care, judgment, dexterity

CRAEFT

Haptic devices for training, simulation, and design

Project Acronym	Craeft
Project Title	Craft Understanding, Education, Training, and Preservation for Posterity and Prosperity
Project Number	101094349
Deliverable Number	D4.2
Deliverable Title	Haptic devices for training, simulation, and design
Work Package	4
Authors	Christian Holz, Rayan Armani

This project has received funding from the European Commission, under the Horizon Europe research and innovation programme, Grant Agreement No 101094349.
http://www.craeft.eu/

Executive summary

In this deliverable, the process of implementing a hand-held controller for supporting experiences in Virtual Reality is described, specifically a haptic apparatus that simulates the tactile sensations of tool use during craft actions, including the tactile examination ("feeling") of surfaces, especially during manipulation. The purpose of this controller and the overall VR system as part of the whole CRAEFT project is to enable practice and increase exercisability for the development of dexterous actuation skills before entering the workshop. They will serve the "education of attention" to tactile features of materials and products.

Document history

Date	Author	Affiliation	Comment
30/08/2024	Christian Holz, Rayan Armani	ETH Zurich	First draft

Table of contents

1. Introduction

CRAEFT seeks to revolutionize craft education and training by integrating cutting-edge digital technologies such as telecommunications, simulators, and immersive interfaces. Within this broad initiative, Task 4.2 is specifically dedicated to developing haptic interfaces that can simulate the tactile sensations experienced in craft activities. These haptic controllers and actuators are essential for translating the physical touch and feel inherent in craftsmanship into digital environments, thereby enabling a comprehensive and immersive learning experience.

1.1. Immersive systems

Virtual Reality (VR) and Augmented Reality (AR) have emerged as powerful tools for capturing and conveying the intricate details of craft practices. These technologies allow for the precise documentation of craft techniques, preserving them in a digital format that can be shared and studied globally. VR/AR environments provide an immersive space where learners can observe complex processes in three dimensions, examine fine details from various angles, and repeat demonstrations as needed. This capability makes these tools invaluable for teaching and studying craft skills, which traditionally require close, hands-on instruction.

Moreover, VR/AR can simulate the workshop environment, enabling learners to engage with craft techniques in a controlled, repeatable manner. This approach not only democratizes access to craft education by overcoming geographical barriers but also allows for the preservation of techniques that might otherwise be lost. Through VR/AR, the essence of craftsmanship—its precision, creativity, and cultural significance—can be documented and conveyed to new generations of practitioners.

1.2. Haptics as the missing component

Despite the significant advancements in visual and auditory immersion provided by VR and AR, a critical aspect of craftsmanship remains underrepresented in these digital environments: the sense of touch. Craftsmanship is inherently a tactile discipline. The feel of materials, the subtle resistance encountered when working with tools, and the delicate manipulation of objects are not mere supplements to the process; they are central to the skill itself. Tactile feedback is what informs a craftsperson's decisions at every step, guiding their hands as they carve, mould, or weave, and contributing directly to the precision and artistry that define high-quality craftsmanship.

This absence of tactile feedback in digital environments represents a substantial limitation. Craft skills are often described as being embodied, meaning they are deeply intertwined with physical actions and sensory experiences. When a craftsperson cannot feel the material or gauge the force applied, their ability to learn, practice, or even preserve these skills in a virtual setting is significantly diminished. Without the ability to replicate these haptic experiences, digital representations of craft processes remain incomplete, reducing the effectiveness of VR/AR systems as tools for training and preservation. The gap between digital simulation and physical reality is most felt in the missing element of touch.

To fully capture the richness and complexity of craft practices in digital environments, the integration of haptic technology is essential. Haptic sensations enable users to experience the physical aspects of craftwork in a manner that closely mirrors real-world interactions. By providing tactile feedback, haptic interfaces bridge the sensory gap, allowing learners to feel the resistance, textures, and forces involved in various craft activities. This is not merely a technological enhancement; it is a crucial step toward ensuring that digital simulations can faithfully recreate the physicality of craft skills.

