Recommended Practices for Haptics in Enterprise VR

Haptics Industry Forum | hapticsif.org
Recommended Practices for Haptics in Enterprise VR

1 Working Group Members .............................................................................................................. 3
2 How to use this document ............................................................................................................. 4
3 Scope and Definition ..................................................................................................................... 5
4 Application Areas .......................................................................................................................... 6
  4.1 Virtual Prototyping .................................................................................................................... 6
  4.2 Training .................................................................................................................................. 8
  4.3 Marketing and Sales ................................................................................................................ 10
  4.4 Tele-existence/Telerobotics .................................................................................................... 12
  4.5 Assistive .................................................................................................................................. 13
5 Integration Workflow ...................................................................................................................... 16
  5.1 Custom Scenario ..................................................................................................................... 16
  5.2 Existing Product ..................................................................................................................... 19
6 Technologies .................................................................................................................................. 21
  6.1 Vibrotactile ............................................................................................................................. 21
  6.2 Resistive Force Feedback ......................................................................................................... 22
  6.3 Active Force Feedback ........................................................................................................... 22
  6.4 Skin Indentation ...................................................................................................................... 23
  6.5 Ultrasound .............................................................................................................................. 23
7 Representative Case Studies ......................................................................................................... 24
  7.1 Electrical Maintenance Training ........................................................................................... 24
  7.2 Automotive Painting Training ............................................................................................... 26
  7.3 Satellite Assembly Training .................................................................................................... 28
  7.4 Discover History with Haptics ............................................................................................... 29
  7.5 Electrical Assembly Training .................................................................................................. 31
  7.6 Nerve damage experience ...................................................................................................... 32
  7.7 Augmented Reality Haptics Showcase .................................................................................... 34
  7.8 Medical Care Training ............................................................................................................ 36
8 Company Resources ..................................................................................................................... 38
9 References ...................................................................................................................................... 39
## 1 Working Group Members

<table>
<thead>
<tr>
<th>Name</th>
<th>Company</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daniel Shor</td>
<td>Contextual Labs</td>
<td>Mechanical Engineer</td>
</tr>
<tr>
<td>Eric Vezzoli</td>
<td>InterHaptics</td>
<td>Systems</td>
</tr>
<tr>
<td>Chris Ullrich</td>
<td>Immersion</td>
<td>Systems</td>
</tr>
<tr>
<td>Gijs den Butter</td>
<td>SenseGlove</td>
<td>Sales</td>
</tr>
<tr>
<td>Kim Oberg</td>
<td>HaptX</td>
<td>Sales</td>
</tr>
<tr>
<td>William Frier</td>
<td>Ultraleap</td>
<td>Researcher</td>
</tr>
</tbody>
</table>
2 How to use this document

This document is intended to orient product and program managers working in enterprise virtual reality (EVR) application areas who are considering adding haptic feedback technologies to their new or existing projects. This document collects several decades of combined experience in this specific area by members of the Haptics Industry Forum. More information available at https://hapticsif.org.

Adding haptic feedback to a new or existing EVR project may seem daunting, but with the correct perspective and expectations, haptics can generate real value-add without derailing project timelines or budgets.

This document provides an overview of EVR use cases in which haptics is known to provide meaningful value. An overview of these use cases is provided in Section 4. The typical integration process for haptics is captured in Section 5. An overview of the key technologies for haptic EVR is provided in Section 6. Finally, a selection of real-world case studies is presented in Section 7.
3 Scope and Definition

Enterprise-grade Immersive Virtual Environments (IVEs) are changing the way that industry collaborates, designs new products, and trains employees. One of the critical barriers to widespread adoption of Enterprise IVEs is that, today, IVEs don't feel real. Without touch, enterprise use cases for VR remain limited.

While there are many companies developing products that aim to address issues that impede the adoption of enterprise IVEs, the lack of standardization and coordination among these companies limit cross-compatibility between various hardware products and software, which stovepipes IVE development.

Before considering integration of haptic technologies into an enterprise VR application, it is critical to precisely determine the role of haptics and the expected fidelity of the experience. Reproduction of the complete fidelity of physical objects with haptic technologies is still not a realistic expectation in most cases. However, haptics do provide important value in the form of presence and skill acquisition speed, and the details of each application area dictate the necessary fidelity.
4 Application Areas

This section provides an overview of the key application areas for haptics in Enterprise VR as well as the most probable value proposition for haptics in particular.

4.1 Virtual Prototyping

4.1.1 Overview

Efficient digital prototyping involves simulating objects’ behavior under real world operating conditions; therefore, sensorial experience is as important as the visual one. While VR makes it possible to model systems and interactions visually, haptics make these interactions lifelike. This will increase the perceived realism of the user.

4.1.2 Investment Range

Consumer ($) to Enterprise simulative training ($$$$)

4.1.3 Non-Haptic Considerations

- **Application maturity.** A successful virtual prototyping application requires the user to be familiar with virtual reality technology and having successfully delivered proof of concepts validating the ROI.
- **Developer/integrator capabilities.** The developer and integrator capabilities are important factors to consider while engaging with VR prototyping content creation. VR prototyping applications are well served with refined accessibility features.
- **CAD to VR pipeline.** One of the key aspects for virtual prototyping is the implementation pipeline for CAD data to enable the review process.
- **Multi versus single player.** Shared experiences help users to speed up the virtual prototyping process through real time communication.

4.1.4 Customer Goals

- **Reduce prototyping costs.** Save on physical prototypes and mock-ups. Reduce cost compared to traditional digital prototyping tools like caves and powerwalls.
- **Speed up development cycles.**
- **Standardized solution.** Have one generic solution for all digital prototyping efforts.
- **Dispersed Locations.** A VR solution is portable and can be positioned anywhere, even in a home environment. VR offers multiplayer solutions where several engineers can be present during the assessment of the digital prototype.

