Research & Development Portfolio

Immersive XR Learning and Training for Electromobility / Powertrain Systems

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Research Identity

Theme. I build immersive VR laboratories for **autodidactic learning** in complex technical domains (electromobility / powertrain), combining **realistic interaction**, **step-by-step guidance** (holographic instruction), and **measurable learning tasks**.
Core research question. How can VR training systems improve system understanding and procedural skill acquisition by integrating (1) meaningful manipulation primitives, (2) contextual guidance, and (3) immediate feedback/validation?
Tooling. Unity (C#), XR Interaction Toolkit / OpenXR, Blender (3D workflow), Cinema4D (holographic instruction videos), deployment on Meta Quest (standalone constraints).

Key Contributions (Selected)

- Designed and implemented an immersive VR powertrain laboratory supporting guided + exploratory learning.
- Developed process-based training modules: wire winding, drilling/screwing, positioning/inspection.
- Added a holographic assistance layer for contextual instruction and adaptive feedback.
- Ran an initial comparative evaluation (VR vs. traditional learning) and gathered expert feedback.

1. Project A - Master Thesis: Immersive VR Powertrain Laboratory

Project type: Master Thesis (FAU / FAPS) Platform: Unity + OpenXR + Meta Quest

Goal: Design and development of an immersive virtual lab for autodidactic learning of powertrain systems in electromobility.

Problem. Traditional teaching methods (slides, 2D diagrams, limited lab access) often fail to communicate the spatial and procedural nature of powertrain systems. Physical labs are costly, constrained by safety, and not always available for repeated training.

Approach. A VR laboratory structured as a learning path from fundamentals to realistic process modules, supported by an in-situ guidance layer (holographic steps) and an interaction validation/feedback loop.

System overview.

- **Learning zones:** onboarding/introduction, theory/information, hands-on exploration, assessment.

- **Training modules:** wire winding; drilling and screwing; component positioning and inspection.
- **Guidance:** holographic step videos/animations that can be activated on demand.
- **Feedback:** highlights, icons, audio prompts, status UI, step validation (correct/incorrect + next action).
- **Constraint:** standalone VR performance and robustness (stable interactions on Meta Quest).

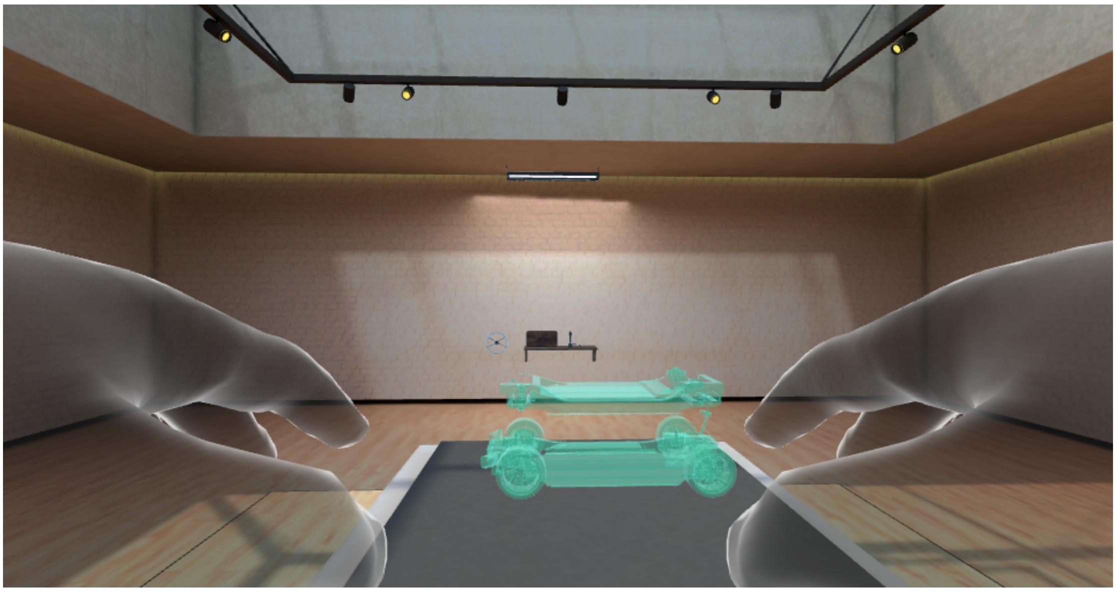

Figure 1: Overview of the immersive VR powertrain laboratory (zones + learning flow).

