambient conditions** and **test setup** at this facility are **not suitable for large attendance**; therefore, **fire resistance tests** are carried out under **strict safety restrictions**, and only **technical staff** are allowed to observe the experiments in person.

The **virtual tour** consists of a total of **13 scenes**, including **three 360° videos**. The scenes are organised sequentially so that, by **navigating through the virtual room**, users can follow the **chronological progression** of the experiment as it occurred in real life. The VT begins at **minute 0** (first scene) and ends after the **77th minute** (final scene). A **360° summary video** at the end reviews the entire test — compressing **77 minutes** of experimentation into **7 minutes** of footage.

The embedded **information hotspots** perform the following functions:

- **Displaying the construction process** of the gypsum board wall;
- **Depicting the exposed side** of the wall before and after the test;
- **Describing the equipment** and **data acquisition system** used in the laboratory;
- **Presenting raw sensor data** and **thermal camera recordings;**
- **Summarising the final results** and **tables related to fire classification;**

The **virtual tour** has been **published in both desktop and VR versions** and made available to students.

Screenshots from the desktop version of the tour are shown in **Figures 5.5–5.8**.

For further information about this virtual tour, please visit the **PARFORCE project website** [28].

Figure 5.5: *Minute 2 scene of the VT from the fire resistance test at UA*

Figure 5.6: *360° video of minute 25 of the VT from the fire resistance test at UA*

Figure 5.7: *Minute 77 scene of the VT from the fire resistance test at UA (test ended)*

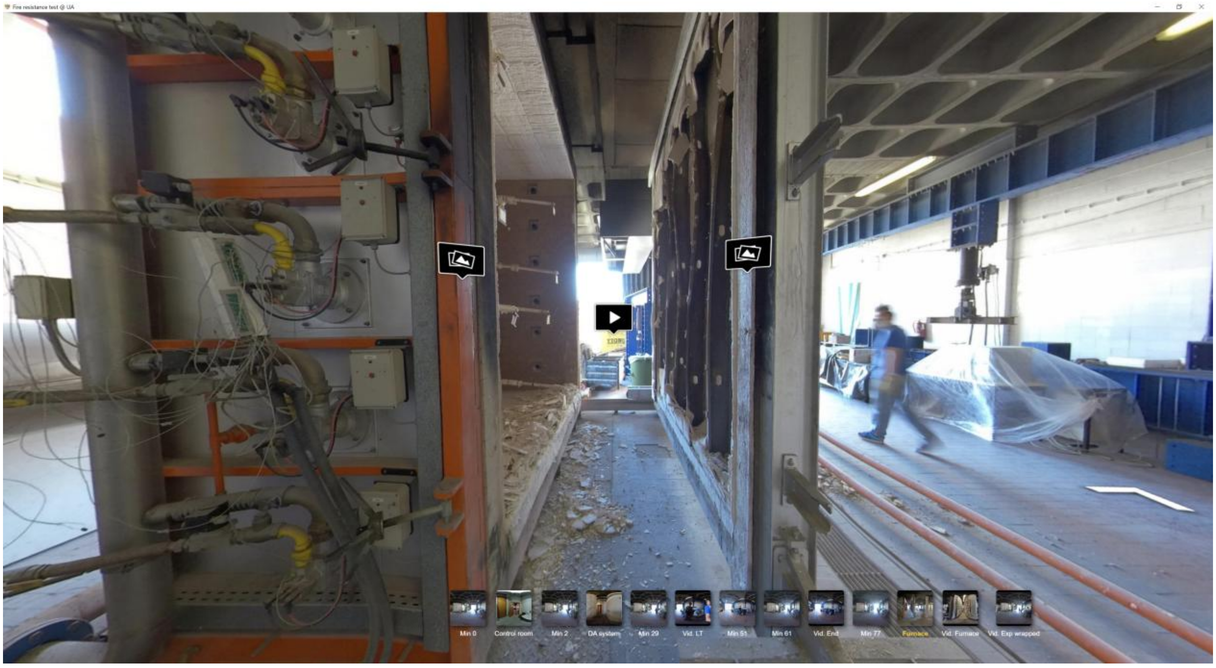


Figure 5.8: *Furnace scene of the VT from the fire resistance test at UA (test ended)*

5. 3. Quasi-Static Test of Polyurethane-Repaired Reinforced Concrete Column Hinges

The **VT** of the **quasi-static test** consists of a total of **four scenes**, including **three 360° panoramas** and **one 360° video**.