4.1.5 Role of Haptics

- **Realism.** A similar behavior between the virtual and real environment facilitates an informed understanding of human behavior. The improved perceived realism makes
it easier for the user to make decisions on UX, manufacturability, or ergonomics of a virtual prototype.

- **Immersion.** Haptics can enhance a user’s sense of immersion during the execution of a test, creating a more realistic and engaging testing environment.

- **User experience.** Hand tracking combined with haptics enables interaction that doesn't require a steep learning curve, as opposed to interactions that rely on controllers where every interaction is programmed differently. This enables the opportunity to work with untrained users. This can be critical in testing virtual prototypes on user behavior.

### 4.1.6 Haptic Considerations for Success

- **Wearability.** Virtual prototyping needs to meet operational targets to justify its ROI. The haptics device used for these applications should be easy to wear, comfortable, and it should not impede users’ natural movements.

- **Embodiment.** The embodiment of the haptic technology should be fit for the right purpose. Is the objective to perform simple ergonomic analysis or to provide designers with a tool to evaluate a prototype from a remote space? Or is the objective to digitalize the objective of a clay model in the automotive design process? Different situations require different embodiments. The transparency of the solution should be based upon the desired fidelity and the associated ROI to the solution.

- **Scalability (hours of use, number of deployments, etc.).** One of the key aspects to consider when thinking about haptics in VR is where the scalability comes from. Do you need repeatability of the same content on different premises, to target hundreds if not thousands of users? Or are you looking to create a one-of-a-kind set up for critical operation training for specific applications? Both scenarios have different needs and requirements that can be addressed by different haptic devices.

- **Integration of non-haptic peripherals and mock-ups.** Mixed reality mock-ups are a very good way to rapidly iterate in prototyping. Consider whether your haptic solution can interact with the physical part of the mock-up and whether it is able to simulate the right fidelity of haptics.

- **Content enablement.** The trade-off that should be considered is the ease of implementation against the quality of haptics. Standard haptic interaction might be compatible with direct CAD to VR pipeline solutions; more detailed haptic interactions would require tailored integrations.

### 4.1.7 Use Cases

In Section 6, a Virtual Prototype use case is reported. Fraunhofer IEM has created an Augmented Reality application with a haptics exoskeleton in a joint research project with Hella Headlights. With a combination of a paper mock-up of an assembly cell, an AR
headset, and the haptics device, Hella was able to optimize their design for manufacturing processes in the early product development stage.

4.2 Training

4.2.1 Overview

VR training (VRT) defines a solution using virtual or mixed reality to transfer useful skills towards the trainee with the use of an extended reality solution.

4.2.2 Investment Range

Consumer ($) to Enterprise simulative training ($$$$

4.2.3 Non-Haptic Considerations

- **Application maturity.** A successful virtual training application requires the company to be familiar with virtual reality technology and to have successfully delivered proof of concepts validating the ROI.
- **Developer/integrator capabilities.** The developer and integrator capabilities are important factors to consider while engaging with VR training content creation. VR training applications are well served with great user experiences, refined accessibility and usability features.

4.2.4 Customer Goals

- Reduce operational costs of delivering practical training, including the real equipment usage for training purposes, maintenance costs for training centers, and travel costs for trainees.
- Ensure repeatability thanks to the digital format of the learning support.
- Ensure learning consistency thanks to the digital support.
- Increase user retention through increased immersion and gamification techniques.

4.2.5 Role of Haptics

- **Skills transfer.** Well-designed applications that incorporate haptic feedback in VR training can generate positive learning reinforcement, enhancing the effectiveness of training. This results in a lower rate of error during the training process.
- **Realism.** A similar behavior between the virtual and real environment facilitates skill transfer between the virtual and real case. The absence of natural interaction and realistic haptics can generate bad practices or negative learning that must be unlearned in real life skill implementation.
- **Immersion.** Haptics can enhance a user’s sense of immersion while experiencing the training content. User immersion increases the embodiment and believability of the training scenario, increasing its effectiveness.
- **User experience.** Hand tracking and natural interactions coupled with well-designed haptic feedback can meet or exceed user expectations of interactive content. Interactions can be more precise and realistic, thus reinforcing the sense of presence. This reinforces the "learn by doing" value of VR training. The hand tracked interaction is transparent and natural, whereas the controller interaction is mediated by a metaphor delivered by the system.

- **Ergonomics/usability.** VR training is accessible to everyone through the use of hands. The use of haptics reduces the friction of adoption of VR training content.

### 4.2.6 Haptic Considerations for Success

- **Wearability.** Virtual reality training needs to meet operational targets to justify its ROI. The haptics device used for these applications should be easy to wear, comfortable, and should not impede users' natural movements.

- **Embodiment.** The ideal haptic device should be "transparent" while the user is not interacting with virtual content, and perfectly reproduce reality while interacting with virtual content. System developers should optimize transparency given their budget constraints.

- **Scalability (hours of use, number of deployments, etc.).** One of the key aspects to consider when thinking about haptics in VR is where the scalability comes from. Do you need repeatability of the same content on different premises, to target hundreds if not thousands of users? Or are you looking to create a one-of-a-kind setup for critical operation training for specific applications? Each scenario has different needs and requirements that can be addressed by different haptic systems.

- **Skills training: hard or soft?** Are you planning to teach how to use a simple HMI system, to ease the use of a soft skill training scenario, or to train how to precisely mount an aircraft? These use cases require different levels of haptics starting with optical hand tracking and moving towards a high-fidelity haptic device for the hand.