This tactile feedback is vital for developing fine motor skills and embodied knowledge that is central to expert craftsmanship. For instance, the subtle variations in texture or the resistance felt when shaping a material provide immediate, sensory information that guides the craftsperson's actions. In the absence of these cues, even a highly detailed visual and auditory simulation fails to convey the full reality of the craft. This limitation hinders the learning process, as students are unable to develop the nuanced touch required for mastery. Moreover, for practitioners looking to preserve or pass on their skills, the lack of tactile feedback in digital tools can result in the loss of critical, non-verbal knowledge that cannot be easily documented through text or images alone.

Hand-held controllers equipped with haptic feedback are key to delivering these tactile sensations in VR/AR environments. Such controllers allow users to engage with virtual objects as if they were real, providing a sense of touch that complements the visual and auditory elements of the experience. These devices do more than simply enhance the realism of the simulation; they create an interactive, sensory-rich environment where learners can engage in meaningful practice. Practitioners can explore the feel of different materials, experiment with varying pressures and techniques, and receive immediate feedback—all without the constraints of a physical workshop. This is particularly important in crafts that rely heavily on manual dexterity and the ability to manipulate materials in precise ways.

The portability and versatility of hand-held haptic controllers make them well-suited for a wide range of craft training scenarios, from basic tool manipulation to complex, multi-step processes. In educational settings, these controllers could transform the way craft skills are taught, allowing students to practice intricate techniques at their own pace, in any location. For experienced artisans, such tools offer a way to continue honing their skills, and experimenting with new materials and methods in a risk-free environment. The ability to simulate different types of materials and tools also opens up new possibilities for innovation in craft practices, as artisans can explore new designs and techniques without the limitations imposed by physical resources.

In response to this need, Deliverable 4.2 introduces a novel haptic controller designed to enhance the immersive experience of craft training in VR/AR. This controller goes beyond the traditional functions of VR controllers, incorporating advanced haptic feedback mechanisms that simulate the tactile sensations of grasping, touching, and manipulating objects. By integrating these haptic capabilities, the controller offers a multi-purpose tool that can adapt to various craft scenarios, providing a more realistic and effective training experience. This versatility is particularly important in the context of craft education and preservation, where the ability to simulate a wide range of tactile interactions can make the difference between a superficial understanding and true mastery.

1.3. Haptic touch and grasp feedback in a hand-held controller

The haptic controller developed in this project represents a significant advancement in the integration of haptic technology into VR/AR environments, particularly for craft skill experiences. Unlike traditional haptic devices that focus on a single type of feedback, this controller is designed to be a multi-purpose tool that supports a wide range of haptic interactions within a single device. This enables users to engage in various craft activities with one controller, making it a useful tool for both learners and practitioners.

1.3.1. Multi-Purpose Haptic Feedback

One of the primary contributions of this haptic controller is its ability to deliver multi-purpose haptic feedback. Conventional haptic feedback devices, such as exoskeletons, fingertip devices, and specialized handheld controllers, typically focus on specific interactions—like grasping objects, sensing textures, or experiencing force feedback. This new controller integrates these diverse functionalities into a single device, allowing users to grasp virtual objects, feel their shapes, stiffness, and textures, and experience approximated realistic feedback, all through one controller. This integration not only simplifies the user experience by eliminating the need for multiple devices but also enhances the immersion and realism of the virtual environment, making it more effective for training and practice.

1.3.2. Adaptive Haptic Rendering

A key innovation of this controller is its ability to switch haptic rendering modes based on the user's grip and the context of the virtual scene. This feature enables the controller to dynamically adapt to different tasks within the virtual environment, providing the appropriate haptic feedback for each situation. For example, when a user changes their grip from a light touch to a firm grasp, the controller automatically adjusts the haptic feedback to reflect this change, whether it's simulating the resistance of a material or the operation of a tool. This adaptability is crucial for accurately simulating the wide range of tactile experiences involved in craft activities, where the user's interaction with objects can vary frequently and unpredictably.

In summary, the design and capabilities of the developed haptic controller represent a significant advancement in the integration of haptic feedback into VR/AR environments for craft training. By combining multiple haptic feedback modes into a single, adaptive device and validating its effectiveness and usability through rigorous testing, the controller addresses the need for versatile, realistic haptic interactions in digital craft simulations. This innovation not only enhances the immersive experience but also ensures that the tactile aspects of craftsmanship are preserved and effectively transmitted in the digital age.

