Guest Editorial
Haptics in the Metaverse: Haptic Feedback for Virtual, Augmented, Mixed, and eXtended Realities

I. Introduction

IN THE last few years, we have witnessed the rapid development of many innovative devices and original techniques for providing haptic sensations, e.g., using force feedback, mid-air interfaces [1], [2], props and encounter-type devices [3], [4], or exploiting perceptual phenomena with cross-modal effects such as pseudo-haptics [5]. While increasingly immersive and realistic experiences have developed at a fast pace, the emergence of a "metaverse" proposes new use cases where prolonged utilisation and social interactions become more frequent and widespread [6]. The metaverse definition is continuously evolving, however, for now it can been seen as a collective virtual shared space, created by the convergence of the physical and digital worlds, where users interact, socialize, and engage with each other through digital representations of themselves. This new direction in social interactions presents the haptics community with new challenges and opportunities. Indeed, as eXtended Reality (XR)[1] technologies continue to gain traction in various fields, the role of haptic feedback and feedforward in enhancing such experiences have become increasingly evident. This growing significance is reflected in the proliferation of research efforts and the emergence of dedicated haptic designs, tools, and rendering techniques. Never before have tactile actuators found such proliferation in 3D applications, akin to that experienced in the early days of smartphones.

This special issue is dedicated to exploring the multifaceted realm of haptics tailored to XR environments, including Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). The collection of studies presented here represents a diverse array of topics and approaches, each contributing to our fundamental understanding of haptics in the context of such immersive technologies. Some of the featured research found in this special issue delves into the theoretical foundations of haptics in XR, unveiling the complexities of human haptic perception, touch, and proprioception. Understanding how users perceive and interact in virtual environments is paramount to crafting truly immersive experiences that mimic the sense of touch and presence of the real world. In parallel, other contributions focus on the practical aspects of haptic interface design, exploring new methods, principles, and guidelines to create more effective and intuitive haptic interactions. These studies aim to strike a delicate balance between providing realistic touch sensations and ensuring comfortable, ergonomic, and user-friendly haptic devices. A significant portion of this special issue is dedicated to the advancements in haptic actuation and sensing technologies. From traditional vibrotactile actuators to more sophisticated systems like ultrasound, electrostatic, piezoelectric, and magnetic actuators, researchers have been striving to create more versatile, precise, and responsive haptic feedback mechanisms that align seamlessly with multimodal and multisensory virtual and augmented realities. Finally, as XR technologies find applications in a wide range of industries, this special issue showcases novel haptic approaches tailored to specific domains. Whether it be industrial training or artistic expression, these studies demonstrate the adaptability of haptic interfaces to diverse applications and contexts.

We believe that the research presented in this special issue will not only advance our knowledge of haptics in XR, but will also inspire further innovation and foster cross-disciplinary collaborations. As technology continues to push the boundaries of what is possible in the realm of virtual and augmented reality, haptic interfaces will play an increasingly pivotal role in shaping the future of immersive (social) experiences.

We have received many exceptional submissions for this special issue, indicating the research community's profound enthusiasm for haptics in such a field. Our gratitude goes to the Editors in Chief, Domenico Prattichizzo, Seungmoon Choi, and Marcia K. O'Malley, for their support to the success of this topic. Additionally, we extend our heartfelt appreciation to the numerous reviewers who contributed high-quality and timely reviews. Lastly, we would like to express our thanks to Shivam Sony, a member of the ToH editorial staff, for his precious assistance throughout the publication process. We hope that this collection of 14 research papers will serve as a valuable resource for researchers, practitioners, and enthusiasts, driving us all closer to a more haptically enriched virtual and augmented world.

II. Haptics in the Metaverse

Haptic sensations play a foundational role in shaping the user's immersive experience when engaging with eXtended Realities (XR). However, the metaverse has introduced several new dimensions including that of social interactions and environments [7]. The concept of metaverse, popularized by science fiction and now rapidly evolving in the real world, envisions a seamless and interconnected network of virtual worlds,

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[1]We use the term eXtended Reality (XR) to encompass Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) dimensions.

augmented realities, and XR experiences. In the metaverse, users can traverse different virtual environments, engage in various activities, and interact with a global community of individuals. From the very first use of the term "metaverse" in 1992 [8] and its early implementations such as Active Worlds (1995) or SecondLife (2003), haptic sensations in the metaverse have been mostly neglected.