- **Integration of non-haptic peripherals.** Increase the fidelity of the training by passive haptics with real objects "dummy objects" with haptic feedback from the device.

- **Content enablement.** The implementation of haptics in existing content requires the specification of the haptics experience to be created. This can be delivered through the purchase of existing haptics assets to be combined into the scenario, the use of haptics design software to create the necessary content, or with the support of a service provider delivering specialized haptics development.

### 4.2.7 Use Cases

In Section 6, several virtual training use cases are reported. Ranging from electrical maintenance training operations to automotive assembly training, automotive painting training, satellite assembly training, as well as realistic first aid training. The role of haptics
is focused on accessibility and skill transfer. The outcome is usually positive, and these use cases are in use to this day.

### 4.3 Marketing and Sales

#### 4.3.1 Overview

Virtual reality technologies have the capability to showcase products and experiences that are extremely costly, if not impossible, to build. Applications range from trade show experiences to in-store experiences for retail, experiential marketing, and so on, all with the goal of raising awareness about specific topics.

#### 4.3.2 Investment Range

($) Consumer to ($$$) high quality production

#### 4.3.3 Non-Haptic Considerations

- **Application maturity.** A successful VR marketing application requires the marketer to be familiar with virtual reality technology and to have successfully delivered proof of concepts validating the ROI.
- **Developer/integrator capabilities.** The developer and integrator capabilities are important factors to consider while engaging with VR marketing content creation. VR marketing applications are well served with great visual content and refined experiences.
- **Asset compatibility.** 3D source material should respect the compatibility necessities for real-time haptic interactions. This is especially relevant when re-using pre-existing assets.

#### 4.3.4 Customer Goals

- **Engage the user.** Well-designed VR marketing experiences generate a deep sense of presence, increasing user retention and engagement.
- **Increase customer conversion rate.** User immersion within virtual reality marketing applications can increase customer conversion. With VR applications, marketers can enhance user immersion and content interactivity. Marketing applications result in a greater lifelike experience and testing capabilities for customers. This is especially relevant for applications in real estate, or complex products like vehicles, tool machinery, or boats.
- **Speed up the sales process.** The sales of complex or spatially large products can be helped by VR applications. The greater benefits happen when a product requires user testing or live presence to evaluate human factors.
- **Reduce marketing costs.** Virtual reality marketing applications can be realized once, and deployed on multiple sites, easily transported, shipped and deployed in
front of the customers. An entire catalogue of complex products can fit in a portable headset.

4.3.5 Role of Haptics

- **Realism/Differentiation of active haptic elements.** Haptics can differentiate and bring closer to reality product aspects and characteristics important for the marketer. Demonstrating how an HMI system of a virtual product responds to the touch, or how a lever activating a certain command can be delivered with the right haptic technology. The user will gain a visceral understanding of how the physical product would behave.

- **Immersion.** Well-designed haptics enhances the user immersion during the marketing activities. The user will feel more present and in control of the situation, resulting in a greater retention and engagement during the experience. In the end, greater customer engagement means greater chance of conversion.

- **Accessibility.** Haptics guarantees that the virtual reality marketing content is accessible like the real product. Users simply use their hands, feel the feedback of the virtual environment, and act much like in reality.

4.3.6 Haptic Considerations for Success

- **Wearability.** Virtual reality marketing needs to meet operational targets to justify its ROI. The haptics device used for these applications should be easy to wear, comfortable, and should not impede users’ natural movements.

- **Embodiment.** What is the continuum between passive haptic realism and simulated active haptic from a cost and fidelity perspective? Marketers have to consider the purpose of the content and the reasons for targeting specific users. They have to balance passive haptic effects, generating a believable albeit incomplete sensorial experience, with the stronger embodiment and deeper experience delivered by simulated active haptics. There are existing haptics solutions balancing passive haptics capabilities vs. fully simulated haptics. The material, integration, and experience design budget usually grow with higher experience fidelity. Marketers should define the success criteria for the experience and derive the best haptics solution.

- **Scalability.** Marketers need to identify what determines the scalability of their content. Will the solution be used by VIPs in high-end retail stores, or realized in hundreds of units and shipped to customers? In both cases, the right haptics can fit with the required scalability.

- **User experience.** Great haptics elicit a “wow effect” among users because most people still remain unaware of the potential for haptic technology to create virtual touch sensations. This is a powerful tool for marketers to use, to substantiate sensorial marketing applications and make the experience memorable.
• **Content enablement.** The implementation of haptics in existing content requires the specification of the haptics experience to be created. This can be delivered through the purchase of existing haptics assets to be combined in the experience, the use of haptics design software to create the necessary content, or with the support of a service provider delivering specialized haptics development.

### 4.3.7 Use Cases

In Section 6.6, a representative use case for marketing of nerve damage therapies is presented. This use case achieved the customer's goal of increasing engagement and enabling marketing of a very novel experience. The haptic component of this use case needed to be usable in a tradeshow environment, be scalable and create a "wow effect" for the target customers.

### 4.4 Tele-existence/Telerobotics

#### 4.4.1 Overview

Tele-existence is the ability to reproduce human capabilities in a physical avatar separate from the human body. Tele-existence is advantageous in dangerous situations/environments, sterile environments, and geographically distant locations. The advantages of tele-existence are the ability for real-time expertise, interactions, and oversight. This can vary from CBRNE (Chemical, Biological, Radiological, Nuclear, and high yield Explosives) to maintenance and medical use cases. Tele-existence systems may consist of at least two of three technological components:

1. The ability to reproduce visual and audio information; this is usually referred to as telepresence or tele-existence.
2. The ability to create mobility, referred to as locomotion.
3. The ability to convey tactile transfer and physical interaction between the robot and the human. The human controls the robot’s actions and the robot accordingly responds to the human’s actions and conveys tactile sensation to the human.