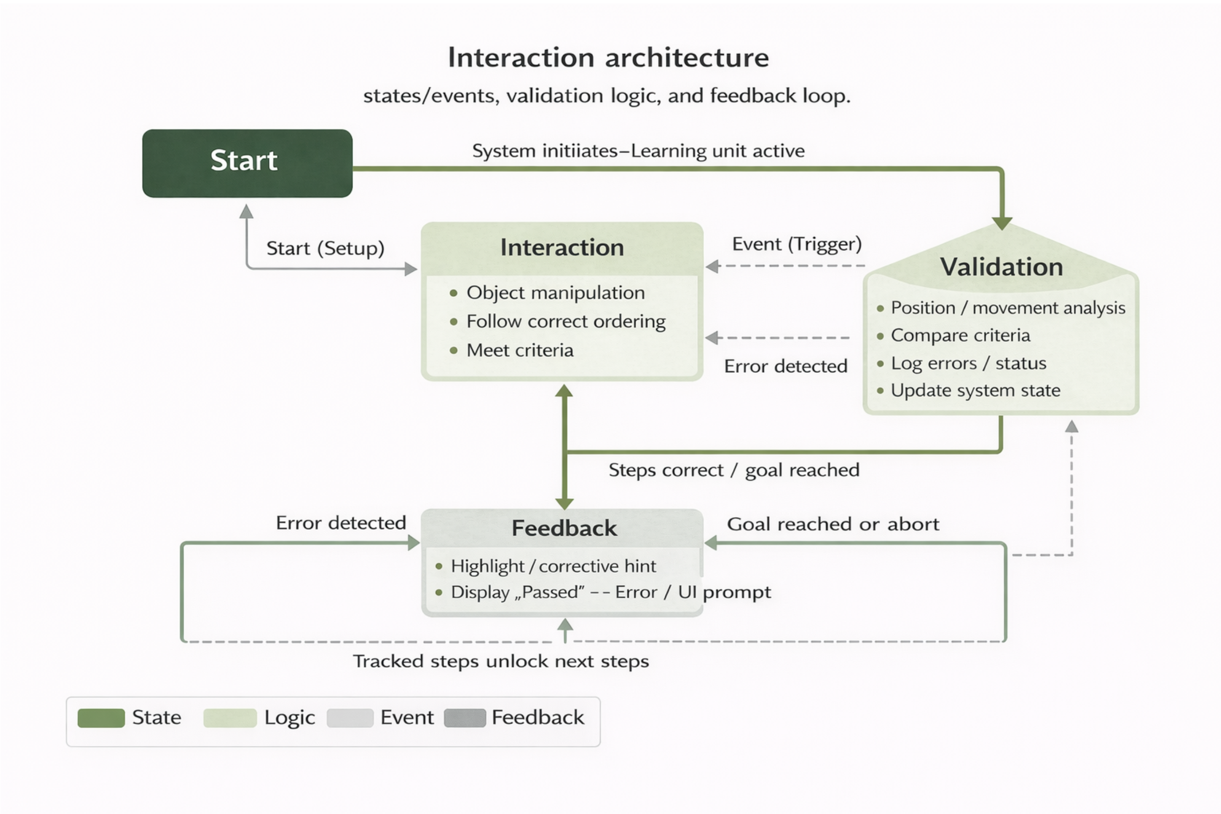

Figure 2: Interaction architecture: states/events, validation logic, and feedback loop.

Why this is research-relevant (not just a demo).

- The system operationalizes autodidactic learning by combining free exploration with structured, validated tasks.
- It studies how guidance layers (holograms) affect success rate, errors, and confidence in procedural training.
- It addresses real deployment constraints (standalone VR), which impact interaction design and evaluation validity.

HCI and Spatial Computing Architecture

Interaction as Spatial Computation.
The immersive VR laboratory is structured as a spatially computed interaction system. User actions are interpreted as transformations within three-dimensional space and evaluated against process-specific engineering constraints.

The interaction architecture consists of four computational layers:

- Spatial state representation
- Constraint evaluation
- Deterministic validation logic
- Multimodal feedback generation

Spatial State Representation.