This rapid re-emergence of the metaverse concept in 2021–2022 with advanced platforms such as Meta Horizon Worlds or Roblox, presents the haptics community with both exciting opportunities and unique challenges [9]. As the metaverse encourages prolonged utilization and social interactions that may rival or even surpass physical reality, haptic feedback becomes even more critical. The ability to touch, feel, and interact with virtual objects and other users within the metaverse has the potential to elevate the sense of presence and realism, deepening the emotional connection and immersion for participants. Including touch sensations in the metaverse experience is expected to lead to a more engaging and captivating virtual environment. Such haptic interactions can create a more authentic and natural experience, fostering a stronger sense of embodiment and connectivity among the users. Additionally, haptics can enhance communication and expression within the metaverse. Subtle haptic cues, such as a gentle touch or a reassuring pat, can convey emotions and intentions that might be challenging to express solely through visual or auditory means. As social interactions form a significant part of the metaverse experience, haptic feedback has the potential to enrich these encounters and establish more profound connections between users. Introducing touch sensations and realizing the above benefits in the metaverse comes with many challenges. The technology needs to be seamless, responsive, and scalable to accommodate a potentially vast number of users interacting simultaneously. Additionally, we also face the same challenges of other application scenarios with respect to introducing haptics, e.g., expensive devices, limited comfort of use, low generalizability of the rendering techniques, limited multisensory capabilities. Achieving this level of sophistication requires innovative haptic devices, authoring tools, and interaction techniques, which can adapt to different virtual scenarios and user preferences, able to provide a wide range of sensations in an inexpensive and comfortable package. Despite the great effort of the research community, we are still rather far from achieving these objectives. Furthermore, there is a need to establish standards and guidelines for haptic interactions in the metaverse, also with respect to the safety of the interaction. Finally, we require more evidence in the form of qualitative and quantitative metrics, showing the effectiveness of haptics in this context as well as guiding research in the correct direction.

The metaverse presents an exciting frontier for haptic technologies, where the fusion of immersive experiences and social interactions opens up a realm of possibilities. As this field evolves, the haptics community must seize the opportunity to shape this virtual landscape by integrating haptic feedback in a way that enhances the sense of presence, fosters social connections, and empowers users to fully engage and interact with the digital world in a safe and positive way. Through such innovation, haptics can play a vital role in creating a metaverse that blurs the lines between reality and imagination, transforming the way we experience and interact with virtual realms and with each other.

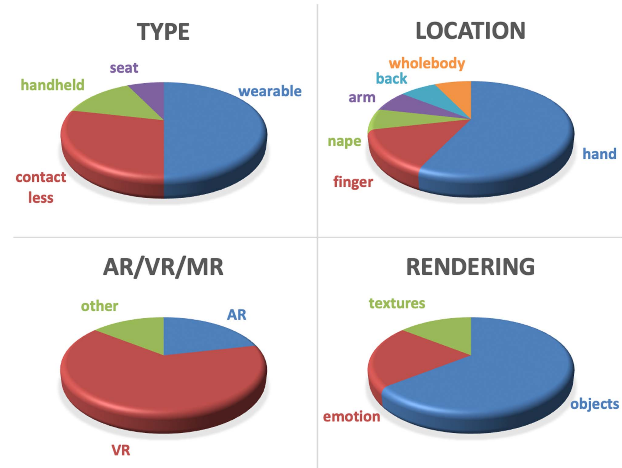

Fig. 1. Proportions of accepted papers that address different type of haptic devices, target different locations on the body, are applied in conjunction with XR content, and attempt to render different tactile effects.

