care, judgment, dexterity

CRAEFT

Haptic devices for training, simulation, and design

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http://www.craeft.eu/

Executive summary

This deliverable for the CRAEFT project focuses on enabling haptic interaction with virtual tools and materials in immersive Virtual Reality. The work supports CRAEFT's goal of cultivating tactile skills and material sensibilities through embodied digital practice, with a particular emphasis on craft education and the transfer of embodied knowledge.

To that end, we developed a handheld haptic controller capable of delivering localized tactile and kinesthetic feedback during craft-relevant tasks such as touching, pinching, shaping, and manipulating materials. This custom hardware supports sensations of compliance, resistance, and surface contact, which are critical qualities that define how materials are experienced and shaped in traditional crafts.

To broaden access and deployment opportunities, we also developed perceptual feedback strategies that combine visual and auditory cues with the vibrotactile capabilities of commodity VR hardware to simulate haptic sensations without the need for specialized actuators. Integrated via modular software APIs, these techniques allow users to experience illusory sensations of contact, compression, and resistance using standard devices on commodity platforms such as the Meta Quest controller.

Together, our contributions offer both a high-fidelity haptic interface for advanced craft simulations and a scalable perceptual feedback framework for wider application. Our work contributes to the immersive systems used in CRAEFT to convey not only how crafts look and sound, but also how they feel, for the purpose of preserving the embodied dimensions of craft knowledge for both experts and learners.

Document history

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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, mold, 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 the fine motor skills and embodied knowledge that are 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, 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 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. Complementing the custom-hardware haptic actuation demonstrator, Deliverable 4.2 also introduces the design of perceptual feedback strategies that simulate haptic sensations using visual and auditory effects in tandem with commodity vibrotactile hardware. Together, these developments broaden access to embodied digital practice and help close the gap between physical and virtual craft interaction

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 such as 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.

The 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.

1.3.3 Perceptual Feedback on Commodity Hardware

In addition to the physically actuated controller, we explored a complementary pathway to deliver haptic sensations through purely perceptual means. This approach leverages the dominance of visual and auditory perception in immersive VR to create compelling illusions of touch and material interaction, all without requiring any physical actuators.

By carefully synchronizing visual deformation cues (e.g., object compression, fingertip displacement) with realistic audio effects (e.g., damped impact sounds, material-specific textures) and the built-in vibrotactile capabilities of commodity VR controllers (such as Meta Quest), we can simulate sensations like resistance, softness, and surface contact. These perceptual effects are not merely enhancements. Rather, they substitute for actual tactile feedback in a way that is cognitively convincing to the user, especially during tasks like pinching, pressing, or shaping virtual materials.

This perceptual haptic approach increases the reach of the system, making it usable by learners and practitioners who do not have access to specialized hardware. While the physical controller provides high-fidelity feedback where available, these perceptual techniques ensure that the training experience remains rich and embodied even on standard hardware. Together, these strategies offer a scalable and inclusive solution to bringing the tactile qualities of craft into immersive VR.

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.