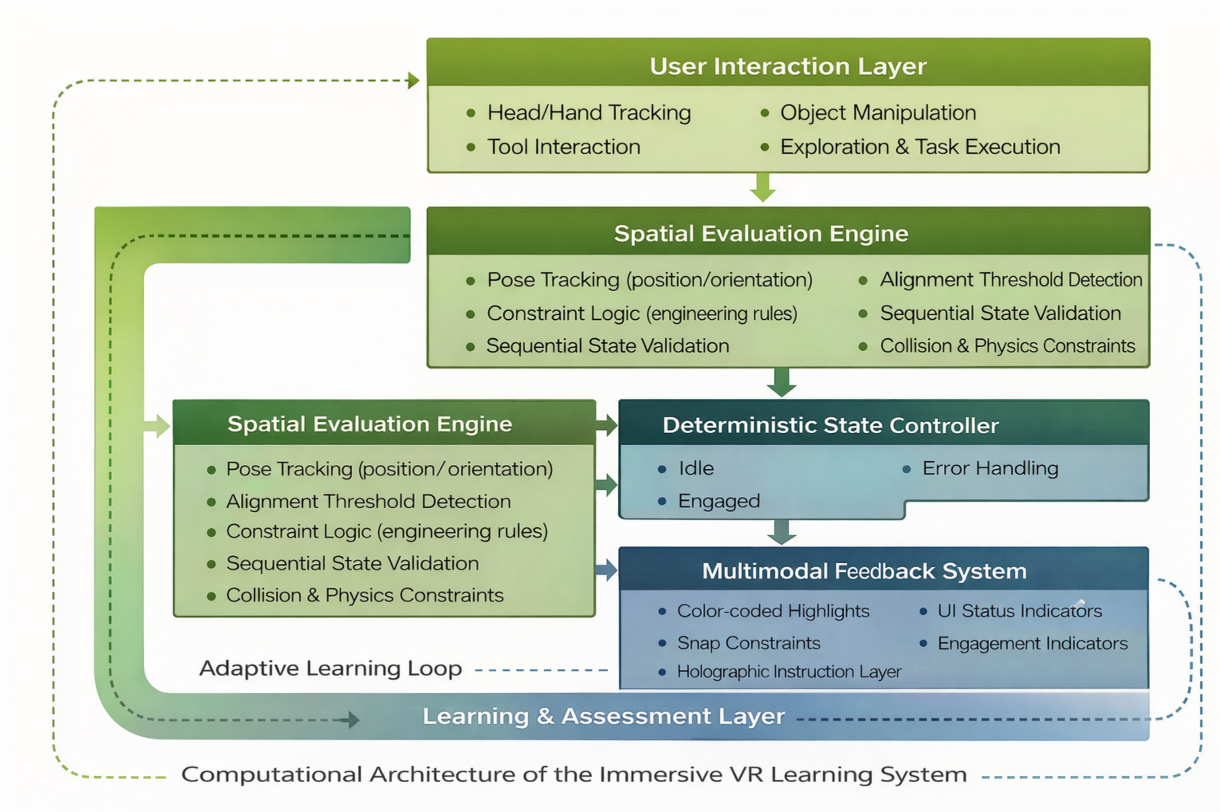

Figure 3: Computational architecture of the immersive VR learning system

Each interactive object continuously maintains:

- Position and orientation (pose tracking)
- Relative transformation to target reference frame
- Alignment tolerance thresholds

System states are computed dynamically from spatial relationships rather than triggered by predefined animation timelines.

Constraint-Based Validation.
Interaction logic enforces:

- Alignment accuracy
- Sequential correctness
- Tool–object compatibility
- Completion verification

This transforms the immersive environment into a deterministic, rule-based computational system.

State Transition Model.
Interaction evolves through defined states:
Idle → Engaged → Aligned → Validated → Completed
Transitions occur only when spatial and logical conditions are satisfied, ensuring predictable and pedagogically clear behavior.

Closed Feedback Loop.
Spatial evaluation is translated into perceptible cues:

- Color-coded highlighting
- Snap constraints
- Context-aware holographic guidance

User Action → Spatial Evaluation → Validation → Feedback → Adaptation

Alignment with Spatial Computing and Automotive UI.
The implemented framework parallels spatial computing paradigms used in advanced automotive interfaces, where pose-driven input, environmental constraints, and real-time feedback determine system behavior.

2. Module 1 - Wire Winding (Process Simulation)

Interaction primitive: controlled rotation + wire handling **Focus: procedural skill + feedback**

Learners perform the full process: pick spool, fix wire, controlled winding, cut wire, place finished winding.

What I implemented.