With these challenges and opportunities in mind, and knowing that haptics research papers are published in a viariety of journals and conferences that cover the highly interdisciplinary topic that is the metaverse, this special issue was launched in mid-2022 and completed in 2023, with the aim to harbour a sample of papers that advance haptics in the metaverse. Four cross-sections of the issue are presented in Fig. 1, from which we can identify that: half of the published papers focused on wearable haptic technologies; most papers target haptics on the hand, most applications involved VR, and most haptic effects involved the rendering of objects. Next, we take a closer look at the content of the special issue.

III. Contents of the Special Issue

A total of 14 papers have been published in this special issue, and we present them below under three main areas, namely, technology and design (5 papers), perception and user experience (5 papers), and application and use in relevant scenarios (4 papers).

A. Technology and Design

The first set of papers in the special issue concerns the technology and design of haptic interfaces. The article "A Wearable Haptic Device for the Hand with Interchangeable End-Effectors" by Lisheng Kuang, Marco Ferro, Monica Malvezzi, Domenico Prattichizzo, Paolo Robuffo Giordano, Francesco Chinello, and Claudio Pacchierotti [A1] presents a versatile 4-DoF hand wearable haptic device designed for Virtual Reality (VR). This device incorporates interchangeable end-effectors, allowing for a wide array of haptic sensations. Demonstrating its efficacy through VR interactions, this study showcases the device's ability to render interactions with diverse virtual objects. In a distinctive approach, "Contactless Electrostatic Piloerection for Haptic Sensations" by Naroa Iriarte, Inigo Ezcurdia, Sonia

Elizondo, Josu Irisarri, Daria Hemmerling, Amalia Ortiz, and Asier Marzo [A2] explores inducing tactile sensations using contactless electrostatics. Their work involves developing high-voltage generators and examining human body sensitivity to electrostatic piloerection. This technology, integrated with a head-mounted display, augments virtual experiences linked to fear, potentially enriching entertainment media. “Haptic Magnetism” by Tor-Salve Dalsgaard, Kasper Hornbæk, and Joanna Bergström [A3] introduces an unconventional modality for tactile stimulation. This concept delivers sensations of distant objects through pseudo-magnetic attraction and repulsion, expanding the possibilities for the use of haptics. Their studies illustrate the feasibility of this novel approach and its implications in guiding movements and revealing affordances. Furthering the exploration of haptic design, “RecHap: An Interactive Recommender System For Navigating a Large Number of Mid-Air Haptic Designs” by Karthikan Theivendran, Andy Wu, William Frier, and Oliver Schneider [A4] contributes an extensive corpus of mid-air haptic designs. This work introduces a design tool employing a neural-network-based recommendation system, facilitating the exploration and realization of diverse haptic sensations for designers at various skill levels. Addressing the realm of perceptual illusions, “Soft Pneumatic Haptic Wearable to Create the Illusion of Human Touch” by Aishwari Talhan, Yongjae Yoo, and Jeremy R. Cooperstock [A5] addresses the challenge of delivering human-like touch sensations in virtual reality. Their approach uses soft pneumatic actuators within a wearable jacket to simulate realistic touch gestures, enhancing immersive experiences in VR environments.