#### 4.4.2 Investment Range

Consumer ($) to clinical facility ($$$$)

#### 4.4.3 Customer Goals

- **Reduce risks.** When dealing with dangerous scenarios like CBRNE or dangerous maintenance tasks, exposing a robot to such danger is ethically more responsible than exposing a human to such danger.

- **Skill teleportation.** Using a robot as a personal avatar, a human may impart their expertise through the robot to a remote location, or a location that is difficult to access through the human form without mechanical assistance.
- **Increase efficiency.** Telerobotics allows for humans to avoid dangerous, distant, and dirty environments and allows the human expertise to be transmitted through the telerobot, potentially eliminating the need for travel while still providing a sense of first-person interaction and expertise through the robot.

### 4.4.4 Role of Haptics

- **Increased realism.** Haptic feedback from the telerobot to the human provides a greater sense of realism embodied in the robot, a greater sense of dexterity and proprioceptive presence to the human through the robot, and the familiarity of natural movement and task conduct through haptic feedback which acts as confirming sensations for task conduct and completion.

- **Increased performance.** Using telepresence, one person can be present in many geographically dispersed environments through the deployed robotic avatar. This person's expertise and know-how is conveyed through the telerobot, enabling the robot to complete the task with the expert's ability.

- **Provide safety and control.** Sparing first-person exposure to dangerous situations or environments, haptic feedback through robotic sensors provides real-time feedback and natural human interface for task completion with high levels of confidence and familiarity with conduct of the telerobotic avatar.

### 4.4.5 Haptic Considerations for Success

- **Realism.** Tele-existence is well served by realistic haptics sensation to optimize the remote control of the robot. Haptics realism should be actively pursued, and it is a critical item for success.

- **Safety.** Remote controlling robots implies potential safety risks for the users. The haptics implementation should put the user-safety first and avoid any haptic feedback above the user tolerance.

- **Integration.** The integration in external robotic system is challenging and requires a specialized approach.

### 4.5 Assistive

#### 4.5.1 Overview

Assistive use cases relate to health and wellness, rehabilitation, and other therapeutic or clinical uses to improve patient outcomes. This area is relatively nascent in its use of haptics but does provide some novel considerations related to the use and value of haptic feedback. Virtual reality technologies are used in rehabilitation processes for impaired patients. Virtual reality is used to target specific movements, or to subject the patient to specific stimuli to accelerate recovery.
4.5.2 Investment Range

Consumer ($) to clinical facility ($$$$)

4.5.3 Customer Goals

The goals of these use cases are typically to influence or generate a measurable improvement in patient responses to standard measures. Measures can include physiological improvements such as reduced heart rate, anxiety, etc., task-related improvements such as task completion times, error rates, etc., or other miscellaneous measures such as therapy duration.

- **Reducing costs.** Well-designed VR experience can enable unsupervised training. The virtual training task should be clear and self-explanatory. In that way, multiple patients can train in groups or at home with just the guidance of one physical therapist.
- **Increased engagement.** VR can help increase the engagement of patients in their therapy. It can be adaptive to the challenge of the patient, providing a challenging but achievable goal. Also, the knowledge of being monitored increases therapy compliance.
- **Improved insights.** VR therapy can increase the level of insight on progress and performances within the physical rehabilitation process.

4.5.4 Role of Haptics

The role of haptics varies materially by use case, but here are some examples:

- **Force/resistance for muscular training/rehabilitation use cases.** Broadly speaking, increasing the resistance in a training bicycle is a type of haptics; moreover, this can be associated with a virtual reality experience.
- **Error feedback for body pose, task progression or other training or rehabilitation-specific measures.** One example is posture-correcting yoga pants (e.g., `wearable.x`) in conjunction with a VR yoga class. Note that the haptic feedback can be automatic or triggered by a coach or trainer in this scenario.
- **Increased immersion.** Similar to other broad use cases, haptics is known to increase the immersive quality of a virtual reality experience. This can be valuable for training or entertainment driven assistive use cases. For example, providing content-synchronized feedback for non-ambulatory users (e.g., in a hospital bed) can increase the quality and duration of engagement.

4.5.5 Haptic Considerations for Success

Assistive haptic feedback needs to consider these key points:

- **Safety.** Devices which generate forces on users need to be engineered so that they cannot cause injury due to inadvertent use. For rehabilitation use cases, this consideration is particularly important as users may have non-normal ranges of
motion, sensitivity, etc. If possible, users and practitioners should be empowered to reduce/eliminate the haptic feedback in real-time to allow for individual variation.

- **Consistency.** In order to use haptics to generate precise, measurable outcomes, the haptic feedback must have a maximum amount of consistency both from use-to-use and from installation-to-installation. For body-mounted feedback, careful consideration should be paid to fit consistency, including having multiple sizes or specific criteria for appropriate body size considerations.

- **Perceptibility.** In addition to consistency, haptic feedback needs to both be noticeable and provide the appropriate dynamic range of sensation. This is particularly relevant to error-driven haptic feedback. If the specific use case involves vigorous physical activity, haptic sensations typically need to be stronger but may also need to be carefully designed to disambiguate them from other scenario-related stimuli. Overly complex haptic signaling can increase cognitive load and confusion.

- **Expressivity.** Haptic devices need to be able to provide sufficient perceptible range of experience so that users can correctly interpret the stimuli. Basic body-mounted error feedback may only need 1-bit of expressivity (on/off), whereas an error measure that indicates the quantity of the error may require many more bits.