- Sequence logic with step validation (correct order and conditions).

- Visual feedback for correct placement and tension/position states.
- A custom visual/mesh-based technique so the wire appears visually separated when cut (intuitive cue).

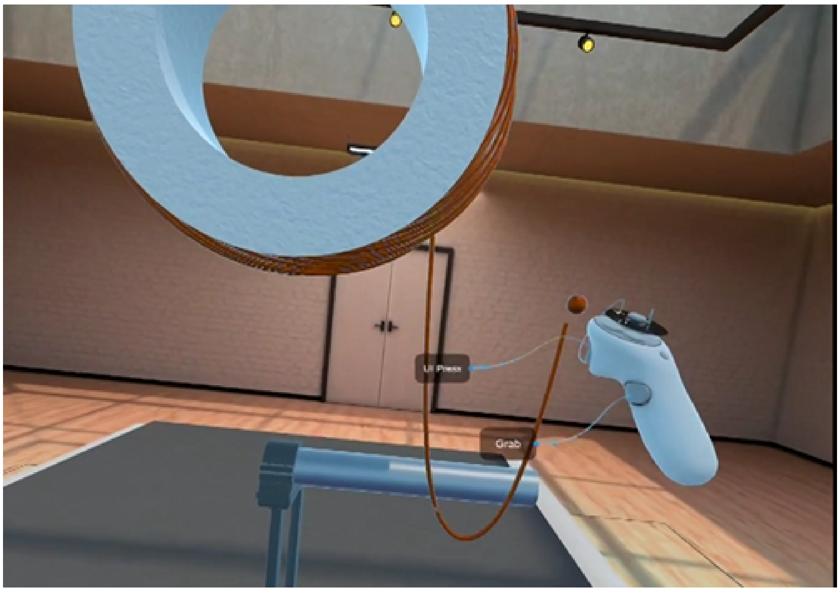

Figure 4: Wire winding station in VR: interaction points and process setup.

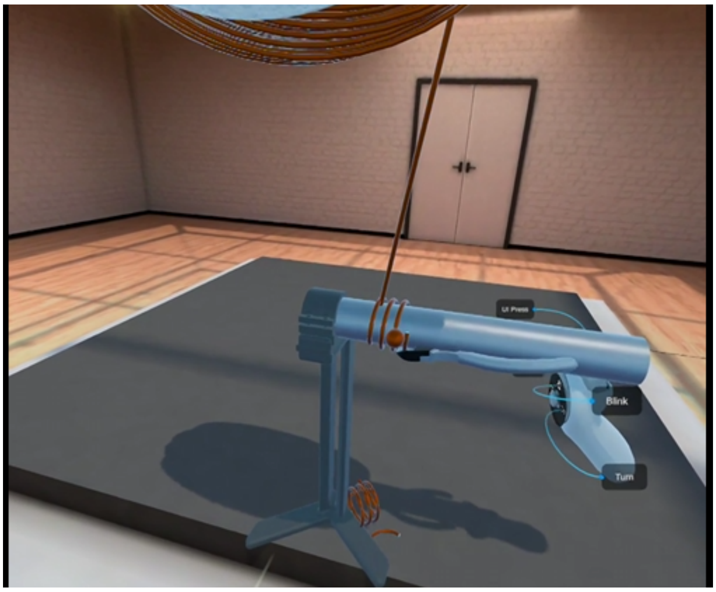

Figure 5: Visual feedback of wire cutting (mesh/visual separation for intuitive confirmation).

3. Module 2 - Drilling & Screwing (Tool Handling)

Interaction primitive: tool selection + alignment + constraint **Focus: order, accuracy, confirmation**

Learners select tools/screws, drill first, then screw with correct orientation and target points.

What I implemented.

- Object pickup/placement workflow with alignment assistance (snap/constraints where appropriate).

- Correct order enforcement (drill → screw) and target validation (correct points, correct tool/screw type).
- Feedback layer: highlights, status indicators, and corrective hints.

Figure 6: Toolbench and interaction setup (pick, place, validate, feedback).

Figure 7: Screwing interaction: alignment + constraints + step confirmation.

4. Module 3 - Positioning & Inspection

Interaction primitive: place component and verify **Focus: correctness + diagnostic feedback**

Learners position components with correct orientation and verify via inspection criteria.

What I implemented.

- Placement criteria (position + rotation thresholds).
- Clear diagnostic feedback (orientation vs. position vs. missing prerequisite).