B. Perception and User Experience

Another group of papers delves into the perception aspects of employing haptics and how they affect the user experience. The paper entitled “Validation of a Soft Pneumatic Unit Cell (PUC) in a VR experience: a comparison between vibrotactile and soft pneumatic haptic feedback” by Femke E. van Beek, Quinten P. I. Bisschop, and Irene A. Kuling [A6] delves into the field of Virtual Reality (VR) applications. This study investigates the efficacy of a fully soft Pneumatic Unit Cell (PUC) in a VR button task, demonstrating its potential for haptic feedback in VR environments. Results showcase that both vibration and PUC feedback reduced participants pressing through the back of buttons, indicating their effectiveness in creating virtual button clicks. Still leveraging vibrations, “Phantom illusion based vibrotactile rendering of affective touch patterns” by Robert Kirchner, Robert Rosenkranz, Brais Gonzalez Sousa, Shu-Chen Li, and M. Ercan Altinsoy [A7] explores the plausibility of recreating affective touch patterns using vibration. This study introduces a haptic armband array to investigate the recreation of affective touch patterns via vibration, demonstrating high plausibility ratings in user studies and affirming the expressiveness of the system in rendering social affective touch in Virtual Reality. “Perceived realism of virtual textures rendered by a vibrotactile wearable ring display” by Rebecca Fenton Friesen and Yasemin Vardar [A8] addresses perceptual sensitivity to dynamic changes in actuation during active movement. The study investigates different methods of modulating vibrations and their impact on perceived realism of virtual textures. Results highlight the influence of modulation type on sensations for different textures, providing insights into creating realistic virtual textures via wearable haptic displays. Moreover, “Perception of soft objects in virtual environments under conflicting visual and haptic cues” by Cagatay Basdogan, Berke Ataseven, and Mandayam A. Srinivasan [A9] examines the perception of soft objects in virtual environments. Their work demonstrates that manipulating the relationship between visual and haptic cues expands the range of object stiffness that can be effectively conveyed to users in virtual environments, enhancing the fidelity of soft object perception. Lastly, “It sounds cool: exploring sonification of mid-air haptic textures exploration on texture judgments, body perception, and motor behaviour” by Roberto Montano-Murillo, Dario Pittera, William Frier, Orestis Georgiou, Marianna Obrist, and Patricia Cornelio [A10] investigates the combined effect of mid-air haptic textures and congruent sound feedback. Results suggest that audio cues influenced participants’ judgment of texture attributes and implicit motor behavior during haptic exploration, emphasizing the potential of audio-haptic associations in creating embodied experiences in emerging application scenarios in the metaverse.

C. Applications and Use in Relevant Scenarios

The last group of papers in the special issue focuses on applications of haptics. Unnikrishnan Radhakrishnan, Lisheng Kuang, Konstantinos Koumaditis, Francesco Chinello, and Claudio Pacchierotti’s study on “Haptic feedback, performance and arousal: a comparison study in an immersive VR motor skill training task” [A11] ventures into the realm of fine motor skill training in Virtual Reality (VR). Their investigation of the relationship between haptic feedback and physiological arousal during motor skill tasks showcases the potential of haptics in such tasks. The findings highlight the nuanced interplay between haptic feedback and arousal, opening new avenues for enhancing motor skill training experiences in VR environments. In a parallel work, Robert Rosenkranz and M. Ercan Altinsoy delve into the perceptual plausibility in haptic virtual reality in their paper titled “A Perceptual Model-Based Approach to Plausible Authoring of Vibration for the Haptic Metaverse” [A12]. Their work challenges the notion of replication of real-world vibrations in VR, proposing a novel generative model-based approach for authoring vibrations that align with user expectations. By shaping vibrations based on users’ sensory tactile profiles, this approach promises to heighten plausibility without requiring real-world recordings, paving the way for more crowd-sourced and user-informed haptic experiences in the metaverse. Erwan Normand, Claudio Pacchierotti, Eric Marchand, and Maud Marchal contribute to the exploration of visuo-haptic rendering in augmented reality in their paper titled “Visuo-haptic rendering of the hand during 3D manipulation in Augmented Reality” [A13]. Their research investigates the impact of visuo-haptic rendering on hand manipulation in AR applications. By analyzing the effects of visual hand rendering and delocalized vibrotactile haptic feedback, their study sheds light on optimizing rendering positions and techniques to enhance the perceived effectiveness and realism of hand manipulations in AR environments. Finally, Anany Dwivedi, Shihan Yu, Chenxu Hao, Gionata Salvietti, Domenico Prattichizzo, and Philipp Beckerle's study, "How Positioning wearable haptic interfaces on the body and its effect on virtual limb embodiment" [A14], delves into the influence of wearable haptic feedback devices on the embodiment of virtual hands. Their findings suggest that the placement of haptic feedback devices does not significantly affect embodiment, but the synchronicity of feedback delivery plays a crucial role. This highlights the potential for wrist-based haptic devices in providing unobstructed hand visibility for improved interaction and motion tracking, essential for precision in pick-and-place tasks.

