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AN IMMERSIVE HAPTIC EXPERIMENTATION FOR DEMATERIALIZED TEXTILE PERCEPTION IN COLLABORATIVE DESIGN PROCESSES

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Abstract

This experimentation arises in the context of the design process of digital tools in the fashion sector of Made in Italy. The contribution presents an overview of the main insights gained from the analysis of the state of the art and experimentation conducted in order to obtain a low-cost digital textile sampling and restitution process useful for possible new advanced modalities of collaborative remote design. This project is related to the extended MICS partnership of the PNRR project that researches at a low TRL level new scenarios for the integration of immersive technologies in traditional craft processes.

Keywords

Dematerialization, Haptics, Advanced Simulation, Multimodal Stimulation, Collaboration.

1. Introduction

The acquisition of reality is a relevant part of the interaction design and of the visualization practices in order to create a correspondence between the real world and its virtual representation (Natkin & Yan, 2005; Whitton et al., n.d.). The digitalization issue is extremely contemporary, especially nowadays where many local and European projects and efforts are being directed toward this end.

The process of dematerialization of artifacts toward an increasingly immaterial design dimension with regards to the process design, known for a long time and described by Maldonado (Maldonado, 1992), has a dated manifestation, and it is still progressing, influencing not only product-service systems but all phases and activities of development and project cultures.

The terms application, mock-up, and Digital Twin are just a few examples of approaches to digital content that can be produced and constructed in the industrial and research field in order to obtain elements that can be analyzed, verified but above all manipulated through simple ways that are quick and non-invasive on the totality of the work to be done.

1.1 The need for dematerializing processes

In an increasingly competitive vast and very high-turnover market, the time factor certainly plays an extremely important role in both design and production as well as fruition. In general, anticipating competitors means gaining substantial market sectors. In this context, speeding up the ideation, simulation, communication, and decision-making processes is crucial and worthy of conspicuous efforts. Digitalization and virtualization methodologies and tools help to address these needs, on the one hand, putting digital alongside a product, a service, allows to extend its use and user involvement, on the other hand having digitalized models and prototypes, allows the production of sufficiently rapid processing, modification and sharing requiring a limited expenditure of resources.

Examples include CAE (Computer Aided Engineering) simulations, such as virtual fluid dynamic or structural simulations, which, starting from a packaged mathematical model validated according to appropriate convergence interactions enable the evaluation of the behavior of objects in specific contexts without the need for a real finished product. Another case that can be considered is that of scanning and subsequent virtual modeling of cultural property, performed to catalog and set up subsequent restoration and conservation work (Liritzis et al., 2015).

1.2 The importance of tactile feedback

Dematerialization has not only advantages, indeed the inability to interact with the physical component of a product or process carries the inherent risk of losing control of some degrees of complexity.

Regarding the theme of virtualization, the need to reproduce a tactile channel feedback simulation is essential in specific activities where sensory input in a work context is necessary. In this sensory field, multiple hardware solutions are capable of digitally reproducing sensations of temperature variations (Matthies et al., 2013), pressure (Kettner et al., 2017), and vibration (Karuei et al., 2011)

Production feasibility or ergonomics are the first technical aspects to suffer, precisely because through a monitor it is possible to observe the visual appearance of the object from various points of view without being able to touch or feel it with most of the other senses. This critical issue, when moving from a two-dimensional view (i.e. projected on a traditional computer display) to a three-dimensional one, such as that of a Head Mounted Display (HMD), tends to be less prominent, because the visual perceptual aspects are further improved when interacting with the object in the virtual scene, however, some of the underlying perceptual problems remain. For example, concerning the visual aspects, the current popular commercial VR devices still suffer from the well-known vergence-accommodation conflict (LaValle, Steven M., 2023; Zhou et al., 2021), or concerning the tactile aspects, the object occlusion and the tactile feedback of surfaces are still missing. For this reason, a growing interest is spreading in the world of haptics and touch restitution devices. Studies in the literature on this area are not new, the main characteristic of touchability, which is to be ambivalent, i.e., valid as both an input action and an output transfer, has been known for some time (Adams & Hannaford, 1999). Among the addressed issues there is stability, which together with presence remains open and investigated to this day.

Presence, meaning the ability to perceive ourselves as involved in an environment different from the one in which we physically are (Witmer & Singer, 1998), is another topic of particular interest both in terms of the success of the immersive experience and the possibility of establishing a certain degree of connectedness in collaborative contexts. In this direction, the contribution of Hornecker and Buum's (Hornecker & Buur, 2006) experimentation is interesting, according to which the possibility of constructing interaction patterns that retrace people's skills refined in the real-life environment confers a greater connotation of intuitiveness and naturalness. Extremising this concept, experiments are emerging aiming to blend not only reality but also the environment, thus obtaining hybrid spaces containing real elements, to be experienced virtually therefore making the virtual experience also physically perceptible (Van Campenhout et al., 2020). This type of approach, however, leads to increased complexity and time consumption in setting up these experiences. Thus, there is a median way represented by the aforementioned haptic feedback, which is useful for the creation of interaction and micro-interaction which stimulate triggers, but also feedback and continuous sensations in the user who gets to benefit from them (Dall'Osso & Pezzi, 2022).

2. An overview of haptic feedback

For a better understanding of the mode of operation and the following experimentations, it is necessary a brief introduction to the haptics field, in fact, according to El Saddik (El Saddik, 2007) it is possible to identify four subareas: human haptics, machine haptics, computer haptics, and multimedia haptics.

The first branch is referred to as human haptics and it is focused on observing, studying, and understanding the natural physiology of touch and its components like sensory systems and responsive muscle activation.

Machine haptics is indeed related to creating mechanical or electro-mechanical devices useful to reproduce or augment the human touch. The third cluster regards computer haptics, in other words, it is the software elaboration of the giveback of touch in its visual and vibrational components. Finally, the Multimedia touch involves all the elements at the boundary of the action environment, meaning (e.g.) the spatial, temporal, and physics elements through audio, video, and text. In particular, the following section is oriented to mainly explore the machine and the computer fields, because more pertinent to the main goal of the experimentation project.