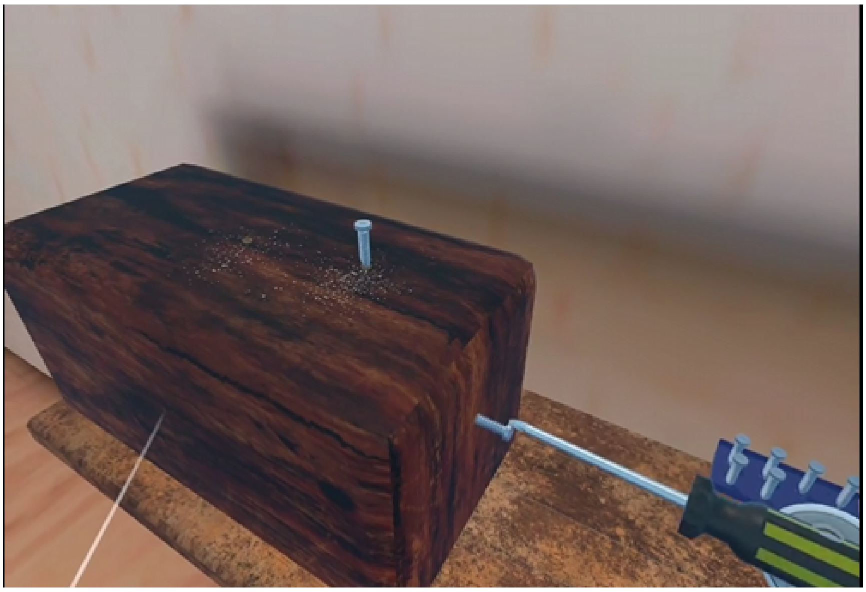

Figure 8: Positioning task: correct vs. incorrect state feedback (diagnostic messages).

5. Holographic Assistance Layer (In-situ Guidance)

Guidance: holographic step videos/animations **Purpose: reduce errors + build confidence**

Learners can activate a hologram to view the ideal movement/sequence and compare it to their own action.

Design intent. The hologram is not always on. It is a support layer learners use when stuck, enabling exploration while still providing reliable step guidance.

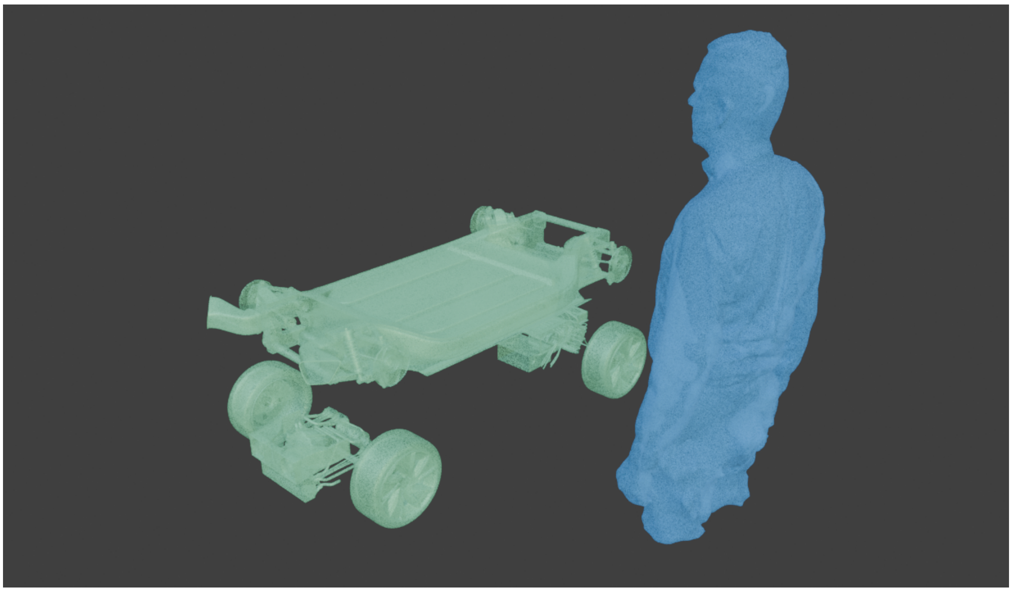

Figure 9: Holographic instruction anchored in the workspace (step guidance on demand).

6. Evaluation (Current Evidence + What Comes Next)

Current: initial comparative test + expert feedback **Next: stronger study design**

Goal: show evidence without overclaiming; be realistic about limitations.