2. Controller implementation

The haptic controller developed within this project aims to advance the integration of haptic feedback in virtual environments, specifically tailored to the needs of craft training and skill development. The primary design goal was to create a device that could be seamlessly used within VR/AR settings, delivering human-scale forces and realistic tactile sensations. These include rendering 3D shapes, simulating the feel of holding both rigid and soft objects, and providing authentic squeeze feedback, all within a compact and lightweight form factor. This design ensures that users can interact freely in mid-air, making the controller suitable for various craft applications with unencumbered movement.

Figure. The components of the controller.

2.1. Design Objectives for the Haptic Controller

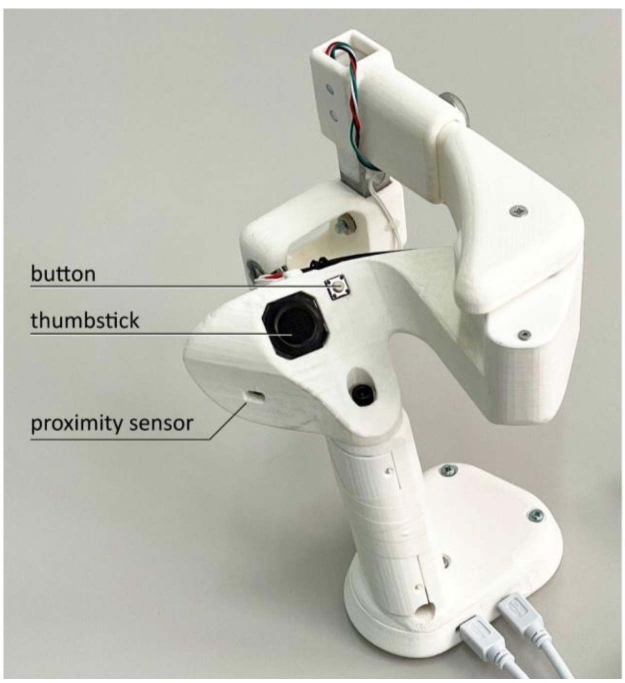
The creation of this haptic controller was guided by a set of design rules, which were formulated to meet both the standard expectations of VR controllers and the specific demands of haptic feedback for craft-related tasks. The challenge was not only to meet these diverse requirements but to integrate them into a single, user-friendly device that could be easily adopted by practitioners and learners alike.

Features Expected of VR Controllers	Features We Would Like to Add

Handheld for ease of use	Ability to render shapes of virtual objects
Input buttons manipulated by thumb and trigger-like element by index finger for grasp	Ability to render forces from touching or grasping virtual objects
6DOF tracked in space	Ability to render textures of virtual surfaces
Untethered operation	Realistic haptic effects for push and squeeze
Ergonomically comfortable	Ability to recognize and respond to natural manipulation gestures

2.2. Detailed Design

Building upon these design principles, the haptic controller was designed to extend and integrate the functions of existing VR controllers while incorporating multiple haptic feedback modes. This controller is handheld, allowing users to comfortably grip it with their middle, ring, and little fingers. The thumb can rest either on the side of the controller or top, depending on the specific interaction. The controller features several buttons and a thumbstick for user input, along with a proximity sensor that detects the position of the thumb, enabling dynamic mode switching based on user actions.



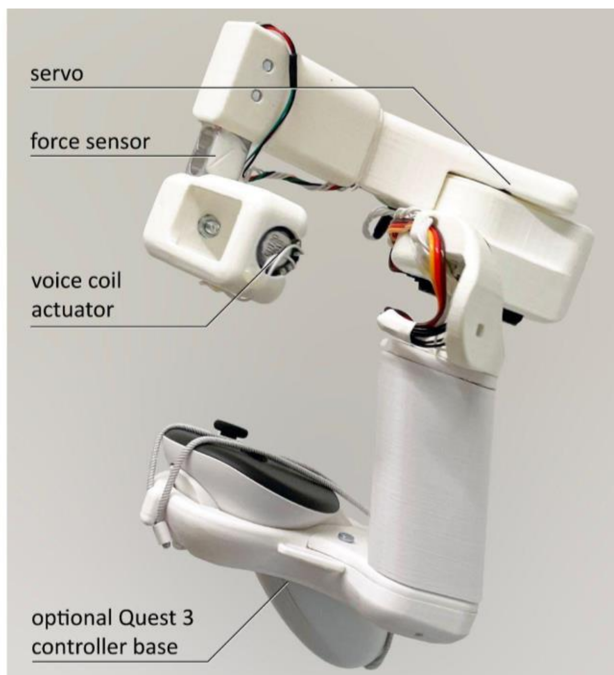


Figure. Controller features.