The **panoramic footage** was captured at different stages of the test:

1. From the **column element before testing**, with **no visible damage** at the hinge area;
2. From **the same column element after repair** with **polyurethane material**, ready to be **retested under identical load cases**;
3. From a **different viewpoint**, showing the **entire experimental setup**.

Figure 5.9 shows a **screenshot** from a **panorama scene** taken at the **beginning of the test**, before the column element sustained **damage around the hinge area**. In this figure, the column element appears slightly **distorted**, particularly along the **vertical midline**. This effect occurs because the screenshot was taken from the **VR version** of the virtual tour, and the **panorama** was originally captured as **stereoscopic footage**.

As a result, when viewed with the **naked eye**, the **stereoscopic image** may appear **geometrically distorted**, or in some cases (as shown in **Figure 5.10**) it may appear **slightly blurred** due to the **depth effect** inherent to stereoscopic imaging.

Figure 5.9: *Column scene of the VT from the quasi-static test at IZIIS (before damage)*

Figure 5.10: *Setup scene of the VT from the quasi-static test at IZIIS (before damage)*

Figure 5.11 presents the **panorama scene** of the **repaired column element** at the beginning of the **quasi-static test**. The **360° video** was employed to provide an **overview of the laboratory** and the **test setup**, as well as to help users **visualise the slow movement** of the column element during each **loading cycle**.

The embedded information hotspots in this virtual tour perform the following functions:

- **Displaying 2D footage** of the **hinge area**, before and after **crack propagation**
- **Providing close-up views** of **cracks** and **test equipment**, including **data acquisition systems**
- **Presenting diagrams** of **loading cases** at the end of each test
- **Showing time-lapse sequences** of **column element deflections** at the end of each test
- **Providing raw sensor data** recorded at the end of each test

The **final hotspot** is designed as a **download button**, allowing students to **download the raw sensor data** at the end of the tour. This functionality helps **educators** to **integrate the virtual tour** as a **learning object** within other **course activities and assignments**.

For instance, if students wish to **access and analyse raw sensor data** for a related assignment, they must first **complete the virtual tour** at least once in the **desktop version**.

The **virtual tour** has been **published in both desktop and VR versions** and made available to students.

For further information about this virtual tour, please visit the **PARFORCE project website** [28].

Figure 5.11: *Column scene of the VT from the quasi-static test at IZIIS (after being repaired)*

Figure 5.12: *A panorama scene of the VT from the IZIIS facility showing the shake table*

6. Application within the PARFORCE M.Sc. Pilot Course

The **implementation of virtual tours** as **supplementary learning objects** within a **blended learning pilot course** marked a **significant advancement** in the **conventional learning experience**, particularly in relation to **project-based learning** (see the *module guide* in **Table 6.1**).

The **pilot course** aimed to **facilitate the practical application** of students' **theoretical knowledge**. The **virtual tours** were employed to **illustrate laboratory setups**, **demonstrate experimental procedures**, and **visualize complex structural responses** under various **loading conditions** such as **wind**, **earthquakes**, and **fire**.

This **interactive and immersive approach** enabled students to **extend their practical understanding** by **auditing experiments** that were **not available at their home universities**.

The **pilot course** was designed with a focus on the **practical application of civil engineering principles**, emphasizing the effects of **various loading conditions** on structural behaviour. The **course content** was primarily based on the observation that **both earthquakes and winds** exert **lateral forces** on buildings, thereby motivating a **comparative study** between the two loading scenarios.

It is important to note that, although **earthquakes** and **winds** generate **dynamic forces** with distinct characteristics, these scenarios are often **approximated by static loadings** in the **simplified methodologies** commonly adopted in **building design codes.**

It is a widely accepted principle that these **two forces do not necessarily need to be considered simultaneously**, highlighting the importance of **identifying the governing lateral load provisions** in any **design problem** where both effects may be relevant.

However, such a **comparison** remains valid **only under specific conditions** and may not adequately account for **critical variables**—such as **geographic location**—that influence the **relative significance of earthquake and wind forces** on a **national scale**.

