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Wearable and Hand-held Haptics

Domenico Prattichizzo, Miguel Otaduy, Hiroyuki Kajimoto, and Claudio Pacchierotti

I. Introduction

Wearables and hand-held haptic devices are increasingly present in teleoperation, gaming, rehabilitation, VR, AR, and many other application domains [1]–[3]. This growing popularity is supported by an increasing number of interfaces being presented as well as research and studies aimed to define methods, principles, and guidelines for the design of wearable and hand-held interfaces [4]–[7]. This special issue features a broad range of studies, some of which advance our basic understanding of haptics, others study the fundamental design, actuation and sensing characteristics of haptic interfaces, and others present new haptic devices targeted to different applications.

II. The rise of Wearable and Portable Technology

Aristotle, in his treatise Περὶ Ψυχῆς (*On the Soul*), defines the sense of touch as the most accurate sense of our species, the one that makes humans the most intelligent animals of all. He also recognizes the hand as the primary tool to interact with the surrounding environment, stating that "the soul is as the hand, for the hand is an instrument with respect to instruments as the intellect is a form with respect to forms". Aristotle's view was also transmitted in various strands of modern Scholasticism. In 1268, Tommaso d'Aquino claims "the hand as the most perfect of the organs" and that "touch needs to exist wherever life exists [8]." Seven hundred years later, University of Virginia Professor Frank Geldard advocated that the sense of touch was a "neglected sense of communication." He observed that, while the auditory and visual sensing systems are respectively superior at temporal and spatial discrimination tasks, the somatosensory system is suited for both [9], [10].

Nonetheless, while haptic receptors in the skin of primitive animals appeared long before the exteroceptors of light and sound, modern human technologies have developed in a reverse fashion [11], [12]. First, in the second half of the 19^{th} century, Thomas Edison claimed the invention of the phonograph. Then, it was the time of moving images, reproduced along with sounds, which preceded modern television systems. Along with the rapid and wide spread use of audio and vision technologies, we also witnessed a drastic change in their form-factor and target usage: from big and heavy machines to small and lightweight objects. Think, for instance, of the first hi-fi speakers, and compare them to the latest portable music players. The same applies to technologies made to reproduce and transmit video signals.

As the revolution of *portability* made these technologies fit in our pockets, the challenge of *wearability* will make them fit our bodies, opening new scenarios we can only now envisage. Everything started back in 1961, when Courtney Graham, a United Airlines pilot, together with his friend and fellow pilot, Keith Larkin, created the first lightweight wireless headset. It was composed of two hearing-aid size transducers placed in a capsule mounted near the ear. Speech was conducted to the microphone via an acoustic tube, positioned near the user's mouth, while incoming communications emanating from the receiver were conducted via a second tube [13]. A few years later, Neil Armstrong wore something comparable to that during the first moonwalk in human history. As for video technology, in early 2013, Google accepted orders for the long-rumored Google Glass, a futuristic idea for virtual and augmented reality hosted in a pair of eye glasses.

What about the sense of touch?

III. Wearable and Hand-held haptics

Haptic technologies have been historically used in robotic teleoperation. A human user, through a haptic interface, controls the motion of a remote robot interacting with the environment. At the same time, through the same interface, the user receives information about the forces and torques exerted by the robot on said environment. Although haptic interfaces are now quite popular in laboratories and research centers, their use still remains underexploited and often limited to research applications. This also happened because haptic interfaces have been traditionally grounded to an external support, such as a table, and portable uses of haptic feedback have been limited for a long time to simple notifications in smartphones and pagers.

A promising approach in evolving from grounded haptic interfaces to more wearable and portable designs has been to move the grounded part of the haptic interface from an external support onto the body of the human user. Such body-grounded haptic interfaces have been called exoskeletons and they have been very successful in the past [2], [14]. However, although exoskeletons do show an increased wearability and portability with respect to grounded solutions, they have one significant limitation. They are designed to provide kinaesthetic feedback between their end-effector and base. As the grounding of the interface is moved toward the point of application of the force, the kinaesthetic component of the interaction is progressively lost [15], [16]. At the extreme of this reasoning, we can find interfaces that have their end-effector placed *very* close to their base. These devices are bound to lose most of their kinaesthetic capabilities, providing solely cutaneous feedback, as shown in [4].

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In the last ten years, haptic systems have started to be designed with wearability and portability in mind. Wearable and hand-held haptic devices are increasingly present in teleoperation, gaming, rehabilitation, VR, AR, and many other application domains [1], [2]. This growing popularity is supported by an increasing number of research and studies aimed to define methods, principles, and guidelines for the design of wearable and hand-held interfaces [1], [2], [4]–[6]. However, the definition of what is a wearable or hand-held device is not always as intuitive and straightforward as it may seem. In this respect, we embrace the definition proposed in [1], which extends the definition of wearable interface beyond something that is merely suitable to be worn: "a wearable haptic interface should be small, easy to carry, comfortable, and it should not impair the motion of the wearer." A similar reasoning can of course be followed for hand-held haptic interfaces, extending this definition beyond something that is merely suitable to be held, toward something that is also easy to carry and move around.