2.3. Kinesthetic and Tactile Feedback Integration

The controller's core innovation lies in its ability to deliver both kinesthetic and tactile feedback, which are crucial for the realistic simulation of craft tasks. Kinesthetic feedback allows users to perceive forces, actuation, and displacement as they interact with virtual objects, providing a sense of physical presence and resistance that is essential for tasks such as shaping materials or applying pressure with tools. Tactile feedback, on the other hand, enables users to feel the textures of virtual surfaces under their fingertips, adding a layer of realism to the interaction that is critical for tasks like sanding, carving, or painting.

To achieve these capabilities, the controller incorporates a voice coil actuator (VCA) for rendering detailed textures under the fingertip and a force sensor above the index finger mount to detect user input force. The force sensor plays a dual role: it senses the pressure exerted by the user, allowing for nuanced control over virtual interactions, and it provides feedback on the resistance of virtual objects, simulating different material properties such as stiffness, elasticity, and damping.

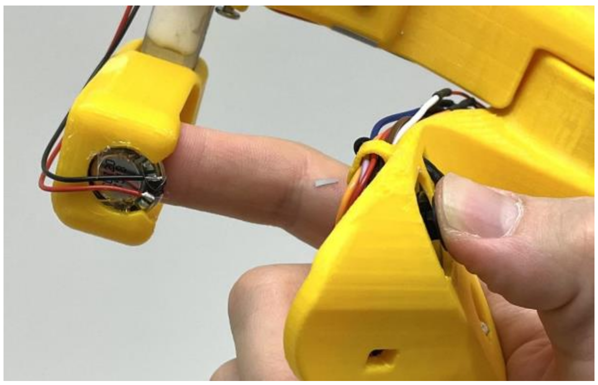


Figure: The voice coil actuator under the index fingers produces texture actuations and sensations during the motion of the finger or the hand in mid-air, thereby allowing users to explore virtual objects and their surface characteristics.

2.4. Mechanical and Electronic Integration

The controller houses key electronic components that are vital for its operation. A Teensy 4 microcontroller serves as the brain of the device, managing the inputs and outputs from the various sensors and actuators. An HX711 ADC board is responsible for force sensing, while a DRV8833 motor driver powers both the VCA at the index fingertip and an optional linear resonant actuator (LRA) embedded in the base. These components can work in tandem to ensure that the controller responds quickly and accurately to user inputs, providing a seamless experience that feels natural and intuitive.

For tracking the controller's position in space, a Meta Quest 3 or Pro controller is mounted at the bottom of the device, providing 6DOF tracking that is essential for accurate interaction in a VR environment. The controller is powered via two cables that provide both power and USB communication, ensuring a reliable connection with the VR system.

At the heart of the controller's haptic feedback system is a rotating arm powered by a Hitec HSB-9370TH servo motor. This arm is designed to render kinesthetic feedback by moving the user's index finger in response to virtual interactions. The motion of the arm is precisely synchronized with the virtual environment, ensuring that the user's finger stays on the boundary of virtual surfaces, providing a highly immersive and realistic experience. The rotating arm is crucial for simulating the sensation of force, actuation, and displacement, which are key elements in many craft tasks, such as manipulating tools or shaping materials.

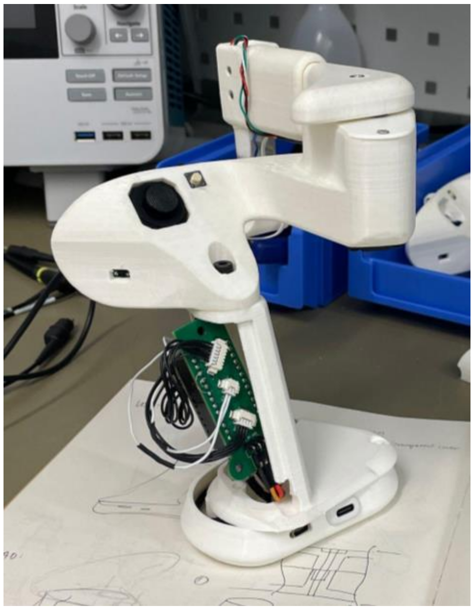


Figure: The electronics components are combined in the handle of the controller for easy access and assembly. This also establishes the centre of gravity and leads to a comfortable experience holding, moving, and operating the controller.