- **Wearability.** Virtual reality rehabilitation needs to match therapy or reimbursement budgets. The haptics device used for these applications should be easy to wear, comfortable, and should not impede users’ natural movements.

- **Embodiment.** The ideal haptic device should be transparent while not interacting, and perfectly reproduce reality while interacting with VR. The ease of use in putting on and removing is key for rehabilitation. System developers should optimize transparency given their budget constraints.

- **Scalability (hours of use, number of deployments, etc.).** One of the key aspects to consider when thinking about haptics in VR is where the scalability comes from. Do you need repeatability of the same content on different premises (for instance clinical therapy)? Or would you like to target hundreds if not thousands of users (home-based rehabilitation)? Both scenarios have different needs and requirements that can be addressed by different haptics devices.

- **Reliability.** A haptic system should be reliable. It should always work especially in home-based environments where no specialist is available to debug a potential problem.

### 4.5.6 Non-Haptic Considerations

- **Security.** Assistive virtual reality use cases deal with patient data which is a regulated area and requires specific management.

- **Cognition.** Virtual reality is a technology which might not fit the cognitive state of some patients.
5 Integration Workflow

The workflow that product managers should follow while considering haptics within their VR application are covered in this section.

One of the most important aspects to keep in mind is: what is the objective of the implementation of haptics within the experience? This objective should drive the implementation of all the scenarios. This section is divided in two macro workflows: the implementation of a custom scenario including haptics in the design phase, and the upgrade of an existing scenario with haptics.

5.1 Custom Scenario

This section concerns the creation of a haptics use case from scratch. In this case, haptics is included in the design phase, and the scenario can maximize the value of this technology for the specific use case.
**Use case and haptics objectives.** In this phase, the objectives of the use case are clearly defined. One of the key aspects is to define objectives of the haptic design following the structure shared within the use case description. For example, developing haptics to enhance realism might prevent us from leveraging the same technology to improve user experience. It is similar to VR graphic content: the maximum scenario realism might prevent portability on standalone headsets. The best advice is to focus on a subset of objectives and measure the success of the implementation on these metrics.

Key decision to perform or documents to deliver:
- Use case objectives
- Haptic design objectives

**Scenario definition.** Document clarifying the scenario expectations for the final user starting from the use case objectives. In this phase, the haptics objectives are translated in the scenario as haptics descriptions of specific interactions, or events.

Key decision to perform or documents to deliver:
- Use case scenario

**General requirements.** In this stage, the scenario is translated in budget and technical requirements to meet the use case expectations.

Key decision or documents to deliver:
- Budget definition
- High-level technical requirements

**Development environment and hardware device choice.** Choice of the development environment and hardware device. The implementation of haptics within VR content is maturing rapidly, but it is important to dedicate a careful evaluation of hardware capabilities and development environment to ensure the success of the use case. Virtual reality hardware and development environments are mostly interchangeable, but in haptics this is not yet the case, even if efforts in that direction are being pursued.

Key decision to be delivered:
- Development environment/3D engines choice (Unity, Unreal, others)
- Haptic design/development framework choice
- VR hardware choice
- Haptics hardware choices

**Software architecture.** Technical document with the software architecture of the final solution.

Key decisions or document to be delivered:
- Build or buy
- Architecture document
**3D Design and haptics iterative process.** The implementation of the interactive case happens at this stage. 3D models, colliders, interactions, and haptics go through an iterative process to optimize the final result based on the use case and haptics objectives.

**Multimodal integration.** Here, visual and sound design happens. Both build in parallel to the interactive scenario to deliver the final experience.

**QA.** Review and testing of the experience.

**User/Customer evaluation.** Presentation of the final result to the customer.

### 5.2 Existing Product

This section concerns the upgrade of an existing VR product to a haptics experience.
**Haptic objectives.** In this initial phase, the objective of the upgrade toward a haptic experience should be clarified and stated, based on the framework of the use cases reported in the document.

Key decision or documents to deliver:
- Haptic objectives

**General requirements.** In this stage, the scenario is translated in budget and technical requirements to meet the use case expectations.

Key decisions or documents to deliver:
- Budget definition
- High level technical requirements

**Hardware device choice.** The implementation of haptics within VR content is maturing rapidly, but it is important to dedicate a careful evaluation of hardware capabilities and development environment, to ensure the success of the use case. Virtual reality hardware and development environments are pretty much interchangeable; in haptics, this is not yet the case, even if efforts in that direction are being pursued.

Key decision to be delivered:
- VR hardware choice
- Haptic hardware choices

**Architecture and input.** The architecture/development analysis is a necessary study to validate that the chosen haptics device fits within the product framework. The input system evaluation and adaptation are needed to upgrade logical input mediated by controller buttons, with hand and finger tracking input mediated by software metaphors or physics engines. Note that haptic devices relying only on output (e.g., the Woojer vest), do not require the input analysis because they do not replace the input system of the product.

Key decision to be delivered:
- Build or buy
- Haptic interaction development framework

**3D Design and haptics iterative process.** The implementation of the interactive case happens at this stage. 3D models, colliders, interactions, and haptics go through an iterative process to optimize the final result, based on the use case and haptics objectives.

**QA.** Review and testing of the experience.

**User/Customer evaluation.** Presentation of the final result to the customer.
6 Technologies

In [1], a basic taxonomy of commercially available haptic devices is presented. It is adapted here for reference.

Haptic feedback covers a wide range of possible stimulation embodiments but is broadly divided into tactile and kinesthetic. Tactile feedback refers to sensations that stimulate subcutaneous mechanoreceptors such as vibration, friction, or micro-deformation. Kinesthetic feedback refers to sensations that provide force sensations which can stimulate both subcutaneous mechanoreceptors as well as proprioceptive mechanoreceptors.