2.1 Typology of haptic devices

To choose a proper device for the development of the experimentation phase, state-of-the-art research of conceptual and technical principles was conducted, creating a base knowledge useful to decompose and categorize the analyzed tools. Here is the report of the main lesson learned about this portion of work.

An initial fundamental consideration is about the comparison between the concept of kinesthetic and cutaneous feedback (See et al., 2022). The kinesthetic one represents the interaction related to the human ability to control his body and movements within space, which is also known as proprioception. The cutaneous one, indeed, is more concentrated because limited to a trigger in contact with the skin, having the focus to stimulate mechanoreceptors, nervous specialized entities located under the skin. To be effective, a haptic experience needs to incorporate both dimensions. Moving forward in breaking up this system, it is necessary to distinguish the typology of action that haptic devices can process.

Concerning the kinesthetics field there are two possible activities, one is determined by an input action consisting of motion tracking, and the second is force feedback which can be considered as an output that returns a response by producing a useful reference for the awareness of one's position in the environment (Park et al., 2022). Motion tracking can be further articulated according to how it is recorded (which can be done by video capture), thus recognizing the morphology of the subject in question or specific markers applied to it, alternatively, through special equipment composed of reference and recognition devices (sensors) that communicate with each other employing specialized signals such as infrared (Niehorster et al., 2017).

The force feedback aspect can be conceptualized by controlled impeding or slowing down of movements by means of special tools that act directly on the part in question. Control over mobility can be by mechanical action, electronically through servomotors, or by hybrid electro-mechanical means, for example through shafts or cables tensioned by servo-driven gears (Gu et al., 2016). In all these cases, the synchronization accuracy between position sensing and connected feedback is particularly important.

Cutaneous feedback is responsible for reproducing tactile sensations, including pressure, texture, puncture, thermal properties, softness, wetness, friction-induced phenomena such as slip, adhesion, and micro failures (Hayward et al., 2004), which are generally simulated by vibro-tactile stimuli. This output could be generated in many ways, the temperature information is generally conveyed by the Peltier cell, a thin thermoelectric system that exchanges heat when a direct current is applied, managing how cold or warm a surface is perceived (Gabardi et al., 2018). The predominantly shape-related material information is approximated through the action of mechanical pressures generated by dynamic elements moved by an actuator, while textures are simulated by vibratory waves that can be induced either by mild electrical stimulation and electronic oscillatory devices or, in the newer and still developing systems, through miniaturized electroosmotic pumps that push a fluid over a flexible membrane generating bubbles that stimulate the skin punctually (Shen et al., 2023).

Then, another important clustering operation involves the typology of the physical interface between haptic devices and the user, for this reason, it is possible to define three main modalities, bidimensional surfaces, joysticks and wearables. The branch relative to two-dimensional solutions encompasses devices that reproduce vibrotactile outputs on planar surfaces such as plates or displays (Kim & Hyun, 2023), whose function is to enrich digital content such as videos or reproductions in museum settings. The world of joysticks is wide and involves both the simplest video game controllers, those equipped with vibrations through the principle of rotating masses, and steering wheels for simulations in sim-racing, up to more sophisticated "pencil" systems useful, for example in freeform sculpting. In these cases, the interactive tool is connected to an arm or pantograph capable of providing force feedback (SensAble, 2017). The last category covers wearable devices, i.e., suits, helmets, and gloves that add to the virtual and haptic feedback experience the dimension of adherence to the body, with the added value of major immersiveness of the experience (*Haptic Glove for Virtual Reality with Force Feedback | TESLAGLOVE*, n.d.; *OWO*, n.d.; HaptiX, n.d.) (Fig. 1).

Concluding this bird's eye view of the state of the art of haptic feedback devices, the working team decided to proceed using the 'Weart Touch Diver' (*WEART Haptic Solutions | WEART*, n.d.), a system consisting of three rings capable of reproducing the pressure, vibration, and temperature cutaneous stimuli. The product is developed by an Italian company, in coherence with the master project goal, which presents a good potential/price ratio, and its strong point is its simplicity of use and configuration, which determined this choice.

Fig. 1: First test with WeArt touch Diver

3. Process demonstrator

The experimentation we are carrying out and presenting originates within a vast national project based on European funds with the extensive objective of exploring, collecting, and creating advanced and virtual practices, systems, and tools useful for the dissemination and practice of a more conscious and empowered design culture along all phases of the life cycle of the manufactured artifacts. The general vision is to disseminate a methodology of approach to design that is aimed at the perspective of the transition towards both digitalization and sustainability of processes, declined in the specific context of Made in Italy. Consistent with the framing, the current development prioritizes three of the four main areas of interest of Made in Italy, namely the "clothing-fashion" sector (A1), "furniture" (A2), and "automation-mechanics" (A3); the food sector is excluded as it is the center of a dedicated project. Within this framing, the research we are conducting focuses on the textile field, as it crosses the A1 and A2 fields; in particular, the effort is directed to the study and design of a workflow built on low-cost acquisition and restitution processes of fabric samples useful for structuring new modes of remote collaboration design.

The topic already sensitive by its nature, has received increasing attention in the recent period also because of the pandemic, in this context, particularly relevant is the study by Ornati, Kalbaska (Ornati & Kalbaska, 2022) according to which the garment communication strategies used by fashion brands during the pandemic were found to be effective even without tactile restitution tools and that these have important limitations while receiving support for their potential use in the future. In that particular demonstrator, however, flat, non-wearable devices had been used, hence the desire to undertake the following experimentation according to two distinct phases, the first one concerning the digital acquisition and the second one regarding the giveback rendering, both competing with the ultimate goal of structuring a digital twin database of textile samples that can be interrogated and exploited in collaborative design in virtual contexts.

3.1 Acquiring and reproducing the visual appearance of sample materials

There are innumerable shading models and methodologies for the reproduction of the visual appearance of digitized materials in a virtual environment. Among the various workflows, modern render engines allow users to import, create, manipulate, and visualize digitized materials with two main approaches based on different analytical models.