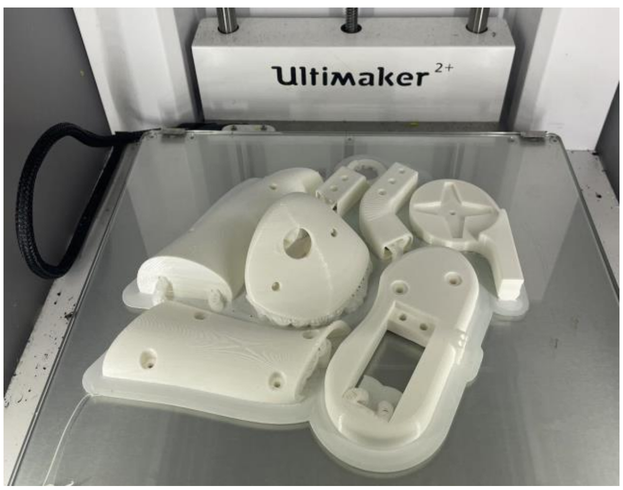


Figure: The individual parts of the controller are 3D printed from various materials to ensure sturdiness during operation, limited amounts of wear during use, and replicability in case of needed maintenance.

2.4. Interaction Mode Selection

A distinguishing feature of the controller is its ability to switch haptic rendering modes based on the user's grip and thumb position. This functionality is crucial for enabling different types of interactions, such as grasping and touching, without requiring complex mode-switching mechanisms that could disrupt the user's workflow.

The controller’s thumb rest includes an optical proximity sensor (QRE1113), which detects when the thumb is positioned on the rest. This sensor plays a critical role in determining the operation mode of the device. When the thumb is aligned with the index finger in a pinching or grasping gesture, the controller enters ‘Grab’ mode. In this mode, the controller adjusts to the virtual object's size and stiffness in response to the user’s squeezing force, providing realistic feedback that is crucial for tasks such as holding and manipulating virtual tools or materials.

When the thumb is off the rest, the controller switches back to ‘Touch’ mode, allowing the user to interact with virtual surfaces and textures under the index fingertip. This mode is particularly useful for tasks that require detailed tactile feedback, such as feeling the grain of wood or the texture of a fabric, where precision and sensitivity are paramount.

2.5. Force Control and Feedback

A key feature of the haptic controller is its ability to generate forces in a closed-loop fashion by sensing the forces applied by the user’s index finger. This capability allows the controller to not only adjust the index finger position to render the shapes of virtual objects but also simulate varying stiffness levels of grasped objects. The force sensor (Phidgets load cell CZL635, 0-5Kg) samples force values at an 88Hz rate, which are then processed to ensure smooth and responsive force feedback.

To enhance the controller's responsiveness, a simple slope extrapolator is used to derive new force values at a higher sampling rate, while a PD controller operating at 333Hz ensures quick and stable servo motor response. The controller's design prioritizes realistic force rendering, which is crucial for accurately simulating the physical interactions involved in craft practices. The ability to sense and respond to user-applied forces in real time allows the controller to simulate the resistance encountered in tasks such as cutting, shaping, or pressing, where the feedback from the material is a key part of the craft experience.

2.6. Technical Specifications

The haptic controller achieves most of the initial design objectives. For fully mobile operation, some features remain for future developments, such as untethered operation and shear force rendering. The technical specifications of the controller are summarised below:

Variable	Value
Max. Continuous Force	Up to 30 N
Stiffness Range	Up to 10 N/deg (5.73 N/mm)
Motion Range	45° (0.2° resolution)
Force Sensing	0 ~ 50 N range, 88 Hz sampling rate, 0.00003 N resolution, 0.01 N noise
Hand Tracking	Meta Quest 3 controller
Weight	540 g
Dimensions	100 x 180 x 180 mm
Power Draw	30 mA (Idle), 1A (Max. force) @ 5V

These specifications highlight the controller's ability to deliver precise and responsive haptic feedback, crucial for simulating the intricate and detailed interactions required in craft practices. The controller's design balances the need for realism with the constraints of portability and power consumption, ensuring that it can be used effectively in various VR/AR environments.