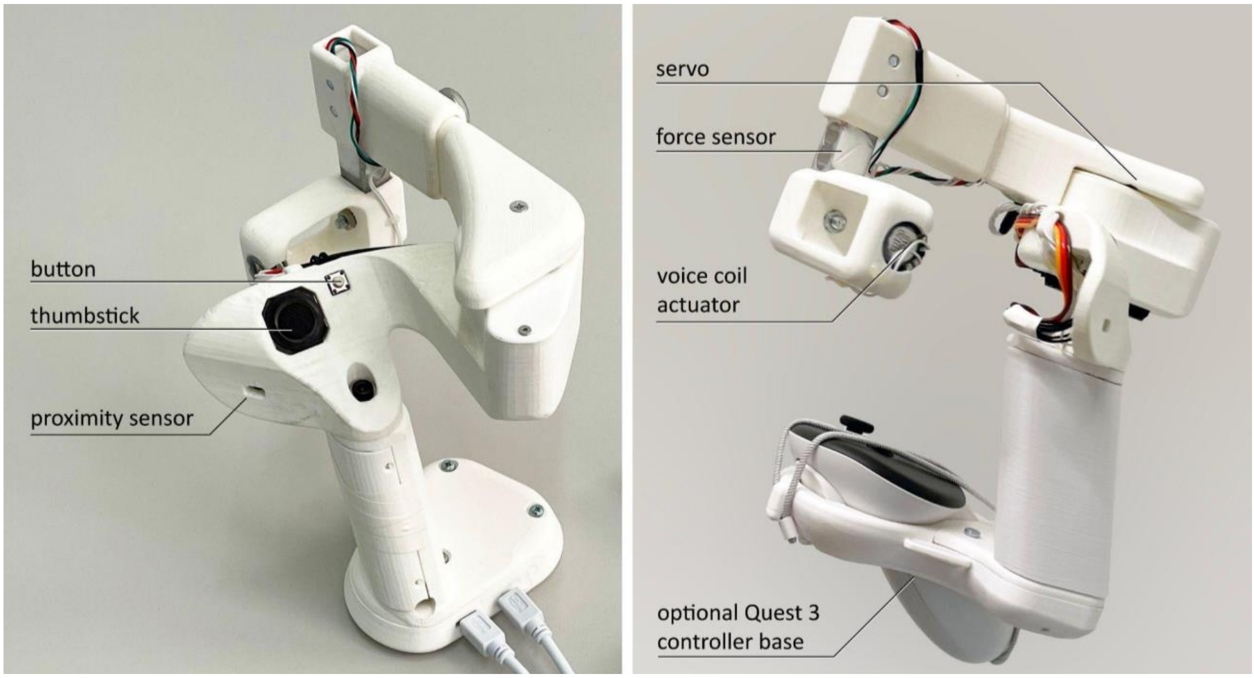
2.1 Design Objectives for the Haptic Controller

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 on 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.



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.

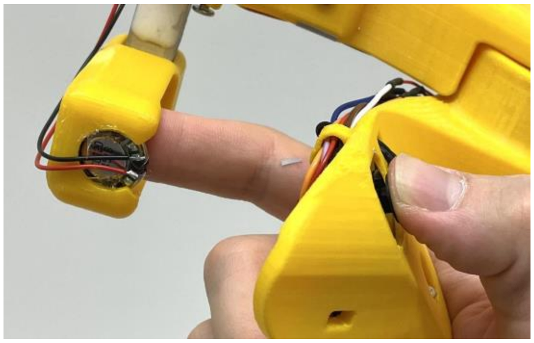


Figure: The voice coil actuator under the index fingers produces texture actuations and sensations during the motion of the finger or the hand in mid-air, thereby allowing users to explore virtual objects and their surface characteristics.

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 center 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.

2.5 Interaction Mode Selection

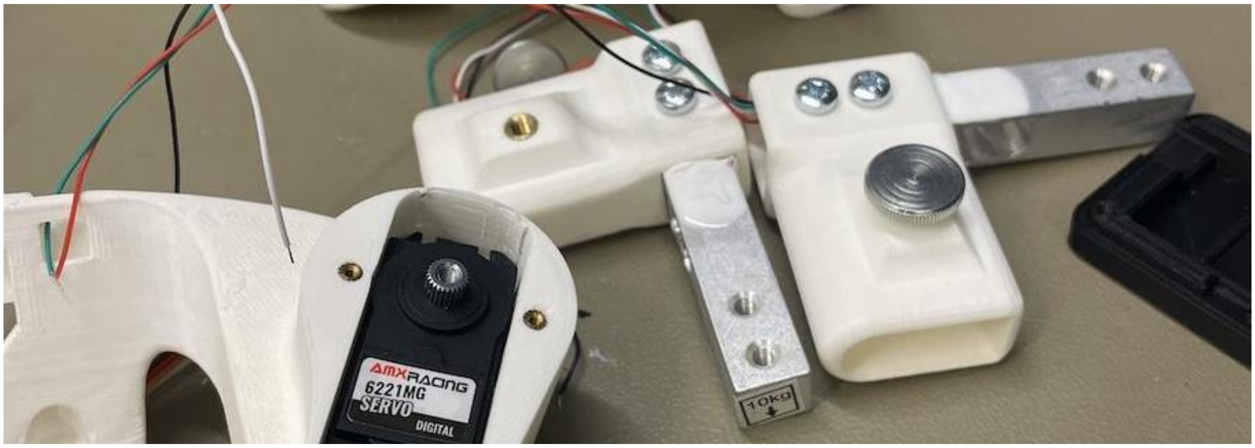
A distinguishing feature of the controller is its ability to switch haptic rendering modes based on the user's grip and thumb position. This functionality is crucial for enabling different types of interactions, such as grasping and touching, without requiring complex mode-switching mechanisms that could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