The first approach consists of embedding the highest possible amount of data acquired from the material sample into proprietary pre-packaged custom shaders, e.g. (*Chaos Scans - Chaos Scans - Global Site*, n.d.; X-Rite, n.d.) that are ready to import with minimal user interaction in the render engines that support them. These shaders are based on advanced analytical models such as the Bidirectional Texture Function (BTF) (Filip & Haindl, 2009). The pros are that they can reproduce more accurately the visual appearance of the material point by point at any angle of view and light condition, without needing to set up complex material networks, load texture maps, or tweak shader settings, and they should increase the consistency of results between one render engine and the other. The cons are that it is usually a more time-consuming and/or expensive solution because it requires the shipping of the material samples when the digitization is outsourced; or requires buying expensive advanced scanners and a proprietary application, e.g. (*TAC7 Webpage*, n.d.; Winter & Company, 2023) when the digitization is made in-house. Furthermore, the editing of the pre-packaged materials is usually much more complex (if possible, at all) and usually requires proprietary apps and can't be performed on the go into the render engine of choice. Examples of commercial solutions that adopt a scanner-based approach capable of outputting pre-packaged custom shaders with various degrees of accuracy are: the TAC7 scanner and digitization service by X-rite and Pantone (*TAC7 Webpage*, n.d.), the scanners and digitization service by Vizoo3D (*Vizoo - xTex Hardware Solutions for Scalable Material Digitization*, 2022), and the Chaos Scan digitization service (*Chaos Scans - Global Site*, n.d.)[1].

The second approach consists of converting the data acquired from the material sample into a series of texture maps that represent various optical properties of the material, based on one of the many models of Bidirectional Reflectance Distribution Function (BRDF), e.g., the well-known principled Disney shader (*Walt Disney Animation Studios - Physically Based Shading At Disney*, n.d.). The cons of this method are that all the BRDF models entail a certain degree of approximation (Ngan et al., 2005) and the results might be inconsistent from one render engine and the other based on which BRDF model is used; furthermore, the texture maps need to be correctly applied to the appropriate native shader of the software of choice to achieve the expected results. The pros are that this texture-based method is less costly since the textures can be produced by editing photographic images of the material without the need for advanced material scanners or software; the various optical properties can be easily tweaked by simply editing the textures with any photo-editing software or procedurally inside the render engine of choice in order to fix eventual inconsistencies in the case, for example, of uncalibrated displays or inaccurate behavior of the chosen render engine; lastly, the texture-based materials are more interoperable since all the most popular render engines support this kind of workflow while only a minority support pre-packaged proprietary custom shaders. In most contexts, such as that of the presented PNRR project, the benefits of this method outweigh its limitations. Examples of commercial solutions that adopt this approach are the software Substance Sampler and Substance Designer by Adobe which support a partially automated digitization workflow based on a low-cost DIY acquisition rig and single or multiple pictures taken with a single camera or smartphone (Adobe Substance 3D, n.d.), the opensource software Materialize by Bounding Box (Materialize, n.d.) and the software Pixplant5 (PixPlant, n.d.) which are capable of guessing the needed texture maps starting from one single image through a user-guided workflow.

Concerning the texture-based approach two main physically based workflows became a standard in the 3D graphics field: the metal/roughness (M/R) and the specular/glossiness (S/G) workflows (*PBR Textures Metallic vs Specular Workflow - A23D*, n.d.; *The PBR Guide - Part 2*, n.d.). Both of them are widely used, and despite the inevitable approximations, they are capable of qualitatively reproducing materials in a physically plausible way. Both of them use textures to describe the optical properties of the materials, some textures are common to both methods some are different. The textures that are common to both workflows are: the height (bump, displacement), the normal, the opacity (cut-out, alpha mask, occlusion), the emissive, the ambient occlusion, the absorption, the anisotropy, and the translucency. The maps that are exclusive for the M/R workflow are: the albedo (or base color), the roughness, and the metallic. The maps exclusive for the S/G workflow are: the diffuse, the glossiness, and the specular. In general, it is possible to convert the maps developed for one workflow to the other, however, in some cases, there might be loss of data. In fact, the S/G workflow allows the representation of a wider variety of materials, especially those that have diffuse and specular reflections of different colors. Despite this, since the S/G workflow is harder to set up, and since the materials with the described properties are much rarer in the real world, the M/R workflow has become more popular in today's rendering applications.

Given these premises, to fulfill the objectives of developing a low-cost acquisition procedure capable of producing interoperable digitized materials by acquiring fabric samples, without

[1] These scanners and services are capable to deliver digitized materials, not only in form of pre-packaged custom shaders, but also in form of textures but with loss of accuracy (as explained in the next paragraph).

relying on advanced or costly tools and technologies or specialistic training, aimed at the medium-small businesses of the Italian textile industry, we oriented toward the texture-based solution (with the M/R PBR workflow) because it fulfills all the requirements with minimal compromises.

3.2 Photometric stereo acquisition

The photometric stereo is a technique capable of interpreting the surface normals by acquiring the material sample from the same point of view under varying lighting conditions (Woodham, 1992). Various commercial and open-source apps capable of performing photometric stereo workflows were investigated for the extraction of the normal and albedo maps: Adobe Substance Sampler (*3D Capture Software - Adobe Substance 3D Sampler*, n.d.), Adobe Substance Designer (*3D Design Software for Authoring - Adobe Substance 3D*, n.d.) , Details Capture (*Details Capture | Photometric Stereo | VFX Grace*, 2021), Four-Light Imaging Simple (*Studio for Scientific Imaging and Archiving of Cultural Heritage | Munsell Color Science Lab | College of Science | RIT*, n.d.), and Relight (*Relight*, n.d.). The solution with the best quality/cost ratio which also allowed for complete control of the process and a transparent workflow was Relight by CNR. This open-source software was developed to create and view relightable images (RTI), nevertheless, it is also capable of extracting the normal map and the albedo map of the sampled surface. The authors of this paper collaborated with the CNR to implement Relight with new features or to simplify the use of the already existing ones, this process is still in progress. Unlike other apps, Relight does not impose to capture and upload a specific number of images but accepts any number of pictures with varying light and the same viewpoint, this allows the user to increase or decrease the number of images based on the required quality or the available acquisition time. Furthermore, it supports both light domes or handheld lights workflows, the former option requires building a light dome and calibrating the software based on the geometry of the dome, while the latter does not require any acquisition rig or calibration but requires capturing multiple chrome balls together with the material sample to infer the direction and distance of each light source.