3. Controller interface with frontends

The developed haptic controller can be used in the context of front-end applications through Unity to enable developers to integrate the controller into their experiences. This integration bridges the gap between the hardware's capabilities and the potentially diverse needs of software developers in AR/VR environments. For those developers, having a seamless interface with the haptic controller is essential to harness the full potential of haptic feedback without needing in-depth knowledge of the hardware.

The developed controller provides an API that serves as an intermediary layer between the hardware and the software. This API is designed to be both comprehensive and flexible, allowing developers to access and control the full range of the controller's capabilities while still providing ease of use. The API is divided into two abstraction levels: the low-level API and the high-level API. Each caters to different aspects of the development process:

Low-Level API: This is designed for developers who require direct control over the haptic controller's mechanical and sensory functions. It exposes the core capabilities of the device, enabling precise adjustments and fine-tuning of haptic feedback. The low-level API is essential for creating custom interactions and ensuring that the haptic responses are perfectly aligned with the specific needs of the application. Developers with a deep understanding of haptic technology or those working on specialized applications can leverage this API to push the boundaries of what the controller can achieve.

High-Level API: On the other hand, the high-level API abstracts much of the complexity involved in managing the haptic controller's functions. It provides Unity developers with intuitive tools for integrating haptic feedback into their applications, focusing on ease of use and rapid development. This API is particularly beneficial for those who may not have a deep understanding of haptic technology but still wish to incorporate advanced haptic interactions into their projects. By using the high-level API, developers can focus on the broader aspects of application design and user experience, trusting that the underlying haptic interactions will function smoothly.

The dual-API approach ensures that the controller can be effectively integrated into a wide range of applications, from those requiring precise, low-level control to those needing a more straightforward, high-level interface. This flexibility is crucial for promoting the widespread adoption of the haptic controller in various domains, particularly in craft training, where the accurate simulation of tactile interactions is essential for effective learning and practice.

3.1. Low-Level API Implementation

The low-level API provides direct access to the haptic controller's hardware functions, offering developers granular control over the device's operation. This API is designed for those who need to customize the haptic feedback for specific tasks or who are developing specialized applications that require fine-tuned haptic responses.

`setOpeningAngle([0..90°])` controls the angle of the rotating arm, which is critical for simulating the act of grasping virtual objects. By adjusting the opening angle, developers can replicate different object sizes, enhancing the realism of tasks such as holding tools or manipulating materials.

`setMinimumOpeningAngle([0..90°])` sets a baseline position for the rotating arm, ensuring consistency in the controller's starting position. It is particularly useful for standardizing user experiences, allowing for predictable interactions across different scenarios.

`setResistance([0..1.0])` adjusts the resistance felt by the user during interactions, simulating material stiffness or tool tension. It allows for the replication of varying force levels, which is essential for accurately simulating the physical effort involved in craft tasks.

`playBackTexture(wave_file)` triggers a texture playback, which provides vibrational feedback that simulates the surface texture of virtual objects. This is crucial for tasks that require users to feel and differentiate between various material textures, such as wood grain or fabric patterns.

`getIsGrasping()` indicates whether the controller is in a grasping state, allowing for context-specific feedback and control. It is essential for managing the interaction modes within applications that require frequent switching between grasping and touching.

`getAppliedForce()` returns the force applied by the user's finger, providing real-time feedback on the pressure exerted during interactions. This is particularly important in craft training scenarios where the correct application of force is critical for successful task execution.

`getOpeningAngle()` provides the current angle of the rotating arm, allowing developers to monitor and adjust the controller's position in real time. It ensures that the virtual representations of interactions accurately reflect the user's physical actions.

3.2. High-Level API for Unity Developers

The high-level API is designed to simplify the integration of the haptic controller into Unity, providing a more intuitive interface for developers. This API abstracts the complexity of the low-level controls, making it easier for developers to implement haptic feedback in their applications without needing to delve into the intricacies of the hardware.

`addColliderObject(GameObject, compliance = 1.0)` allows developers to associate Unity GameObjects with the haptic controller, enabling the controller to interact with these objects in the virtual environment. The `compliance` parameter adjusts the object's responsiveness to forces, simulating different material properties. This feature is essential for craft training applications where understanding material behaviour is a key learning objective.