***Table 6.1**: Module guide of the pilot course*

<table>
<tr><th colspan="6">Experimental testing based on impact and resistance: wind, fire and earthquake</th><th>Module-No.: …</th></tr>
<tr><th>Semester No.</th><th>Frequency of the module offering</th><th>Duration</th><th>Type of module</th><th>Credit points (ECTS)</th><th>Language(s)</th><th>Student workload</th></tr>
<tr><td>3</td><td>annually in Winter Semester</td><td>1 Semester weekly</td><td>Elective compulsory</td><td>6</td><td>English</td><td>- 180hs, Thereof:
- 60hs attend. time,
- 60hs project work
- 60hs self-study and exam-prep. time</td></tr>
<tr><td>Recommended course requirements</td><td>Course program</td><td colspan="3">Form of examination / Duration of examination</td><td>Teaching and learning methods</td><td>Responsible for the module</td></tr>
<tr><td>B.Sc.
Basics in:
- signal processing
- dynamics matlab or python</td><td>NHRE
other</td><td colspan="3">Project presentation (oral), 50%
Project report, 50%</td><td>Lecture (L)
Project (P)</td><td>…</td></tr>
<tr><th colspan="7">Course content</th></tr>
<tr><td colspan="7"><u>Lectures: (hybrid format)</u>
Theoretical background about experimental testing based on impact and resistance with focus on wind, fire and earthquake; testing facilities and technical equipment; demands on specimens and scaling requirements; arrangement of sensors; application of equivalent impact/action (e.g. forces) in pseudo static and dynamic testing; physical interpretation and presentation of experimental data;

<u>Project:</u>
Training of modelling and analysis methods; study of code requirements and their application to different structural systems; evaluation of structural performance for wind and seismic action; Tools: Matlab or Python; SAP2000

<u>Workshop / Excursion (presence):</u>
Training in and practicing presentation skills; visit of construction sites; networking;
Date: from 24th to 31st of March 2023

<u>Place</u>: Weimar and Bochum</td></tr>
</table>

The **course** was structured to include **integrated lectures** throughout the semester, employing a **blended learning approach** (*see Table 6.2*). This format enabled the **incorporation of digital tools and resources**—including **virtual tours—thereby enhancing the learning experience** while **preserving the benefits of face-to-face instruction**.

The **in-person training week** held at the **end of the course** provided students with opportunities for **immediate feedback** and **in-depth discussions**, further enriching the **teaching–learning process**.

As part of the course activities, students also participated in an **excursion to the Dillenburg branch of the Westphalia Highway Authority**, where a group of **25 students** observed the **A45 replacement project** for the **Bornbach and Bechlingen viaducts**. The goal of this excursion was to **combine analytical and practical knowledge**, thereby enabling students to **enhance their problem-solving skills in real-world engineering contexts**.

Overall, the **pilot course**, combining **lectures**, **project work**, and a **technical excursion**, served as a **model for digital and collaborative learning**, demonstrating the **potential of blended education** to **enhance learning outcomes** and **foster practical competence** among students.

Table 6.2*: Overview of integrated lectures.*

Wind I: Physical modelling of wind effects at structures	**Fire I:** Introduction to fire safety in buildings	**Earthquake I:** Experimental mechanics – fundamentals
Wind II: Evaluation techniques (processing of measurement signals)	**Fire II:** Requirements for fire resistance tests to construction products	**Earthquake II:** Remote access experiments in Earthquake Engineering
Wind III: Example of a wind tunnel experiment	**Fire III:** Experimental practice in laboratory	**Earthquake III:** Large scale shake table test experiments of RC and masonry buildings
Wind IV: Vortex Induced vibrations	**Fire IV:** Analysis and evaluation of the test results	**Earthquake IV:** Experimental research in earthquake geotechnical engineering – element and model tests

At the **end of the pilot course**, students were invited to participate in an **anonymous survey** designed to evaluate various aspects of the course. The survey was divided into several sections, focusing on the **online lecture content**, **presence week activities**, and **project work structure and procedures**.