2.6 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.

2.7 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 summarized 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, which is 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 a wide range of 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 behavior 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 are 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.

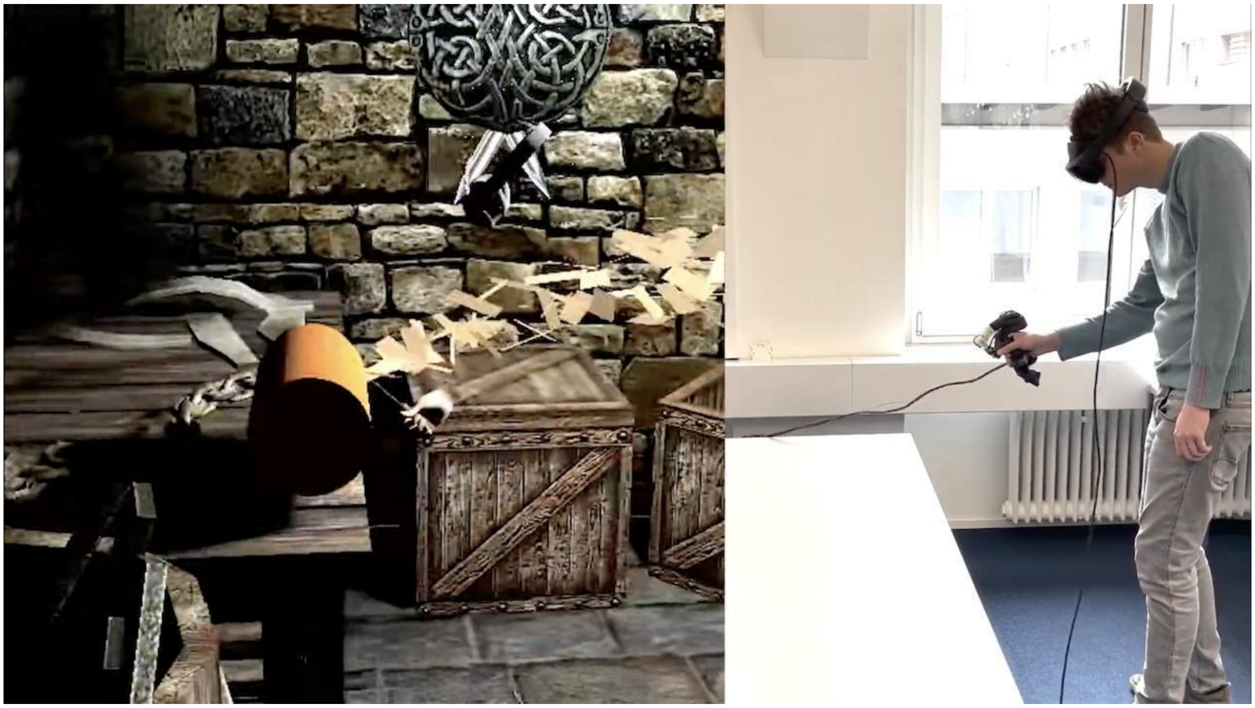


Figure: A user experiencing a digital wood carving demo with haptic feedback in Virtual Reality.

4. Controller revision after deployment

Following initial user testing and system integration sessions, several revisions were made to the handheld haptic controller. The focus was on improving mechanical reliability, software responsiveness, and ergonomic comfort based on feedback from project partners and internal technical evaluations.