`setColliderTexture(GameObject, wave_file)` assigns a tactile texture to a GameObject, which is rendered by the controller as vibrational feedback. This allows developers to simulate various surface textures, enhancing the realism of the virtual environment and providing users with a more immersive experience.

`addTouchEventCallback(GameObject)` registers a callback that is triggered whenever the controller touches a specified GameObject. It enables developers to create interactive responses, such as providing immediate feedback or triggering instructional content, which is crucial for maintaining engagement in training scenarios.

`addGraspEventCallback(GameObject)` registers a callback for when the controller grasps a specified GameObject. This is particularly useful in applications that involve manipulating virtual tools or materials, allowing for context-sensitive feedback that enhances the user's learning experience.

`Vector3 getFingerPosition()` returns the position of the user's finger in the virtual environment, enabling precise tracking of hand movements. Accurate finger tracking is essential for tasks that require fine motor skills, such as detailed carving or intricate assembly work, which are common in craft training.

`Quat getControllerOrientation()` provides the orientation of the controller in the virtual space, represented as a quaternion. Understanding the controller's orientation is vital for tasks that involve spatial manipulation, such as rotating objects or applying force in specific directions, which are integral to many craft activities.

3.3. Integration with Meta Quest

The API and its Unity implementation are designed to work seamlessly with the Meta Quest headset, ensuring that the haptic controller can be used in a wireless VR environment. The Meta Quest's untethered nature, combined with the controller's haptic capabilities, allows users to experience simulated realistic craft environments. This integration ensures that the controller's advanced haptic features are fully utilized with the potential of providing an immersive training experience that faithfully replicates the tactile aspects of activities that involve craft skills.

In summary, the development of both the low-level and high-level APIs for the haptic controller has provided a comprehensive interface for integrating advanced haptic feedback into Unity-based VR/AR applications. These tools enable developers to create rich, sensory-driven experiences that are essential for the effective teaching, learning, and preservation of craft skills in a digital format.

Figure: A user experiencing a digital wood carving demo with haptic feedback in Virtual Reality.

4. Conclusion and future steps

The advancement of craft skills, their preservation, and the ability to train future generations in these skills are of paramount importance in maintaining the rich heritage of craftsmanship. This part of CRAEFT seeks to show that AR/VR technologies possess immense potential to benefit the way craft skills are taught, practised, and documented. Through the power of immersive virtual environments, learners can engage with craft techniques in ways that were previously unimaginable, accessing detailed simulations of craft processes that can be repeated, studied, and perfected without the limitations imposed by physical resources.

As motivated above, the tactile dimension of craftsmanship—the sense of touch, the feel of materials, and the resistance encountered when working with tools—is a critical component for these ambitions. For this purpose, we have developed a haptic feedback controller for AR/VR environments for Deliverable 4.2, to bridge the gap between digital simulations and the physical realities of craft practice. By integrating advanced haptic feedback into the AR/VR experience, the controller can make it possible to simulate the full spectrum of sensory inputs involved in craftwork, ensuring that the tactile knowledge and fine motor skills essential to craftsmanship are not lost in the digital transition.

The implementation of the haptic controller, with its ability to render multi-purpose haptic feedback, adaptive interaction modes, and precise control over tactile sensations, could significantly advance the digital representation of effects and activities while performing craft skills. The developed APIs enable the controller to be integrated into Unity, making it accessible to a wide range of developers and ensuring that its advanced features can be fully utilized in various VR/AR applications. This integration allows for the creation of richly detailed, sensory-driven training environments that closely replicate the physical experience of working with materials, tools, and techniques.

The developments in this project were a prerequisite for the next step to evaluate if learners can practice and refine their craft skills in a virtual environment that not only visually and audibly simulates the real world but also provides the essential tactile feedback that is so crucial to mastering these skills. This capability would be valuable in scenarios where access to physical workshops or materials is limited, enabling learners to gain hands-on experience in a controlled, repeatable, and immersive setting.

Looking forward, the future steps in this part of the project will focus on further enhancing the capabilities of the haptic controller, proofing its application for craft practices, and evaluating its performance with target audience members. There is also an opportunity to explore the use of this technology in collaborative and remote learning environments, where practitioners can share their skills and techniques in real-time, across distances, with the full tactile experience preserved.