The **most important section** of the survey concentrated on **students' feedback regarding the virtual tours**. Nearly **90% of the participants** reported having tried at least **two virtual tours** on **desktop computers**. These students rated the **content quality** of the desktop version **4 out of 5** and indicated that they **did not experience any technical difficulties** while viewing the tours.

Fewer than **10% of students** did not try the virtual tours on **VR glasses**, citing reasons such as **limited device availability** or **discomfort when wearing VR headsets**. Among the remaining respondents (**91%**), approximately **70%** had **never used VR glasses** for any purpose (e.g., gaming) prior to the course.

In total, only **6% of students** reported **minor technical issues** while using VR glasses, including **motion sickness**, **blurry images**, or **uncomfortable settings**. Interestingly, when asked to compare **footage quality**, students rated the V**R version higher than the desktop version** (41%).

Approximately **70% of participants** agreed with the statement:

The immersive footage made me feel as if I were in the laboratory, and I felt comfortable standing close to the objects.

This finding is particularly relevant for experiments such as the **fire resistance test**, where **realistic spatial awareness** is an essential pedagogical feature.

Finally, the **majority of students (88%)** expressed that they would **like to experience the virtual tours on VR glasses again** in future courses.

7. Conclusions and Outlook

The present report has focused on the proposed **framework for implementing *virtual tours* as remote-access experiments**. *Use cases* extended by the **strategic partnership**, as well as results from the pilot course have been briefly discussed.

It has been proven that virtual tours not only can **enhance the learning process** but also can **provide a unique perspective on the practical implications of theoretical concepts**, thereby **bridging the gap between theory and practice**. The implementation of *VR tours* in the pilot course stands as a **model for collaborative teaching and learning**, demonstrating the **potential of digital intellectual effort** in an educational setting.

The *virtual tours* as **PARFORCE project results** are published as **web-based tours** on the public education portal *360-degree.education* [27]. Using **a public web-based platform** increases accessibility, hence, any user that has internet access can benefit from **PARFORCE virtual tours** as *free online learning objects*. Educators may integrate *PARFORCE virtual tours* within their **course curricula** and may access other *VT versions* on demand.

Virtual tours are currently designed for the **single user view**, which may be potentially extended for **simultaneous multi-user views**, hence, a **collaborative virtual laboratory** may be achieved in the near future. Moreover, **live streaming functions** may be added to *virtual tours*, *e.g. the student performance may be monitored and an opportunity to ask for instructions may be supported*.

Lastly, **VR-related comfort** may be increased, i.e. *interactions with hotspots* to be improved or to be replaced with *hand gestures*. Also, parameters related to footage clarity and stability that can easily lead to issues such as *motion sickness* may be further investigated.

References

[1] Winkelmann, U., Kurniawati, I., Höffer, R., Braungardt, K., Penava, D., Apostolska, R., Kähler, U., Mirboland, M., Hasan, P. L., Salzinger, J., Kalender, C., & Abrahamczyk, L. (2023). *Instructional design guide: Didactics of media learning environments* (University Handbook). ERASMUS+ Strategic Partnerships 2020 for "Digital Education": Partnership for Virtual Laboratories in Civil Engineering (PARFORCE).

[2] Kähler, U., Cerejeiras, P., Pereira, I., Lopes, N., Hasan, P. L., Apostolska, R., Höffer, R., Penava, D., & Abrahamczyk, L. (2023). *Methods and algorithms for digital learning tools evaluation: Guidelines for evaluation* (Report on Intellectual Output 2, IO-2). ERASMUS+ Strategic Partnerships 2020 for "Digital Education": Partnership for Virtual Laboratories in Civil Engineering (PARFORCE).

[3] Vezirov, T. G., & Bakmaev, A. (2019). *Pedagogical capacity of multimedia laboratory of educational resources in specialists training within the conditions of online learning.*

[4] Liu, J. (2020). Online teaching practice and reflection based on the perspective of learners. *International Journal of Frontiers in Sociology, 2*(3). https://doi.org/10.25236/IJFS.2020.020306

[5] Chen, P., Yang, K., Liu, Z., & Zhang, B. (2021). Research on online teaching practice of specialized course. In *2021 2nd International Conference on Big Data and Informatization Education (ICBDIE)* (pp. 629–633).