4.1 Hardware Revisions

During early usage phases, mechanical failures were observed in the cable connection near the base of the controller. These failures were attributed to internal strain on the wiring harness and connector stress caused by the continuous torsional movements typical in virtual reality interactions.

To address these issues, the base chassis was redesigned to incorporate a dedicated strain relief channel. The internal cable routing was adjusted to increase the bend radius of the wires, preventing long-term material fatigue at the connection points. The mounting brackets for the internal electronic components were augmented with threaded brass inserts rather than relying on standard friction fits, ensuring that the main microcontroller board remained secure under physical load. Furthermore, the 3D-printed outer shell was updated. Wall thickness was increased and a higher infill density was applied to load-bearing sections, significantly limiting structural flex during prolonged manual manipulation. These structural changes resolved the hardware failure rates in subsequent deployments.

4.2 Latency and Responsiveness

During system integration into the wider CRAEFT frontend applications, a noticeable delay was reported between user motion and the resulting haptic response. Diagnostic profiling revealed that the source of the latency was the serial communication implementation in Unity, where synchronous, blocking read operations prevented the timely execution of the haptic control loop.

The communication layer was subsequently rewritten to decouple the haptic update rate from the application rendering framerate. The updated integration now implements an asynchronous data processing strategy. A dedicated background thread continuously polls the serial port, reads incoming force sensor payloads, and writes target actuator commands to a thread-safe ring buffer. The main Unity thread reads the latest device state from this buffer during its fixed physics update cycle. This approach eliminates the serial buffer bottlenecks, so that the controller maintains its target control loop frequency.

Because these changes were localized to the Unity connector plugin, the manufactured prototypes required no firmware modifications. Follow-up integration tests confirmed that haptic feedback became immediate and stable, supporting the real-time responsiveness required for virtual shaping interactions.

4.3 Ergonomics and Handling

Several ergonomic adjustments were introduced to improve user comfort and reduce wrist fatigue during extended training sessions. Initial observations indicated that users occasionally struggled to maintain a consistent grip while applying downward force on the actuator.

The contour of the primary handle was reshaped following anthropometric guidelines and to improve the weight distribution. The pivot point of the servo-driven actuator arm was adjusted to match the natural kinematic arc of the human index finger during a standard pinch-grasp motion. This kinematic realignment minimizes parasitic shear forces on the user's fingertip and ensures that the physical contact pad remains flush against the skin throughout the controller's entire range of motion. Additionally, the placement of the secondary input buttons was modified. The tactile switches were slightly recessed and their actuation force thresholds were adjusted to prevent inadvertent inputs when users naturally tightened their grip during simulated high-effort tasks.

4.4 Integration and Use

The revised controller was deployed in several CRAEFT scenarios by CRAEFT partners, who integrated it in Unity-based applications and used it in workshops with other institutions. The controller operated in a manner that no new mechanical or integration failures were reported during these sessions.

The controller is considered complete for the intended scope. All required feedback modes for tactile shaping and material interaction are supported. While future iterations may introduce additional sensing or tracking, the current version fulfills the objectives set for craft training in immersive VR.

5. Simulating Haptic Feedback via Visuoauditory Illusions

The handheld haptic controller developed in 4.2 enables localized force feedback for the finger and tip, allowing users to physically interact with virtual materials by pressing, grasping, and shaping. However, relying exclusively on custom hardware can introduce deployment limitations for wider training and use. To broaden access to the applications developed as part of CRAEFT alongside the haptic sensations developed for them, we explored a software-driven approach that is complementary to custom-hardware haptic actuation and that aims to recreate key haptic sensations through perceptual feedback strategies. By coordinating visual deformation and synchronized audio, we contribute a range of seemingly tactile impressions entirely without physical actuators. Finally, we augment these visuoauditory illusions with the plain vibrotactile feedback options that are present in commodity VR controllers to evaluate how even such comparably impoverished feedback can lead to compelling sensations when paired with our perception strategies.