The controlled procedure (Fig. 2) developed to acquire fabric samples with consistent qualitatively relevant results is explained in the next paragraphs. First, the setup for the acquisition is prepared as follows: (**1**) choose an environment that can be blacked out with curtains or shutters; (**2**) prepare a graduated base or ruler and place it on a planar surface free of obstacles around, it will serve later to set the scale of the digitized sample; (**3**) to acquire the translucency and/or opacity maps (alpha mask) orient a display horizontally on the plane facing upwards (e.g., a tablet or a laptop monitor); (**4**) disable the automatic turn-off timer and set the brightness to maximum; (**5**) set a white background; (**6**) for a better light diffusion from the display, place a sheet of white translucent paper on top of it, this helps to make the light diffusion more homogeneous and avoids the moiré effect that could be caused by the pixels of the display; (**7**) place the fabric sample to be acquired in the middle of the display; (**8**) for the identification of light sources place some chrome balls near the fabric sample, making sure to not cast shadows on the sample itself (we used four 15 mm steel bearing balls placed on four washers to keep them in place next to the corners of the frame); (**9**) for colour calibration place a small sized colour

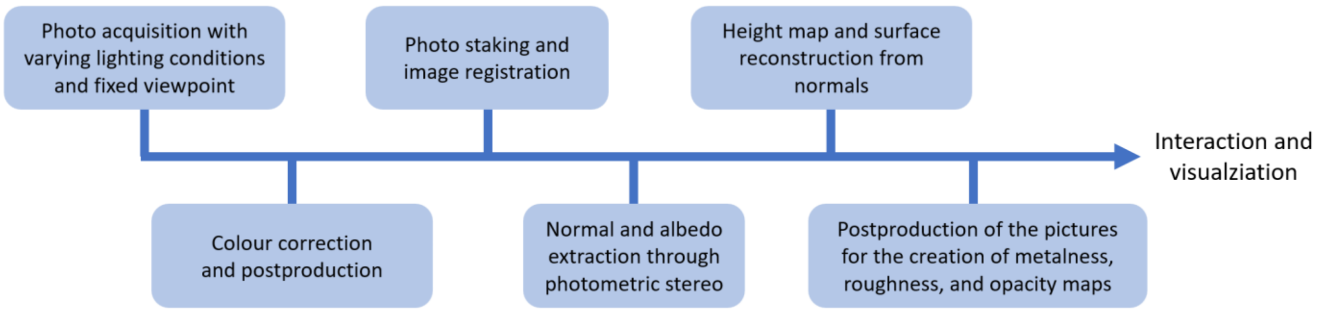


Fig. 2: Low-cost digitization workflow of samples of fabrics

checker in frame (we used the X-RITE Calibrite ColorChecker Passport); (**10**) alternatively if the colour checker is not available, it is necessary to correct at least the white balance by using a white reference surface; (**11**) ensure that the fabric is as flat as possible without wrinkles or folds; (**12**) place a camera on a tripod pointing downwards as parallel as possible to the sample surface; (**13**) choose a lens with minimal optic deformations if possible, a focal length greater than 50mm (full frame equivalent) is advisable; (**14**) prepare a white mobile light source, preferably between 5000 and 5500 Kelvin (e.g. the flash of a mobile phone or a handheld wireless flash are good options); Fig. 3 shows the setup.

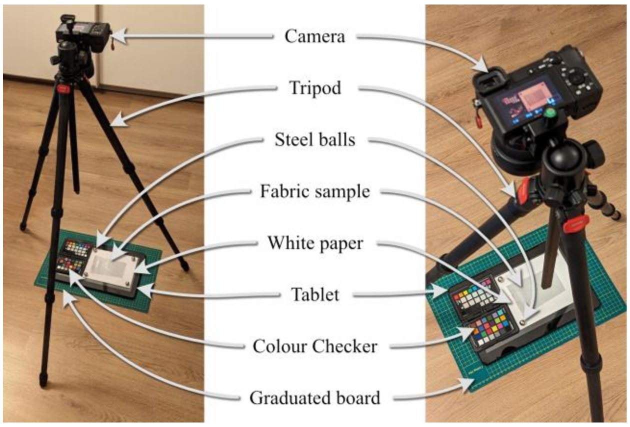


Fig. 3: Fabric acquisition setup

Once the equipment is positioned it is crucial to not move it anymore for the rest of the acquisition phase to avoid misalignments. The next phase is the preparation of the camera: (**1**) Set it in manual mode; (**2**) set the white balance to manual (it is advisable to perform an in-camera white balance calibration if available); (**3**) set a shot delay of at least two seconds, and set the silent shooting mode, to avoid vibrations (when using a shutter remote, the shot delay is not needed, but the silent shooting is still advisable); (**4**) activate the histogram to check the exposure; (**5**) set the aperture to values that allow to focus both the spheres and the sample (values greater than f3 are suggested); (**6**) set the ISO to the minimum native value; (**7**) adjust only the shutter speed to expose the photo correctly (try to maximize the use of the available dynamic range without clipping); (**8**) check the exposure by illuminating the fabric sample with only the handheld light placed at the expected distance (after turned off all the other lights and blacked out the windows); (**9**) Adjust the focus manually in order to focus properly the sample and the spheres (use the camera focus peaking feature if available); (**10**) take some test shots and inspect them using the zoom function; (**11**) it's advisable to shoot in RAW for a better post-production; (**12**) all these steps can be performed also with a smartphone instead of a camera as long as the manual camera settings are available. Fig. 4 shows two test shots to check the focus and exposure under the various lighting conditions.