[6] Li, Y., Zhang, L., Tian, Y., & Qi, W. (2022). Research on teaching practice of blended higher education based on deep learning route. *Computational Intelligence and Neuroscience.*

[7] Nabizadeh, A. H., Gonçalves, D., Gama, S. P., Jorge, J. A., & Rafsanjani, H. N. (2020). Adaptive learning path recommender approach using auxiliary learning objects. *Computers & Education, 147*, 103777.

[8] Matar, N. A. (2011). Adaptive learning objects repository structure towards unified e-learning. In *International Conference on Information Society (i-Society 2011)* (pp. 404–410).

[9] Karampiperis, P., & Sampson, D. G. (2006). Adaptive learning objects sequencing for competence-based learning. In *Proceedings of the Sixth IEEE International Conference on Advanced Learning Technologies (ICALT'06)* (pp. 136–138). Kerkrade, Netherlands.

[10] IEEE Standards Association. (2020). *IEEE standard for learning object metadata (IEEE Std 1484.12.1-2020)* (pp. 1–50).

[11] Montoya, D. M., Vargas, J. E., Giraldo, J. S., & Hincapié, N. C. (2020). Developing a pedagogical method to design interactive learning objects for teaching data mining. *Journal of Educators Online, 17.*

[12] González-Lluch, C., Vergara, M., Bayarri-Porcar, V., Bellés, M. J., & Gracia-Ibáñez, V. (2021). Application of flipped methodology in computer-aided design teaching. In *ICERI2021 Proceedings.*

[13] Dagman, A., & Wärmefjord, K. (2022). An evidence-based study on teaching computer-aided design in higher education during the COVID-19 pandemic. *Education Sciences, 12*(1), 29. https://doi.org/10.3390/educsci12010029

[14] Wermann, J., & Pohn, B. (2022). VR training for laboratory environments. In *2022 International Conference on Software, Telecommunications and Computer Networks (SoftCOM)* (pp. 1–6). Split, Croatia.

[15] Try, S., Panuwatwanich, K., Tanapornraweekit, G., & Kaewmoracharoen, M. (2021). Virtual reality application to aid civil engineering laboratory course: A multicriteria comparative study. *Computer Applications in Engineering Education, 29*, 1771–1792.

[16] Lohre, R., Bois, A., Athwal, G., & Goel, D. (2020). Improved complex skill acquisition by immersive virtual reality training: A randomized controlled trial. *The Journal of Bone and Joint Surgery, 102*(6).

[17] Institute of Structural Engineering, Bauhaus-Universität Weimar. (2023). *4-point bending test.* Available at: https://www.uni-weimar.de/en/civil-engineering/institute/iki/ (Accessed: 2023-07-07).

[18] Chair of Computer Vision in Engineering, Bauhaus-Universität Weimar. (2023). *3D-RealityCapture-ScanLab.* Available at: https://www.uni-weimar.de/en/media/chairs/computer-science-department/computer-vision/research/3d-realitycapture-scanlab/ (Accessed: 2023-07-07).

[19] Chair of Computing in Civil Engineering, Bauhaus-Universität Weimar. (2023). *Structural Health Monitoring Laboratory.* Available at: https://www.uni-weimar.de/en/civil-engineering/chairs/computing-in-civil-engineering/research/shm-laboratory/ (Accessed: 2023-07-07).

[20] Tasliarmut, F., Vogt, A., Montag, M., Zander, S., & Koch, C. (2022). Conducting user studies in engineering education during the COVID-19 pandemic. In *Proceedings of the 2022 European Conference on Computing in Construction.* Ixia, Rhodes, Greece.

[21] Mirboland, M., Tasliarmut, F., Abrahamczyk, L., & Koch, C. (2022). A mixed reality application for holographic structural analysis experiments. In *Proceedings of the 2022 European Conference on Computing in Construction.* Ixia, Rhodes, Greece.

[22] CodeF53. (2019). *Comparison of the horizontal FOV of different headsets.* Available at: https://www.reddit.com/r/ValveIndex/comments/b9lp7t/comparison_of_the_horizontal_fov_of_different/ (Accessed: 2023-07-07).

[23] Immersion VR. (n.d.). *What is the difference between monoscopic and stereoscopic VR?* Available at: https://immersionvr.co.uk/blog/monoscopic-vs-stereoscopic-360-vr/ (Accessed: 2023-07-07).