Current evidence (to report clearly).

- Small comparative setup: VR learning vs. traditional material with identical content.
- Observed outcomes: higher motivation/engagement in VR and improved spatial understanding for powertrain relations.
- Qualitative feedback: usability/clarity, comfort, and perceived learning value.

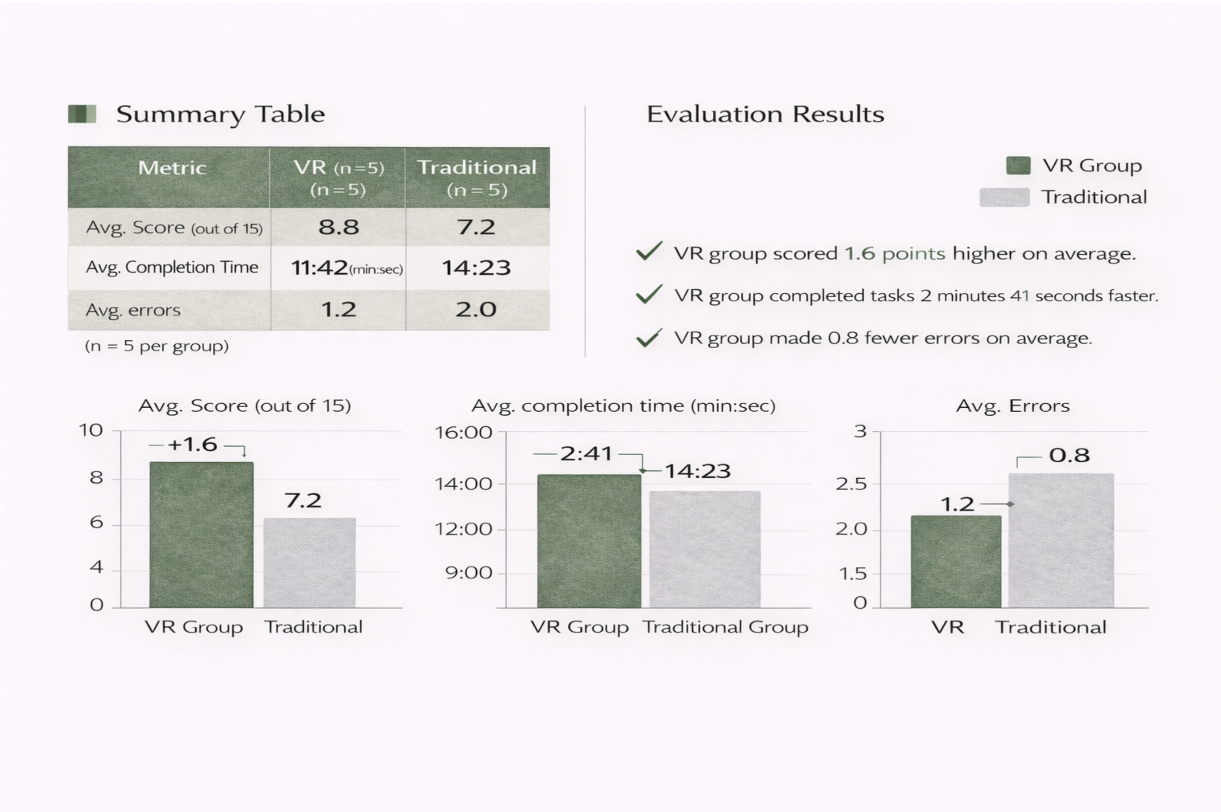

Figure 10: Evaluation results summary (score, completion time, and errors; n=5 per group).

Limitations (state openly).

- Small sample size; results are indicative, not conclusive.
- Mostly short-term measurement; retention and real-world transfer still open.

Next steps (PhD-ready direction).

- Larger study with standardized metrics (task time, errors, success rate, cognitive load, SUS).
- Measure transfer: VR training performance → real task performance (where feasible).
- Compare guidance types (hologram vs. text/voice vs. mixed) and quantify impact.

7. Project B - VR-based Autodidactic Learning for Electromobility (Project Thesis)

Scope: EV fundamentals learning environment **Focus: learning zones + assessment**

A zone-based VR learning platform: onboarding, theory, hands-on exploration, assessment.

Key features.