6.1 Vibrotactile

Vibrotactile technology is probably the most widespread technology used in haptics devices for VR. Typical solutions include the rumble-like feeling of ERM (Eccentric Rotating Mass actuators) towards more expressive LRAs (Linear Resonant Actuators), and wide band actuators like VCM (Voice Coil Motors), or PZT (Piezoelectric Transducer actuators). Devices equipped with these actuators are able to consistently deliver vibration patterns, which are useful to enhance user experience during virtual reality scenarios. Vibration effects can be thought of as a kind of audio for the skin. In an enterprise VR application, vibration actuators are typically used for surface texture and to substitute for more expensive and complex force-feedback systems.
These technologies are usually coupled with finger and hand tracking technologies for VR glove implementation.

Example of vibrotactile based devices are:

- Manus VR
- Bebop Sensors
- Tactus

### 6.2 Resistive Force Feedback

Resistive force feedback is used in haptics exoskeletons and gloves to impede the movement of the fingers in virtual reality. Resistive devices act as a kind of brake for finger or body motion. They are usually used to simulate manipulation gestures, and they are effective at enhancing the realism of the hand interactions. Resistive force feedback devices are typically based on electromechanical brakes which increase the friction of a sliding cable. The modulation of the friction allows modification of the resistive force experienced by the users. They are usually coupled with finger and hand tracking technologies.

Example of resistive force feedback devices are:

- SenseGlove
- Haptx

### 6.3 Active Force Feedback

Active force feedback is used in haptics exoskeleton and handheld haptics devices to apply an active force on the user's articulations or fingers. This type of feedback is normally based on electromechanical motors actively applying a force to the user's body part. This force simulates an interaction with a virtual object; or simulates a realistic interaction with a specialized haptics device like a haptics-enabled rifle or flight stick.

They are effective to simulate manipulation tasks and interaction with non-static virtual objects (ex: holding a beating heart), and to simulate realistic behavior of simulated interfaces.

They tend to be more fragile compared to resistive or vibrotactile devices due to a more complex mechanical implementation. They are also normally the most expensive option and the most complex to integrate into a virtual reality simulation.

Examples of active force feedback devices are:

- Dexmo
- Haption
6.4 Skin Indentation

Skin indentation devices are used to selectively compress the user’s skin to create the sensation of interacting with objects. Skin indentation devices can be used to render vibrations pattern, textures, or light forces perception, giving them a large spectrum of expressivity.

Examples of skin indentation devices are:

- Haptx
- Go Touch VR
- Weart

6.5 Ultrasound

Ultrasound devices are used to generate haptics sensations by focusing acoustic pressure at given location within a large volume above the ultrasound transducers' surface. At this location, acoustic radiation force is produced, which slightly indents the human skin, generating a perceivable tactile effect that can be modulated to produce various tactile experiences. Ultrasound devices are known to generate light sensations which can be perceived simultaneously on different part of the human body. These devices are not required to be worn, while still being able to generate haptic effects in a large spatial volume above their ultrasound transducers' surface.

Examples of ultrasound devices are:

- Ultraleap
7 Representative Case Studies

7.1 Electrical Maintenance Training

7.1.1 Overview

A well-known electrical equipment provider commercializes low and medium voltage electrical equipment needing maintenance on regular basis. The customer's workforce needs to perform scheduled training to learn and refresh the procedures to perform the maintenance operations. This training is performed at training centers around the globe. The sessions are extremely expensive, involving the travel of the workforce to the training center, a few days stay to perform training activities on dummy machines under the supervision of the trainer. The electrical equipment manufacturer developed a haptics training solution to digitize the maintenance and security training for the workforce to bring the training sessions to the customer. The solution also commercializes a VR training system, including haptics and VR equipment, to allow their customer to keep the training scenarios and experience as documentation.

Electrical equipment maintenance and training system allows trainers to train on novel scenarios.

7.1.2 Customer Goals

Risk reduction, skill transfer, reduced costs, increased margins.

7.1.3 Project Budget

>$100,000 USD
7.1.4 Haptic Technologies Used

The system was developed in Unity and incorporated 4 VR Touch (Go Touch VR) gloves. These gloves provide skin indentation feedback to enable tactile sensations primarily related to grasping and manipulation.

7.1.5 Role of Haptics

Haptics was added to the simulation in order to increase usability and skill transfer. It was initially challenging to communicate this value to the customer. Once the customer understood that haptics does not reproduce reality with perfect fidelity, it became easier to have a pragmatic discussion about the correct use of haptic feedback in the simulation.

7.1.6 Outcome

The project continues to be used, after two years, by the customer. The enhanced usability created with haptic feedback is a key reason for the lasting success of this use case.
7.2 Automotive Painting Training

7.2.1 Overview

VR-based training application for automotive painting. A range of vibrations were introduced to guide the user through the painting processes, errors, and the set of guidelines. If the applied pressure is high, user gets a particular feedback. If the applied pressure is low, user gets the appropriate feedback. An entire set of feedbacks is utilized for different sections of the training guidelines.

The custom haptics interface allows a realistic experience while training for automotive painting task.

7.2.2 Customer Goals

Risk reduction, skill transfer, product/experience insights.

7.2.3 Project Budget

$10,000–$100,000

7.2.4 Haptic Technologies Used

The type of haptic feedback used for the project was based on vibrotactile perception. The actuators were VCMs supplied by Actronika, called Hapcoil One. with a resonant frequency of 65 Hz. These actuators have a resonant frequency of 65 Hz and are 11.5 x 12 x 37.7 cubic mm in size. They have the potential to operate with promising results in the range of 10 Hz to 1 kHz. The acceleration ranges between 8 g-pp to 11.4 g-pp depending on the type of signal sent. The actuators were driven by embedded solutions which is essentially a software-based control (Unitouch Embedded). The vibrations used were part of our library of UI effects.
7.2.5 Role of Haptics

Immersion, usability, user experience.