[24] Visbit. (n.d.). *Virtual reality (VR) and 360 videos 101 — A beginner's guide.* Available at: https://medium.com/visbit/virtual-reality-vr-and-360-videos-101-a-beginners-guide-70bbade8e39 (Accessed: 2023-07-07).

[25] Insta360. (n.d.). *Insta360 Pro 2.0.* Available at: https://www.insta360.com/product/insta360-pro2/ (Accessed: 2023-07-07).

[26] 3DVista. (n.d.). *3DVista Virtual Tour Pro.* Available at: https://www.3dvista.com/en/products/virtualtour/ (Accessed: 2023-07-07).

[27] Bildungsportal "360° Bildung." (n.d.). *Education Portal "360° Education": Virtual learning experiences and excursions.* Available at: https://360-degree.education (Accessed: 2023-07-07).

[28] Bauhaus-Universität Weimar. (n.d.). *PARFORCE: Partnership for Virtual Laboratories in Civil Engineering.* Available at: https://www.uni-weimar.de/en/civil-engineering/international/strategic-partnerships-erasmus/ (Accessed: 2023-07-07).

Annex A: Hardware Recommendation List

The present list provides **recommendations for hardware equipment** used for **producing VR-compatible footage** and for **displaying the created content** through various types of **VR headsets** (*see Tables A.1-A.6*).

Further information about the PARFORCE project and access to the developed virtual tours can be found on the **official project website**: https://www.uni-weimar.de/de/bau-und-umwelt/professuren/komplexe-tragwerke/forschung/abgeschlossene-projekte/parforce/.

7. 1. A.1. 360°/180° degree VR cameras

Most of the **cameras mentioned above** are equipped with **on-board stitching functions** or come with a **proprietary desktop stitching application** provided by the manufacturer.

In case users wish to **perform manual stitching** or require **greater control over the editing process**, the use of ***Adobe After Effects*** is **recommended** for post-processing and stitching of VR footage.

Table A.1: 360° camera (Monoscopic footage only)

#	Name	Intended for	Price	Availability	Top features
1	Insta360 One X2	Consumer	+ From 500 Euros (only the camera) + different kits/accessories available	In stock	- Live streaming - Video quality up to 5.7K @ 30 FPS
2	Kandao QooCam 8K Enterprise	Consumer / Prosumer	+ From 1.600 Euro	In stock	- Highest tested video quality (8K @ 30 FPS) - Live streaming at 8K (highest available in the market in the consumer category)
3	Ricoh Theta X	Consumer /Prosumer	+ From 999 Euro	In stock	- Best and the newest Ricoh product - Live streaming quality 4K @ 30 FPS
4	GoPro Max	Consumer	+ From 490 Euro	In stock	- - Video quality 6K - suitable for beginners - good for 360 videos
5	Ricoh Theta Z1	Consumer	+ From 1.300 Euro	In stock	- Best for 360 Images and panoramas - Image quality and reliability is high
6	Trisio Lite 2 VR 8K	Consumer	+ From 400 Euro	In stock	- Best budget camera for 360 images
7	Insta360 One RS twin edition	Consumer	+ From 500 Euro	In stock	- Together with One X2, the best consumer cameras for 360 videos
8	Labpano Pilot One EE (512 GB)	Consumer/Prosumer	+ From 2.000 Euro	In stock	- Direct connection to Google Street View - Can upload footage to google drive - On the top 5 list of 360 cameras for 2022

***Table A.2**: 360° camera (Monoscopic + Stereoscopic)*

#	Name	Intended for	Price	Availability	Top features
1	Insta360 Pro 2	Prosumer	From 5.000 Euro (basic kit), Premium kit for 6000 Euro	In stock	- Best Profi camera within a low-budget - Live streaming 8K 30 FPS - on-board stitching for 4K videos - Video quality at 8K for 3D
2	Mosaic51	Prosumer	From 20.000 Euro	In stock	- High resistance against harsh environment - up to 12 K resolution - High dynamic range, suitable for street view mapping
3	Kandao Obsidian Pro	Prosumer	From 2.100 Euro (standard kit)	In stock	- 12K 3D videos - max. Live streaming quality 8K @ 30 FPS - 8 APS-C lenses (other alternatives have max. 6 lenses)