- Guided onboarding with clear navigation and low VR-experience barrier.
- Theory zone with diagrams/media and structured knowledge chunks.
- Hands-on zone to explore and compare vehicle concepts and components.
- Assessment zone to check system understanding of battery/inverter/motor/powertrain.

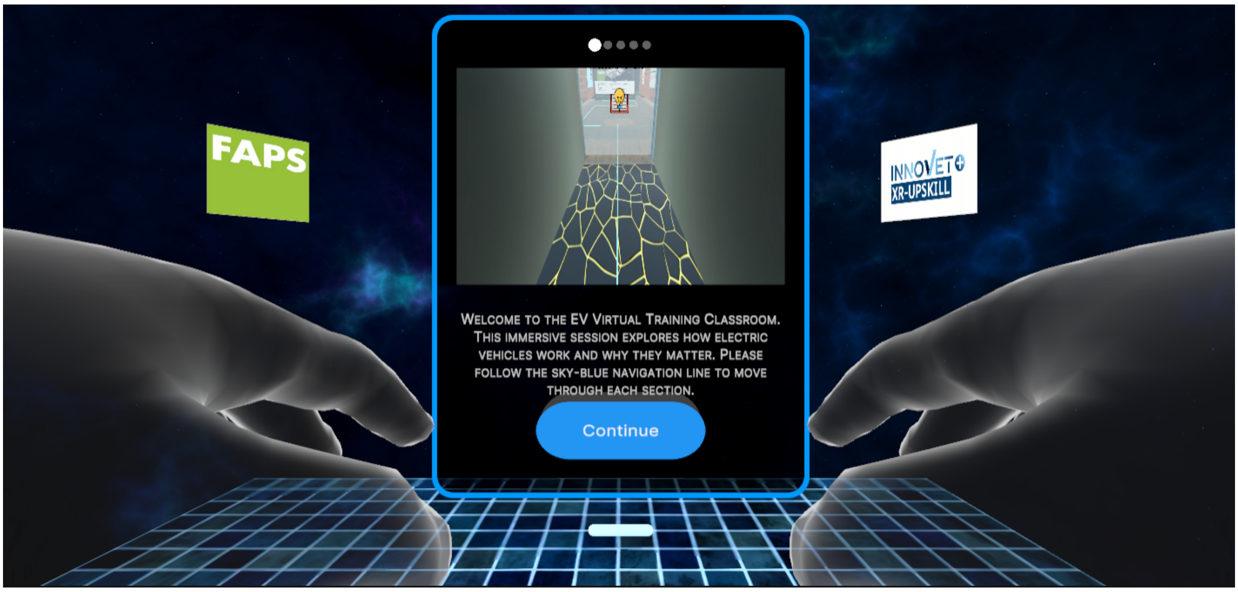

Figure 11: Onboarding: learning goals and navigation cueing.