5.1 Motivation of Non-haptic Perception Strategies for Tactile Impressions

In immersive environments, the perception of touch and grasp does not rely solely on mechanical force. The human sensorimotor system continuously integrates visual, auditory, and tactile information to infer physical events. In immersive settings rendered with full sensory substitution by VR systems, visual input typically dominates this multisensory integration. When a user observes a physically plausible visual response, such as a virtual object deforming, while simultaneously hearing a corresponding sound and feeling a basic vibration, the brain interprets this synchrony as physical causation.

This perceptual phenomenon forms the foundation of our approach in this part of our deliverable. We exploit the dominance of visual impressions and augment them with auditory and vibrotactile cues. This can induce haptic illusions of weight, compliance, friction, and resistance.

Our approach is motivated by the limitations of consumer VR hardware. Commodity controllers, such as those bundled with the Meta Quest platform, lack localized force feedback, kinesthetic resistance, and fingertip-specific actuation, which are the types of actuations we custom-designed the haptic feedback controller detailed in Section 2 for. In contrast, the haptic output of commodity controllers is restricted to internal vibrotactile actuators, such as Linear Resonant Actuators or Voice Coil Motors. These motors can produce variations in amplitude and frequency, but they cannot mechanically oppose finger motion or render directional forces. We explored and show that when these transient vibrotactile cues are time-locked with visual and acoustic discrepancies for the purpose of rendering feedback, they ground the visual illusion and allow users to feel complex material interactions.

5.2 Haptic Effects Supported by the Interaction Model

The physical controller previously developed for CRAEFT in Section 2 delivered tactile interactions through an actuated arm at the user's index fingertip. To create perceptual substitutes in this stage, we decomposed the controller's capabilities into distinct perceptual effects central to craft manipulation.

These effects include touch and surface contact, which represents the distinct sensation of the fingertip striking a material boundary. We also identified grasping and pinching, representing the closure force and structural resistance felt when holding an object between the thumb and index finger. A third effect is deformation and compliance, which captures the depth-dependent resistance felt when pressing into yielding materials like soft clay or hot glass. We further accounted for grip force modulation, defined as the sensation of an object's stiffness based on how the material pushes back against varying grip strength. Finally, we isolated tool-mediated transfer, which involves the indirect transmission of force, vibration, and texture felt through the handle of a virtual tool. Each of these interactions served as a reference template for the software implementations detailed below.

5.3 Implementation of Multimodal Perceptual Effects in Unity

For each target haptic sensation, a perceptual substitute was developed. The core design decision across all implementations was to ensure that visual, acoustic, and vibrotactile events execute within a single frame window to preserve the illusion of a unified physical event.

5.3.1 Simulated Touch and Surface Contact

The goal of this effect was to provide a clear, instantaneous cue that the user has collided with a solid surface, substituting the physical stopping force of a mechanical actuator.

Contact detection leveraged Unity's `OnTriggerEnter` and `OnCollisionEnter` events applied to the virtual fingertip colliders. To sell the illusion of impact, we immediately introduced a visual collision constraint. A small local visual deformation was rendered at the collision point using a GPU-based vertex-displacement shader. A normal-offset vector was applied to nearby vertices within a 1.5 cm radius of the contact point, scaled proportionally to the relative impact velocity and clamped to a maximum depth of 3 mm.

Simultaneously, a high-frequency acoustic cue was triggered via spatial auditory feedback rendering, using `AudioSource.PlayClipAtPoint`. The acoustic clip was dynamically selected from a material-specific sound bank and spatialized using the surface normal. For experimentation, we also tried grounding the visual and auditory impact using the commodity controller's built-in vibration motor via `XRController.SendHapticImpulse`, using a 35 ms duration and an amplitude derived from the dot product of the relative velocity and the collision normal.

5.3.2 Simulated Grasping and Pinching

The goal of this effect was to create the impression of squeezing an object between the thumb and index finger, establishing a sense of tension and structural volume.

In the software implementation, grasp intent is detected by monitoring the proximity between the virtual thumb and index finger anchors in relation to the object's collider. When the distance falls below a 2.5 cm threshold and the user's physical trigger crosses a threshold, the grasp state is activated.