The third phase is the acquisition of the sample: (**1**) black out the windows, turn off every artificial light in the room except for the display (tablet) with the white background; (**2**) take a photo under these lighting conditions making sure to expose properly the sample, then turn off the white screen being careful not to move the fabric sample; (**3**) turn on the handheld light and point it

Fig. 4: Test pictures to check the focus and the exposure of the sample under various lighting conditions

at the fabric sample at a defined distance (a distance between 40 and 80 cm is advisable); (**4**) to help positioning the light a string of a known length can be attached to the light and tensioned towards the fabric sample (be careful not to touch the fabric sample); (**5**) start taking pictures with the light at a very low height pointing toward the fabric sample (10 or 20 cm from the sample plane) and move the light in circle around the sample, maintaining the same height, taking a photo for each new positioning of the light; (**6**) reposition the light every 45 degrees of rotation around the Z-axis (imagine a compass rose placed on the ground and cantered on the sample, position yourself on the North and proceed clockwise: N, NE, E, SE, S, SW, W, NW); (**7**) after one full rotation, repeat this process by increasing the height of the light and its angle with respect of the horizontal plane but same distance from the sample (in our testing we performed 3 rounds of 8 pictures for a total of 24 pictures, more picture could give better results but are suggested only for particularly complex cases, e.g., very glossy surfaces); (**8**) at the end of the acquisition the captured set should have evenly distributed lights on a hemisphere centred in the middle of the sample; (**9**) it has been observed that, on average, 24 shots produce optimal results, but even with just 4 photos satisfactory results can be obtained (therefore in case of limited time, and when a certain quality loss is acceptable, it is possible to decrease the number of photos to 4, positioning the light at the four cardinal points, with an angle between the lights and the support plane of about 45 degrees).

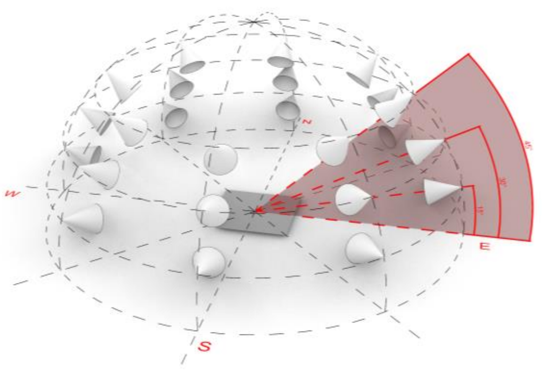


Fig. 5: The suggested light layout around the sample

Fig. 5 shows the distribution of the 24 lights around the sample.

Next, the pictures are postprocessed in order to extract the texture maps. (**1**) If a colour checker was used, perform colour calibration of the raw files, we used the opensource software dark table (*Darktable*, n.d.), if no colour checker was used just perform the white balance by sampling a white or neutral grey surface; (**2**) register the pictures in order to reduce as much as possible eventual misalignments due to shutter or tripod vibrations, we are currently testing various scripted solutions (Pizenberg et al., 2021) that will be integrated in Relight in a future update, but any photo editing software with photo staking function (such as Adobe Photoshop *Trasforma le foto e crea grafiche di grande impatto | Adobe Photoshop*, n.d.) would give similar results[2] (if the pictures were acquired via shutter remote and no relevant misalignment is observed this step can be skipped); (**3**) import uncropped calibrated pictures in relight (if the shots are cropped the focal length estimation will not work properly) do not import the picture with back light, because this will be used only for the production of the alpha mask and will not serve to the photometric stereo process; (**4**) manually mark the chrome balls (if the spheres projections are noticeably elliptical due to short focal lengths being used, five points or more can be used in order to fit an ellipse rather than a circle, to improve the estimation of lights direction); (**5**) scale the image by marking the reference graduated plane or ruler; (**6**) run the algorithm that estimates the light position (which works by cross-referencing the hotspots on each sphere picture-by-picture); (**7**) Save the RTI file and export the normal map and the albedo map; (**8**) for the fabric samples that require it, extract the alpha mask from the single backlight picture with any photo editing software by simply converting it to black and white, inverting the colours, and setting the proper contrast in order to make the sample fibres pure white and the backlight pure black, in case of translucent cloths the alpha mask contrast and colour range can be tweaked directly into the rendering software; (**9**) the missing metallic and roughness maps at the moment are extracted by converting the albedo map in black and white and tweaking the contrast and exposure qualitatively

[2] The photo stacking of normal photo editing applications sometimes might give unexpected results because, in a photometric stereo set of pictures, the shadows change in each picture which might cause registration errors, if the fabric sample has a high contrast printed pattern this problem is mitigated.

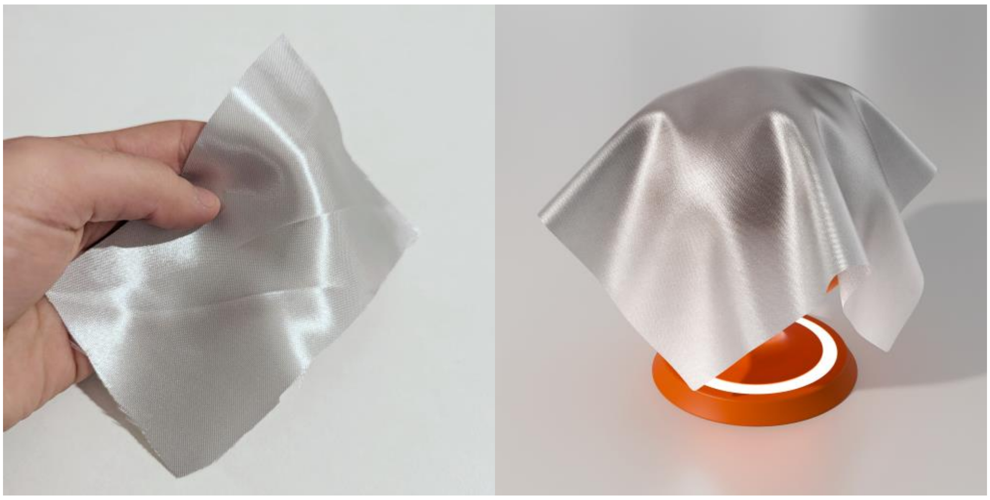


Fig. 6: Silky translucent fabric test sample. Left real sample, right simulated sample (Blender cycles)