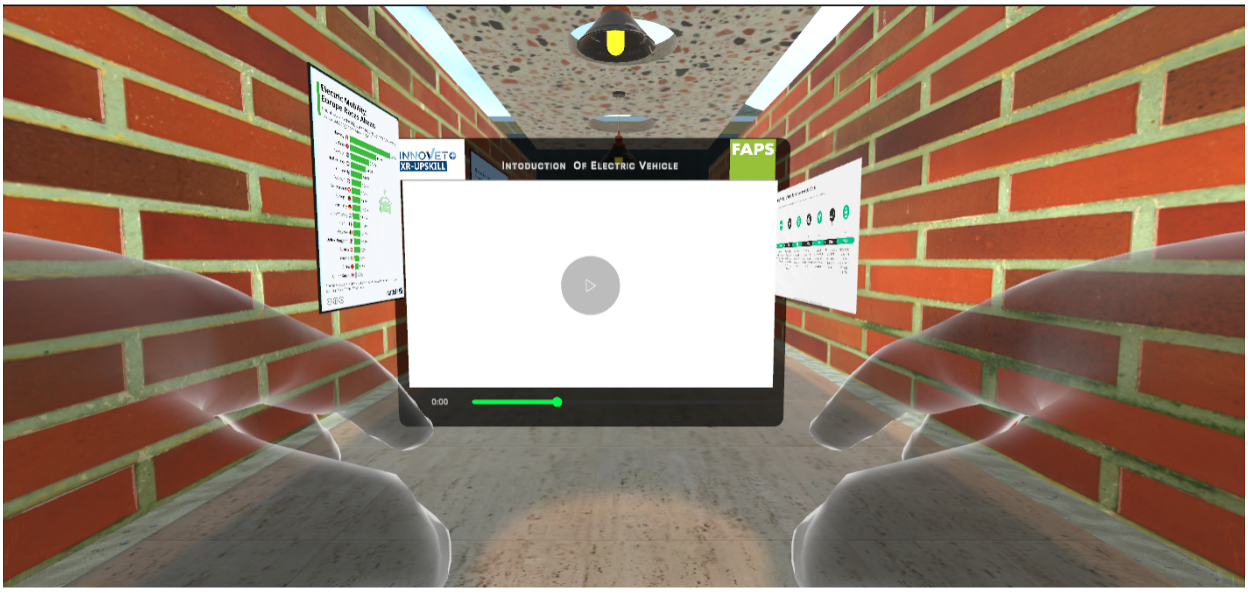

Figure 12: Theory zone with diagrams/media supporting the introduction.

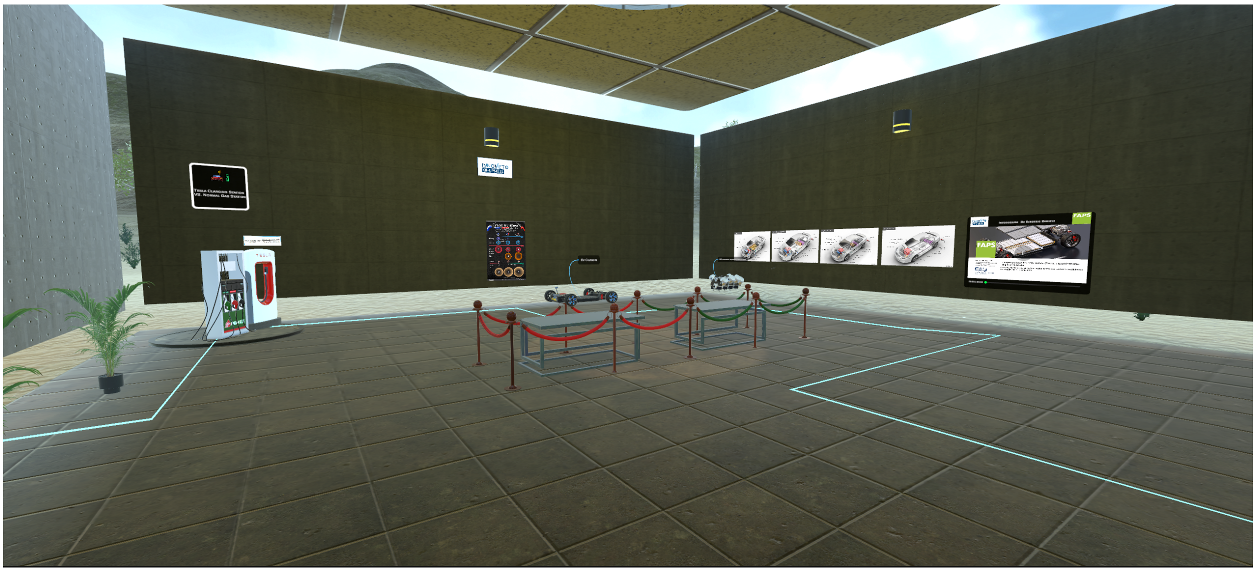

Figure 13: Hands-on zone for interactive exploration and comparison.

Figure 14: Assessment zone for checking core component understanding.

8. Technical Skills (What I can build independently)

XR / Unity / C#.

- Unity: scene setup, prefabs, XR Interaction Toolkit, OpenXR, Timeline/Animator
- C#: interaction logic, events, state machines, validation systems
- Physics-based interactions: rigidbodies, colliders, constraints (robust for VR)
- Standalone optimization for Quest: mesh/texture budgeting, lighting strategy, stable FPS targets

3D workflow.

- Blender: modeling, UV, materials, CAD mesh cleanup, segmentation, export pipeline to Unity
- Cinema4D: holographic instructional sequences and explanatory animations

HCI/UX in VR.

- spatial UI design, feedback systems, comfort/ergonomics, iterative testing
- user journey design: entry → orientation → tasks → closure/feedback

Current status and ongoing work.

The master's thesis is currently ongoing. In addition to the modules presented above, current development extends the VR laboratory with **joining operations (adhesive bonding)** and **material separation processes (cutting)**. These extensions reuse the existing interaction, validation, and feedback framework to cover additional manufacturing steps.