To simulate resistance, the grasped object dynamically morphs using pre-configured blendshapes representing varying states of physical compression. These blendshapes are linearly interpolated every frame based on the raw analog input from the controller, accessed via the Unity input device interface for the grip feature. Audio feedback plays a central role in this simulation. A looped elastic tension audio texture is played. The pitch and volume of this loop are dynamically shifted over the grip value range. Visually seeing the object resist compression, hearing it groan under pressure, and feeling a continuous low-frequency rumble refreshed via a coroutine gives the user an illusion of holding a physical mass under tension.

5.3.3 Simulated Deformation and Compliance

The goal of this effect was to replicate the sensation of pressing into soft, yielding materials that deform under pressure and rebound upon release, which is vital for virtual pottery and glass shaping.

Compliant objects in Unity were assigned a custom script containing a scalar compliance coefficient. When the virtual hand collides with these objects, Unity's physics engine calculates the exact interpenetration depth. This depth vector drives a real-time vertex displacement shader, exaggerating the visual deformation to prompt the perception of compliance. The visual deformation amplitude is directly proportional to the penetration depth multiplied by the compliance factor.

Auditory feedback utilizes muffled, low-pitched pressure sounds. As the penetration depth increases, the playback pitch decreases, simulating increasing density. Haptic vibration is applied as an escalating ramp. A coroutine triggers haptic impulses every 15 ms, with the vibration amplitude interpolating upwards as the visual depth increases. If the user releases the material rapidly, a spring-back visual animation is triggered alongside a distinct acoustic recoil snap.

5.3.4 Simulated Grip Force Modulation

The goal of this effect was to differentiate between soft and rigid materials based strictly on how they perceptually respond to the user's applied grip force. Because we cannot physically stop the user from closing their hand around a rigid virtual object, we resort to adapting the control-to-display ratio.

The analog grip value dictates the response based on the object's assigned stiffness. For soft materials, the visual deformation is immediate and maps directly with the grip input. For rigid materials, visual deformation is clamped and visually delayed by 50 to 100 ms. Seeing the virtual hand stop moving while the physical hand continues to squeeze causes the brain to perceive a hard surface.

The vibrotactile profiles differ to support this distinction. Stiff objects trigger short trains of high-frequency vibration in 10 to 20 ms pulses, simulating a hard limit. Soft objects trigger a continuous low-frequency rumble that scales gradually in amplitude, mimicking yielding resistance.

5.3.5 Simulated Tool-Mediated Interaction

The goal of this effect was to simulate the transfer of kinetic energy and surface friction when manipulating a virtual tool, such as striking or scraping a workpiece.

Tools are configured as rigid bodies with specialized contact points. Upon collision, the impact force is captured via the collision impulse vector. This magnitude is scaled logarithmically to trigger a haptic pulse on the holding hand.

To simulate the physical shock traveling through the tool handle, a brief visual micro-jitter is applied to the tool. This is calculated using a spring-damped sinusoidal offset in local rotation. A dedicated script queries the material tags of both the tool and the target. It cross-references these tags to pull the correct acoustic profile, triggering a synchronized sound. The combination of visual tool recoil, acoustic impact, and a scaled haptic burst creates a sense of striking a physical object.

5.4 Integration of Commodity Vibrotactile Capabilities

The success of the perceptual techniques can be increased by adding vibrotactile feedback of varying quality. For this, we leverage the wideband Voice Coil Motors in modern commodity controllers, which allow for greater dynamic range compared to older motors.

Our system leverages the Unity XR haptics API to construct complex haptic envelopes rather than simple on or off rumbles. By shaping these envelopes, we generate sharp pulses to denote discrete events like surface contact or rigid impacts. We also dynamically tie the amplitude and frequency of the motors to real-time physics variables to simulate continuous friction or building tension. Because these wideband actuators lack spatial localization, the precise temporal synchronization with the visual and audio shaders localizes the perceived sensation to the virtual contact point in the user's mind.