7.2.6 Outcome

The product is in use by the customer who is ordering parts every quarter, and who is listed as one of the most satisfied customers.
7.3 Satellite Assembly Training

7.3.1 Overview

SenseGlove Nova has been implemented in the military VR training for assembling a satellite receiver in order to avoid damaging expensive training equipment. Using haptic gloves in a virtual environment, the trainees are able to install the virtual parts of the satellite receiver in a similar way as they would install the real equipment.

7.3.2 Customer Goals

Skill transfer, reduced development costs.

7.3.3 Project Budget

$10,000–$100,000

7.3.4 Haptic Technologies Used

The SenseGlove Nova force and haptic feedback gloves. A multiplayer game based on the Unity engine and in integration solution of VREE, a Dutch VR development agency.

7.3.5 Role of Haptics

Realism, immersion, user experience.

7.3.6 Outcome

The study is not finished yet after 4 months of activity, but the first results are positive. There need to be some tweaks, but it has a high chance of becoming the standard way of interaction for this training of the Dutch defense.
7.4 Discover History with Haptics

7.4.1 Overview
Transforming education and history research with haptics. The goal of the research is to explore how haptic technologies combined with VR can better engage viewers in the museum and heritage sectors.

7.4.2 Customer Goals
Product/experience insights.

7.4.3 Project Budget
$1000–$10,000

7.4.4 Haptic Technologies Used
SenseGlove DK1 and virtual reality headset.

7.4.5 Role of Haptics
Realism, immersion, user experience.
7.4.6 Outcome

"The haptics spark the potential to revive how we interact, communicate, and preserve ceramic artifacts long term. This innovative way of interaction reinvents the way we communicate history, aids interpretation, and increases visitor engagement," according to Emma Fallows, a researcher at Staffordshire University. Early tests have shown that VR with haptics may become a popular option for the preservation of ancient artifacts via a digitized archive. The project is a four-year PhD study and continues to be active as of Spring 2021.
7.5 Electrical Assembly Training

7.5.1 Overview

Volkswagen and SenseGlove have created a virtual reality assembly training of the electric components within the sliding door of the T6 van. In this scenario, participants are able to train the full procedure of all actions in this particular assembly process.

7.5.2 Customer Goals

Skill transfer, reduced development costs.

7.5.3 Project Budget

$10,000–$100,000

7.5.4 Haptic Technologies Used

SenseGlove DK1. A CAD to Unity pipeline. And the Unity game engine to create the content.

7.5.5 Role of Haptics

Skills transfer, realism, immersion, usability.

7.5.6 Outcome

The project satisfied the objective as a research project. For the desired implementation, a new follow-up project is needed with improved usability. This specific project lasted for 4 months and is finished. A follow-up project is scheduled for 2021.
7.6 Nerve damage experience

7.6.1 Overview
SenseGlove has created a VR environment where the symptoms of nerve damage can be experienced. This simulation was used in a worldwide campaign for Procter & Gamble Health to raise awareness about nerve damage and to build empathy for those who suffer from it.

7.6.2 Customer Goals
Product experience insights.

7.6.3 Project Budget
$10,000–$100,000

7.6.4 Haptic Technologies Used
SenseGlove DK1, Unity plugin by SenseGlove.

7.6.5 Role of Haptics
Immersion, user experience, empathy creation.

7.6.6 Outcome
For P&G Health, it is hard to communicate a marketing message of a disease that is commonly overlooked by people and general practitioners. Therefore, they wanted to create a campaign to increase the awareness of nerve damage. The SenseGlove was the ideal tool for P&G Health. At conferences, they can let physicians experience the symptoms of nerve damage themselves so that physicians can learn to diagnose these symptoms earlier. This innovative way of marketing also creates significantly more traffic to their
stand at conferences and roadshows. The project lasted for a year. It kicked off with a movie in 2019, and the showcased travelled around the world in countries like Brazil, the Philippines, Malaysia, Switzerland, and Portugal. Via the spreading of the video, P&G Health is able to increase the awareness in the public on the symptoms of nerve damage and build their brand in an effective and innovative way.
7.7 Augmented Reality Haptics Showcase

7.7.1 Overview

In collaboration with Meta, Ultraleap worked on a vision for the future of design. With the participation of Dell and Nike, they first presented this vision through a short clip, showing a rethink of the designer workspace. Specifically, using today’s hand tracking and mid-air haptic technology, they can blur the digital and physical worlds and deliver meaningful applications and tools to the workspace.

In this second stage of this collaboration, Ultraleap was joined by ZeroLight and developed the first proof of concept using automotive as the use case. In this demonstrator, Ultraleap replaced all conventional elements of a workspace (screen, keyboard, computer mouse) with an AR headset, a mid-air haptic display, and a hand-tracking sensor, so that users could interact and manipulate visual holograms, while receiving haptic feedback through the various interactions. A total of 6 scenes composed the demonstrator. In the first scene, users were activating the interface by pressing and holding down a mid-air haptic button in the center of the interaction space. In the second scene, users were invited to pick the color of a car from a rotary dial that they could spin. The resulting car visual was presented as a floating hologram in the center of the interaction space. In the third scene, a closeup view of the car engine was show to the user. Upon touching the motor, users could hear and feel (with haptics) the engine roar. In the fourth scene, the car was presented as a floating hologram at the center of the interaction space. When users reached and touched the car’s roof, the car visuals will change into an exploded view, showing all the components it was made from. This exploded view represented the fifth scene of the demonstrator. If users withdrew their hand, the interaction would revert to the fourth scene, but if users kept pushing their hand down, the elements from the exploded view will be sent around the users at a bigger scale, which represented the sixth and final scene. In this last scene, users could pan the different elements around them using their hands.
7.7.2 Customer Goals

Product experience insights.