IV. Conclusion

The compilation of studies presented in this special issue showcases the evolving landscape of haptic feedback in the context of virtual, augmented, and extended interaction. These contributions unveil pivotal directions in haptic research, where advancements converge at the intersection of technology, perception, and user experience. Researchers across these studies have demonstrated a shared commitment to addressing the inherent limitations of haptic interfaces and rendering techniques, paving the way for innovative solutions that transcend traditional barriers (simplicity in utilisation, applicability over haptic field, exploitative investigations). Their efforts underscore a deeper comprehension of the perceptual underpinnings of haptics, leveraging cutting-edge design and manufacturing techniques to overcome some of the inherent constraints of haptic systems. The interdisciplinary nature of this field continues to drive progress, as collaborative endeavors between mechatronics, ergonomics, robotics, and perception yield multifaceted insights. The surge in applications across serious gaming, rehabilitation, training, and immersive scenarios experiences highlight the escalating demand for rich haptic solutions, further stimulating advancements in this dynamic field, especially with respect to tactile/cutaneous haptic technologies.

Indeed, local (tactile) stimulation, if provided coherently with the other senses, can be as compelling as more standard kinesthetic sensations [10], [11], [12], [13]. This effect is explained by how our sense of touch works, especially considering the larger role of skin deformation in providing proprioceptive cues. It can be also seen as part of an "uncanny valley of haptics", a phenomenon where ameliorating the realism of an interaction brings a feeling of increasing unease as its representation becomes more – but never quite fully - realistic [14]. These results hint to the fact that, sometimes, less haptics can be the best choice and that, by better understanding the underlying mechanisms of our sensory systems, we can achieve results that might seem counter-intuitive at first. Indeed, *just enough* haptics might one of the right answers to bring haptic technologies a wider use in the future [15], [16], focusing on designing simpler devices able to only provide those pieces of feedback or information that are truly important for the task at hand.

V. Future Directions

Moving forward, research in haptic technologies is poised to continue flourishing. The anticipated growth will stem from ongoing collaborations and interdisciplinary endeavours, promising a trajectory marked by enhanced user experiences, expanded applications, and deeper integration of haptics within the metaverse landscape. Such a landscape opens the opportunity for future relevant investigations.

Indeed, from one side, the several novel research results presented in this issue highlight how mechatronics innovation remains crucial in the haptic research evolution field, while psychophysics is fundamental in correlating generated stimuli to perception. Novel designs aim to provide solutions that provide immersive and effective haptic experiences in XR scenarios. At the same time, it remains evident how the user's experience is a fundamental tool for validating novel design concepts in the in-field tests.

On the other hand, the haptic field connected to the evolution of XR technology opens novel and important research directions that deserve to be explored from their fundamentals. Understanding essential principles of utilisation of cutaneous cues (such as vibration, for example) represents a promising direction to enhance realism in texture rendering or users' cutaneous feedback expectations. These aspects of cutaneous feedback utilisation in immersive virtual reality scenarios (or "metaverse" experiences) highlight the importance of utilising haptics to enhance immersion, improving interaction by providing a more realistic user experience while keeping feedback systems' complexity constrained.

In conclusion, this issue underscores the focus of research studies on fostering interdisciplinary collaboration. This involves areas like virtual reality training, designing for enhanced immersion realism, and optimizing haptic technology in metaverse scenarios, all while consistently prioritizing user feedback experience.

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APPENDIX
RELATED WORKS

[A1] L. Kuang et al., "A wearable haptic device for the hand with interchangeable end-effectors," *IEEE Trans. Haptics*, vol. 17, no. 2, pp. 129–139, Apr.-Jun. 2024.

[A2] N. Iriarte et al., "Contactless electrostatic piloerection for haptic sensations," *IEEE Trans. Haptics*, vol. 17, no. 2, pp. 140–151, Apr.-Jun. 2024.

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