5.5 CRAEFT Use Cases and Ongoing Evaluation

These perceptual feedback strategies have been deployed as a potential fallback interaction layer in a Unity-based environments that is of relevance to the tasks investigated by CRAEFT. For example, in virtual glass shaping scenarios, users pinch and stretch soft virtual glass. They rely on the visual blendshape compression, the acoustic stretching tones, and the ramping vibrotactile rumble to gauge the material's viscosity and temperature state. In tactile exploration scenarios, users drag their virtual fingers across colliders. Surface normals and curvature maps modulate the vibration frequency and trigger scratching audio, allowing users to perceive structural transitions without mechanical resistance.

To validate the effectiveness of these perceptual strategies, user experiments are still ongoing. In these experimental validations, we are comparing the capabilities of the perceptual strategies developed as part of this deliverable with the raw haptic capabilities of the custom-hardware haptic feedback controller developed in this deliverable. The purpose of the evaluation is to establish the extent to which the developed perceptual strategies may substitute the use of the custom haptic controller and what the importance of the lacking feedback cues is for applications in the CRAEFT context. We are also conducting ablation studies to isolate the impact of individual modalities on the user's sense of material compliance and presence, directly comparing efficacy, efficiency provided to users in task completion, as well as their throughput during interaction. At the time of this deliverable, the formal ethics approval process for the full-scale comparative human-subject study is actively underway.

6. Summary and Conclusion

The preservation of craft skills and the facilitation of training for future practitioners are central to maintaining tangible and intangible cultural heritage. This component of the CRAEFT project investigates the application of virtual reality technologies to the teaching, practice, and documentation of craft skills. Immersive virtual environments allow learners to engage with craft techniques through repeatable simulations, reducing reliance on physical materials and workshop access. Because the tactile dimension of craftsmanship, such as the perception of material compliance, surface texture, and tool resistance, is integral, incorporating haptic feedback is a critical requirement for effective simulation.

To address this requirement, this part of the project adopted a dual-track approach to haptic interaction. The initial phase focused on engineering a custom handheld haptic actuator designed to deliver localized mechanical forces to the user's fingertip. This hardware provides kinesthetic resistance for tasks requiring manual dexterity, supporting the nuanced physical interaction between the maker and the material. Providing physical haptic feedback is relevant for training scenarios where practitioners must learn to evaluate material properties, modulate applied force, and execute specific tool gestures. The accompanying software APIs enabled the integration of this controller into Unity, thereby allowing developers to create training environments that aim to approximate the physical use of traditional materials and tools in the effects users perceive during interaction in VR.

Acknowledging that custom hardware may present scalability and deployment constraints for broader user bases, the subsequent phase of the project developed software-driven perceptual feedback strategies. We have investigated methods to simulate the sensory impressions of craft interactions using the standard vibrotactile actuators available in consumer-grade VR headsets. By coordinating visual deformation models, dynamic acoustic cues, and structured vibrotactile envelopes, the system leverages multisensory integration to approximate sensations of physical resistance and compliance. This secondary approach extends the reach of the tactile training modules developed within CRAEFT, allowing deployment without the prerequisite of specialized mechanical hardware.

Together, these developments establish a technical foundation for learners to practice craft skills in a virtual environment that provides visual, auditory, and tactile feedback. The dual-track strategy promises to offer flexibility for the preservation and dissemination of traditional techniques by relying merely on commercial commodity platforms in the VR space today. Vocational programs and specialized training institutions could utilize the custom haptic hardware to support high-fidelity sensorimotor skill transfer. Concurrently, remote students and independent learners could access perceptual training simulations using standard VR equipment. This capability is applicable in scenarios where physical workshop access is restricted, providing learners with structured experience in a controlled immersive setting.

By broadening the access of embodied knowledge transfer, the methodology of Deliverable 4.2 presents opportunities for collaborative and remote learning paradigms in craft education. Our aim was for practitioners and instructors to be able to share techniques across distances, utilizing either mechanical haptic preservation or perceptual simulation to convey tactile requirements. These outcomes were directly aligned with CRAEFT’s broader objectives.