7.7.3 Project Budget

$10,000–$100,000

7.7.4 Haptic Technologies Used

For this project, Ultraleap used ultrasound mid-air haptic technology. This technology uses an array of ultrasound speakers to focus inaudible acoustic waves at a given point in space and time. At this specific point, pressure is sufficient to slightly push the skin and induce tactile sensations. Controlling this point pressure amplitude and position over time, the display can convey a range of different haptic effects. Combined with hand-tracking technology, the haptic effect can be projected directly onto the user's palm. In this case, Ultraleap used a leap motion controller as the hand-tracking solution, which is also commercialized by Ultraleap. The APIs of both devices are compatible with a wide range of tool and languages. For this project, Ultraleap used Unity as the 3D engine. For the AR mounted display, the Meta 2 headset was used, produced by the company Meta, which no longer operates.

7.7.5 Role of Haptics

Skills transfer, realism, immersion, usability.

7.7.6 Outcome

The primary objective for the project was a working demonstrator, which was completed to the satisfaction of the customer. The project lasted six months. Product integration was not pursued.
7.8 Medical Care Training

7.8.1 Overview

In 2020, the United States Defense Health Agency awarded a contract to HaptX and others to develop a haptic training system to improve the skills of U.S. Army soldiers who administer emergency trauma care on the battlefield. The contract funded HaptX and its partners Engineering & Computer Simulations and Mayo Clinic to integrate the true-contact haptics of HaptX Gloves with the Army’s Tactical Casualty Combat Care (TC3) environment. For many years, TC3 used VR to teach soldiers to perform airway management, access vascular systems, apply tourniquets, and more. But without realistic touch feedback, trainees were only able to learn abstract procedural steps and were unable to naturally practice key skills and physical interactions. This contract funded research and development to improve the quality and retention of training with the goal of saving more lives on the battlefield.

Soldier uses HaptX Gloves with U.S. Army’s Tactical Combat Casualty Care Simulation.

7.8.2 Customer Goals

Skills transfer, increased training effectiveness

7.8.3 Project Budget

>$100,000 USD
7.8.4 Haptic Technologies Used

The project incorporated multiple HaptX Gloves DK2 systems. These gloves maximize realism by combining high-fidelity tactile feedback which displaces skin up to 2 mm, variable force feedback delivering up to 40 lbs of resistive force per hand, and electromagnetic finger tracking.

7.8.5 Role of Haptics

The developers of this project applied haptic effects to the virtual interactions to enable trainees to physically feel and practice the training program's dexterous manual motions. These interactions included grasping and using supplies, feeling correct locations on the patient's body, turning the patient's body, and more. Haptics enabled the developers to achieve the project's core mission of advancing training through improved manual interfacing with the environment.

7.8.6 Outcome

The Army is midway through the project and will report its findings upon completion. Initial feedback has been positive.
8 Company Resources

This section provides a set of resources for haptic system components and system integration.

<table>
<thead>
<tr>
<th>Company name</th>
<th>Type</th>
<th>Solution / Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Immersion Corporation*</td>
<td>Technology and license provider</td>
<td>Haptic technology solutions, product development kits, haptics innovation program</td>
</tr>
<tr>
<td>TDK*</td>
<td>Component supplier</td>
<td>PowerHap &amp; PiezoHapt piezo actuators, evaluation kits, design guides</td>
</tr>
<tr>
<td>Interhaptics*</td>
<td>Haptics software provider</td>
<td>Haptics design suite to customize the haptics experience. Haptics rendering software to synthetize haptics signals for any device.</td>
</tr>
<tr>
<td>SenseGlove*</td>
<td>Haptics hardware supplier</td>
<td>Force-feedback gloves and exoskeletons for XR and tele-robotics purposes.</td>
</tr>
<tr>
<td>HaptX*</td>
<td>Whole-Hand exoskeleton system vendor</td>
<td>HapX Gloves DK2</td>
</tr>
<tr>
<td>Ultraleap*</td>
<td>Technology provider</td>
<td>Mid-air haptics solutions, product development kits, haptic partner program</td>
</tr>
<tr>
<td>Actronika*</td>
<td>Technology provider</td>
<td>Vibrotactile haptics solutions, product development kits, Skinetic XR suit, HapCoil VCA actuators</td>
</tr>
<tr>
<td>Manus VR</td>
<td>Haptics gloves vendor</td>
<td>Manus VR prime 2</td>
</tr>
<tr>
<td>Sensoryx*</td>
<td>Tracking gloves vendor</td>
<td>VRfree</td>
</tr>
<tr>
<td>Bebop Sensors</td>
<td>Haptics gloves vendor</td>
<td>Forte Data Glove</td>
</tr>
<tr>
<td>Haption</td>
<td>Haptics exoskeletons vendors</td>
<td>Hglove, Virtuose series, Scale, inca, Able</td>
</tr>
<tr>
<td>Dexmo</td>
<td>Haptics gloves vendors</td>
<td>Dexmo Haptic Glove</td>
</tr>
<tr>
<td>Teslasuit</td>
<td>Haptics wearable vendor</td>
<td>Teslasuit and Teslasuit Gloves</td>
</tr>
</tbody>
</table>

* Member of Haptics Industry Forum
9 References