Fig. 7: Textured woven fabric sample test. Left real sample, right simulated sample (Blender cycles)

by comparison with the real sample looked at various angles and under varying light conditions. This last step is empirical, however, for visualization purposes, the current qualitative method proved to produce sufficiently reliable results for fabric samples since the roughness and metalness are rarely complex to simulate. Furthermore, even with textures acquired with more advanced scanners, real-time render engines such as those used in VR environments often require tweaking these textures manually anyway, since the BRDF functions of each render engine work slightly differently despite using the same texture maps. Fig. 6 and Fig. 7 show the comparison between the real fabric sample and the simulated one (rendered with Blender Cycles).

3.3 Qualitative assessment of the normal map acquisition through photometric stereo

The photometric stereo technique in this context is only used for the acquisition of the albedo and normal map. None of these maps are used to 3D model the actual geometry of the fabric, they are only used to describe the visual appearance of the material. Nevertheless, a qualitative assessment of the normal map accuracy is still useful to demonstrate the robustness of the achieved result.

To do that, two ground truth meshes were 3D modeled and 3D printed. Then the 3D printed models were acquired through the photometric stereo method described (Fig. 8). The normal map acquired with the photometric stereo technique is converted into a mesh surface through Bilateral

Normal Integration (Cao et al., 2022) and compared with the ground truth geometry (Fig. 9).

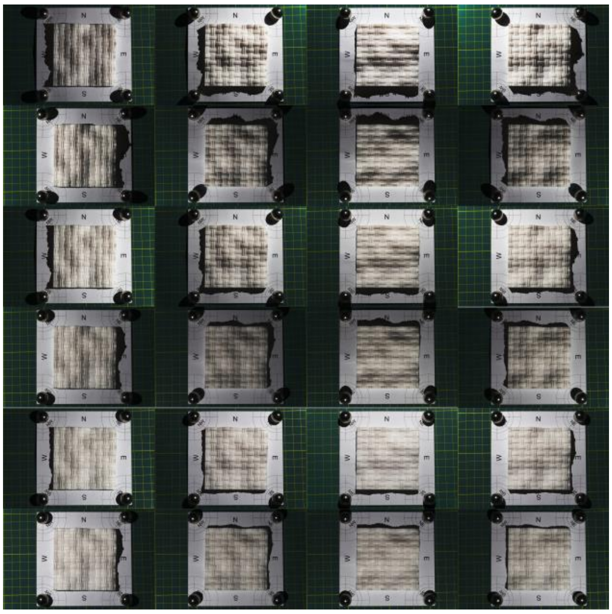


Fig. 8: photo set of the displaced 3D printed model.

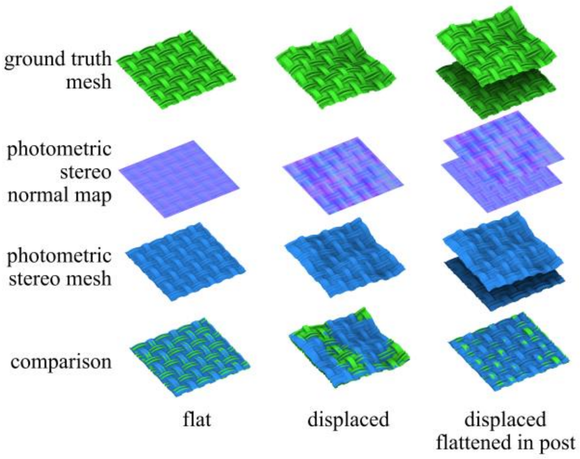


Fig. 9: Comparison between ground truth 3D models and output geometry acquired through photometric stereo.

The photometric stereo technique is known to produce more or less dimensionally inaccurate results due to various boundary conditions and biases. Nevertheless, despite some dimensional inaccuracies of the lower frequency geometric details (e.g. bumps, folds, creases, etc.), this assessment demonstrates that the higher frequency details (e.g. threads) are acquired accurately and consistently locally. Higher frequency protrusions and cavities are never flipped or completely flattened out thus the acquired normal map is consistent with its real counterpart locally, when no undercuts or vertical discontinuities are present. The ability to acquire very fine details (e.g., the threads) consistently up to the resolution of the used camera, added to the fact that the fabric samples do not have undercuts or vertical discontinuities, and low-frequency deformations are not relevant, proves that this technique is a robust choice for the acquisition of fabric samples for visualization purposes.

3.4 Haptic glove restitution environment

When the acquisition and postprocessing of the textures is completed, the virtual scene can be set up. The use of the Unreal engine (Unreal engine, n.d.) was chosen for this test in order to contain the complexity of software management and ensure a more stable interface with the haptic glove. In this regard, the proprietary development kit of WeArt (*WEART Haptic Solutions | WEART*, n.d.) was implemented to enable the communication of the scene with the device and to simplify the preparation of the haptics of the scene, always keeping in mind the main goal of making the proposed workflow as intuitive and usable as possible.