***Table A.3**: 360°/180° camera (Monoscopic in 360°, Stereoscopic in 180° mode)*

#	Name	Intended for	Price	Availability	Top features
1	Kandao QooCam	Consumer	From 299 Euro	In stock	- 3 wide angle fisheye lenses - 4K @ 30 FPS video quality
2	Z Cam K1 Pro	Prosumer	From 4.200 Euro	In stock	- Only 180° §D footage - Cinematic usage - 6K @ 30 FPS output quality - Live streaming at 4K @ 60 FPS

7. 2. A.2. VR and MR wearables

Standalone VR goggles are equipped with **on-board display processors**, **batteries**, and **integrated sensors/cameras** that enable **spatial orientation** and **position recognition**.

Six degrees of freedom (6DOF) headsets allow users to **move freely** within the real environment, incorporating **rotations and translations along three axes**. In contrast, **three degrees of freedom (3DOF)** goggles only enable **head tilting and directional viewing**, without real-world positional tracking.

***Table A.4**: Standalone glasses*

#	Name	Intended for	Price	Availability	Top features
1	Oculus (Meta) Quest 2	Consumer/Prosumer	From 410 Euros (128 GB)	In stock	- Glasses + hand controllers - Best budget standalone set - Field of view: 90˚ - Facebook product (requires a FB account!)
2	HTC Vive Focus 3	Prosumer	From 1400 Euros (kit)	In stock	- Best standalone VR kit - limited to specific enterprises/VR applications games
3	Pico Neo 3 Pro (eye)	Consumer/Prosumer	From 700 Euro	In stock	- Standalone AND PC - hand controllers included - built-in eye tracker (EYE version)

PC-connected VR goggles (also known as *tethered VR headsets*) require a **high-performance computer**, **base stations** for **real-world tracking**, and **controllers** for interaction. While **wired connections** can **limit mobility** and **constrain applications**, these systems typically offer **superior image resolution** and **more accurate tracking**.

Standalone goggles are generally **preferred** when the **computational or rendering demands** are moderate, or when **user mobility** and **portability** are essential—such as in educational or demonstration environments. It is also worth noting that **standalone headsets** are typically **more affordable** than their **PC-tethered counterparts**.

The following section lists **leading VR and MR hardware currently available on the market**.

Table A.5*: PC VR glasses*

#	Name	Intended for	Price	Availability	Top features
1	HP Reverb G2	Consumer/Prosumer	From 500 Eruo (only glasses- currently low availability) From 650 Euro (+ hand controllers)	In stock	- High image resolution for PC VR glasses - Field of view: 114˚
2	HTC Vive Pro 2/ Eye	Consumer/Prosumer	From 800 Euro (only glasses) From 1400 Euro (full kit: hand controllers + base stations)	In stock	- Highest image resolution for PC VR glasses (5K) - Field of view 120˚ - better processor than the older version (HTC Vive Pro) - the Eye version has built-in eye tracker
3	HP Valve Index VR	Prosumer	From 1650 Euro (kit)	In stock	- Gaming monster PC VR kit - Field of view 120˚ - Finger tracking
4	HTC Vive Cosmos XR	Prosumer	From 600 Euro (only glasses), 1000 Euro (kit)	In stock	- high resolution - supports many applications (suitable for business)

Another category of **VR headset** are the **smartphone-based VR goggles**, which require users to **insert a smartphone** into the headset and use the **smartphone's display** as the **visual interface**.

These goggles contain only **two optical lenses**, which **project separate images** from the smartphone screen to each eye, thereby **creating a stereoscopic effect**. Consequently, the **image quality** is directly **dependent on the smartphone's screen resolution and refresh rate**.

Smartphone VR headsets are typically intended for **leisure and educational purposes**, such as **playing simple VR games** or **exploring virtual tours**, offering a **low-cost introduction to immersive environments**.

***Table A.6**: Smartphone VR headsets*

#	Name	Intended for	Price	Availability	Top features
1	BoboVR Z6	Consumer	From 50 Euros	In stock	- Smartphone VR headset: ONLY works with a smartphone in it, has no display! - Similar alternatives such as BNext VR headsets exist

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