The haptic environment was created as follows: (**1**) creating a new scene by selecting the canvas dedicated to virtual reality; (**2**) editing or creating the scene by setting the environment and inserting the virtual objects of interest; (**3**) assigning a material for each object. Up to this point the procedure has no discrepancies from canonical virtual modeling operations, but at this point the process begins to specialize as follows: (**4**) for each shape that is to be made perceivable we need to select it and add the touchable object component integrated thanks to the SDK; (**5**) next we need to add the object collider component and modify its geometry so that it accurately matches the mesh state; (**6**) then enable the option that allows "dynamic events" thus enabling object collision detection; (**7**) open materials configuration panel and insert the images derived from the acquisition progress into the respective slots, albedo, normal map and possibly roughness & metallic and proceed with parameter adjustment until the desired rendering is obtained (Fig. 10); (**8**) open the touchable object panel and assign a reference material, to which a vibration sampling will correspond; (**9**) adjust the temperature, intensity, and speed parameters until feedback consistent with the set texture is obtained (Fig. 11); (**10**) from the "content drawer" panel, add the appropriate object required for

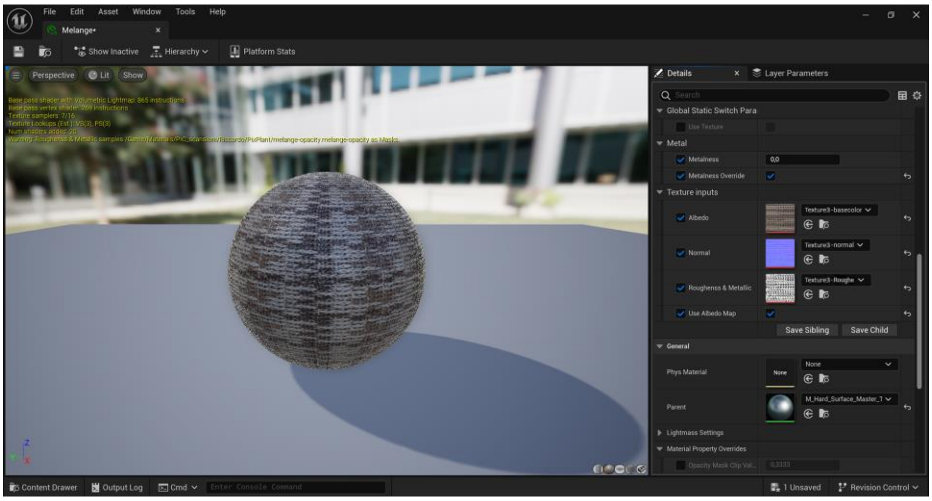


Fig. 10: Material set-up panel (step 7)

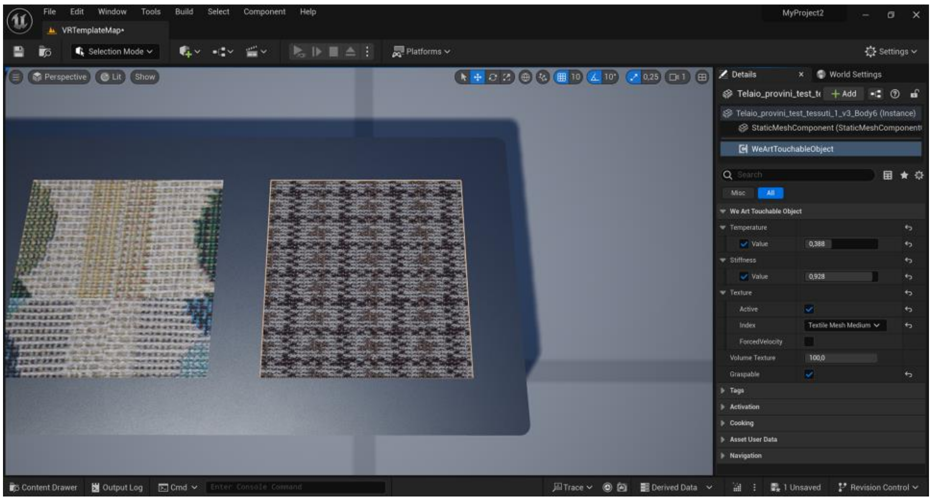


Fig. 11: Touchable object set-up panel (step 8 & 9)

glove calibration to the scene input and virtual experience.

Currently, the scene was set up with materials of different natures, the test object thus containing one fictional material native to the software and used as an easy-to-set-up material reference, two materials derived from scans with XTEX (*xTex Website*, n.d.) used as reference standards for rendering, and two materials derived from the proposed low-cost acquisition process. In order to simplify the process and reduce the necessary user interactions with the model, a workflow that heavily exploited the presets available in the proprietary plugin was tested in favor of a qualitative material adjustment process that leveraged user experience through a comparative process between virtual material vision, real touch, and haptic rendering. The current outcomes achieved, present a good visual rendering quality of the acquired materials, but an early stage haptic interaction, nevertheless it confirms a relevant potential for further development. Specifically, temperature and intensity can be easily perceived and set, however, the vibrotactile pattern that characterizes each material, at the moment, can only be set by comparison through a qualitative assessment, imposed by the proprietary implementation of the glove in Unreal Engine which does not allow for a more articulated elaboration.

3.5 Haptic feedback test

To gather data and feedback for initial evaluations, a comparative test between a real environment and a virtual environment was designed, for each of which a frame was constructed to hold four fabric samples in a stretched and static condition for comparison. Among the available physical fabrics, four samples were selected by balancing material diversity with surface texture similarity, resulting in the choice of a red cotton jersey, an embroidered open-knit fabric, a white silk, and a fine houndstooth knit.

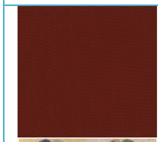
The four fabrics were subsequently sampled to be incorporated into the virtual counterpart. The first two were digitized using commercial software xTex to establish the target quality level, while the latter two were digitalized using the acquisition workflow proposed and developed during this research to understand the discrepancy between the two solutions. The initial phase involved seven users who were not textile experts but were proficient in virtual reality to understand the potential of the prepared environment without the hindrance of unfamiliarity with the equipment. The test was divided into two phases: in the first phase, users were asked to wear a haptic glove on one hand and touch the virtual samples while touching the physical fabrics with the other hand, and then they were asked to associate each virtual texture with the correct physical sample without looking at the appearance of the real counterpart and the digital one as well. To do so the textures were removed from the digital counterpart and only the haptic feedback was left enabled. In the second phase, the samples were mixed and the textures on the digital samples were re-enabled, users had to touch both the virtual and physical samples and associate them without looking at the physical samples but looking at the virtual ones ony, through an HMD. A summary of the collected results is shown in Table 1 (numbers represent the correct guesses).

Tab. 1: Haptics trial results

User	Haptic recognition	Visualization recognition
Tester_01	2/4	4/4
Tester 02	2/4	2/4
Tester 03	2/4	4/4
Tester 04	1/4	4/4
Tester 05	2/4	4/4
Tester 06	4/4	4/4
Tester 07	1/4	2/4

The findings from this initial trial phase indicate that the haptic rendering needs further development before the experience can be administered to a more significant and representative sample. However, the results can be considered positive and encouraging as this experiment deals with one of the most complex and challenging areas for tactile simulation; fabrics, due to their consistency, texture detail, and behavior upon interaction, are among the most intricate to reproduce.

Tab. 2: Fabric samples

Texture	Tissue	Acquisition
	S_01 Fabric	xTex
	S_02 Embroidered	xTex
	S_03 Silk	Proposed
	S_04 houndstooth	Proposed

Specifically, the data from the first test highlight the main difficulty in distinguishing between samples S_01 and S_04 (refer to Table 2), as they correspond to the most similar vibratory styles in amplitude and frequency. Additionally, another observed element is how the failure to associate the previous samples impacts other associations, necessitating a rethink of the most effective strategy for ordering the sample administration. The last aspect related to the first test, which introduces the results of the second one, is that the extreme results, both negative and positive, are proportional and dependent on the tester, indicating that subjective sensitivity was a significant element. This suggests that involving more experienced individuals in both the setting and testing phases could ensure more accurate results. Regarding the second phase, excluding the issue of personal sensitivity, very positive results were obtained, showing no significant qualitative discrepancies between the standard and tested acquisitions. Further evidence of this is that the six errors made were attributable to one of the two acquisition methods used. Fig. 12 shows the scheme of the setup for the visual-haptic-responsive VR environment.

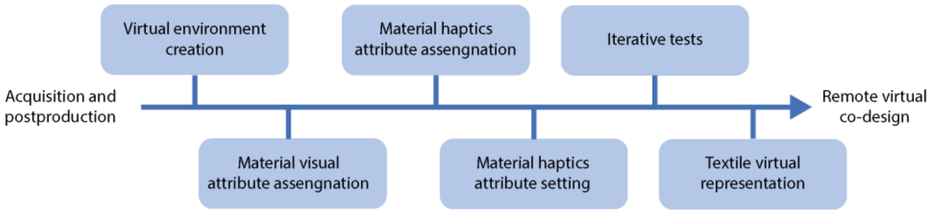


Fig. 12: Scheme for the setup of the visual-haptic-responsive VR environment

3.6 Haptics render implementation

The preliminary testing of the haptic feedback provided by the gloves highlighted promising potentialities, however, since the vibrotactile patterns of each digitalized sample were set by a qualitative assessment, based only on a critical comparison with their real counterpart, reduces reproducibility and embeds inevitable criticalities and biases. For this reason, future work already ongoing is aimed at automating the acquisition and implementation of custom vibrotactile feedback for each sample.

Two possible ways have been identified, the first possibility is to cross-section the height map of each material object of study, to obtain a two-dimensional profile useful for creating a wave audio file that will be used as input for the blueprint responsible for activating and controlling the haptic feedback.

Alternatively, in the case of fabrics, the proper vibrotactile frequency could be automatically inferred by sampling a small portion of the acquired fabric, measuring the distance between threads, and calibrating the vibration wave proportionally to the measured distance.

This implementation aims to increase the controllability and reproducibility of the process, overcoming the typical "black box" limitations otherwise present in proprietary software.

This would also allow for the exploration of other issues that have emerged from this initial experimentation such as the management of edge perception, which is currently lacking, and especially the creation and management of anisotropic fabrics that can exhibit different vibrotactile feedback depending on the direction of touch movement.

3. 7 Implications for the surrounding productive tissue

Even though the project is mainly related to the fashion field, it is a work designed with a transversal perspective. The skills learned and the outcomes could be shared in other fields in full view of technological and knowledge spillover.

For example, the furniture sector (A2), could benefit from this project, e.g., in the Romagna area an important district related to upholstered furnishings could inherit an archive infrastructure and workflow very similar to those currently being developed. At the same time, the automotive world (sector A3), which is increasingly approaching these solutions to anticipate customer interactions and to ensure increasingly better-personalized experiences, could also benefit from figures who can skillfully manage and manipulate haptics in a virtual environment, to increase the potentialities and perceived qualities of the digital assets that this field is already used to create and maintain. These are just two examples of interest as they relate to the excellence of Made in Italy and specifically to the fields of study under consideration for the master project. Other possible stakeholders may come from the museum and education field where there are already successful experimentations concerning virtual reality using digital assets; in this context, any study bringing forward the field could add value both from the learning point of view and the social and inclusiveness point of view. Another possible field where this project could be of great interest is in the area of skills assimilation for industrial automation (sector A3); the familiarization and use of haptic devices in this field could help to structure virtual training experiences that are increasingly immersive and exploit the principle of learning by doing and motor memory to facilitate the internalization of knowledge and procedures.

4. Conclusion

The work has reached the minimum TRL3 required and its advancement will continue in parallel with the other activities of the main PNRR MICS project, determining future steps as a result of the main research developments. Moreover, the output will be available on an open-source platform dedicated to the MICS partnership. First of all, the experimentation and tests conducted demonstrate the feasibility of the workflow and validate its conceptualization of the process. The tools used so far have proven to be suitable for the designed tasks, although their use needs to be carried out with the necessary care in order to ensure their good performance and stability. As mentioned in the course of the contribution, there is no lack of critical issues, and it is towards these that future developments are targeted. In particular, on the topic of acquisition, the tiling of the acquired texture, and the extraction of metalness and roughness maps is performed manually in third-party photo editing applications, however, we are in the process of implementing Relight software to create a single environment suitable to accommodate the entire acquisition and editing process. Furthermore, in the area of haptic restitution, the topic of automating the translation of tissue to vibration pattern will be central in the process of remote interaction with digitalized tissue samples.

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