The primary advantage of such haptic interfaces is indeed their reduced form factor and weight compared to grounded solutions, a feature that opens the possibility of easily engaging in multi-contact interactions. With such devices, multi-contact haptic feedback does not require cumbersome and complex systems anymore, but rather multiple instances of smaller devices, that can be spread across the user's body. Another interesting advantage is the reduced cost of these interfaces, which opens great opportunities in the consumer market for applications such as gaming and interaction in VR and AR. In the same way as affordable VR headsets have tremendously enlarged the number of engineers and researchers using these technologies, we expect wearable and portable haptics to elicit a similar effect to the fields of haptics. We can already witness applications using such interfaces in other domains [17]–[20]. Of course, there are also significant drawbacks in using this new haptic technology, namely the limited actuation and sensing capabilities. To overcome these limitations, researchers should devise ad-hoc interaction techniques and methods, similar to how redirection techniques in VR address the problem of having a limited physical workspace.

IV. Contents of the Special Issue

This special issue presents the most recent research on wearable and hand-held haptics in three main areas, namely, technology and design, perceptual illusions, and human-robot interaction.

A. Technology and Design

The first papers of the special issue concern the technologies and design of wearable and hand-held devices.

Vibrotactile technology is the most commonly used technology in wearable and hand-held haptics, thanks to its compact form factor, light weight, and low cost. This technology is quite mature, but – as it often happens in research – it suffers from the fact that most of the research around it has been performed in controlled environments inside research facilities, and it is often not ready for real applications. The paper "Getting Your Hands Dirty Outside the Lab: A Practical Primer for Conducting Wearable Vibrotactile Haptics Research" by Jeffrey Blum, Pascal Fortin, Feras Al Taha, Parisa Alirezaee, Marc Demers, Antoine Weill–Duflo, and Jeremy Cooperstock addresses the recurring issues arising when moving from core haptic perceptual studies and in-lab experiments to real-world testing of wearable vibrotactile haptic systems. From their contribution, both novice and experienced haptic researchers will find suggestions to design real-world applications exploiting the most recent results on wearable vibrotactile haptics.

Beyond vibrotactile feedback, the technology behind the design of wearable and hand-held devices has developed towards providing richer contact sensations. Wearable and hand-held devices conveying skin stretch stimuli are a good example of this evolution. However, it is very difficult to control the strength of the skin stretch stimulus to be noticeable across subjects and tasks. The study "Resonant Frequency Skin Stretch for Wearable Haptics" by Peter Shull, Tian Tan, Heather Culbertson, Xiangyang Zhu, and Allison Okamura uses cyclic lateral skin stretches to match the skin's resonant frequency to create highly noticeable stimuli that are quantified at the forearm, shank, and foot. Cyclic stretches are a new approach to wearable haptics and will facilitate a more widespread use of wearable skin stretch stimulation.

Other promising technologies for designing wearable haptic interfaces use the thermal expansion and contraction of wires, the variable impedance enabled by layer jamming, and magnetorheological foam actuators. The study "Wearable Tactile Display Based on Thermal Expansion of Nichrome Wire" by Hiroyuki Kajimoto and Lynette Jones presents an innovative design for a multi-element tactile display based on the thermal expansion and contraction of nichrome wire. The device comprises elastic rods that are pulled by tiny nichrome wires. When an electrical current is applied to the wire, displacement of the elastic rod occurs with thermal elongation of the wire. To prove the effectiveness of their design principle, the authors showed that perceptible vibrations up to 320 Hz can be presented, thus making it possible to display both position and movement cues. The study "Passive Force-feedback Gloves with Joint-based Variable Impedance Using Layer Jamming" by Dangxiao Wang, Yu Zhang, Ziqi Wang, Yuru Zhang, and Jing Xiao involves the design of a force feedback glove using light layer jamming sheet at each finger joint. In simulating free space, the layer jamming sheet is soft and easy to deform, while in simulating constrained space, the sheet becomes stiff, providing resistance torques to prevent rotation of the finger joints. Experiments are performed at the joint level and indicate the potential of the proposed approach for developing lightweight hand exoskeletons. The study "FW-Touch: A Finger Wearable Haptic Interface with a MR Foam Actuator for Displaying Surface Material Properties on a Touch Screen" by Aiguo Song, Dapeng Chen, Lei Tian, Liyue Fu, and Hong Zeng presents the design of a finger-worn device providing vibrotactile normal and lateral forces at the finger. In combination with more traditional types of actuation, they use a magnetorheological foam actuator that employs a Hall sensor to correct for the output force. The results are promising for touch screen interaction.

The sixth paper of this special issue deals with a very complete interaction device. All the above-mentioned contributions deal with a reduced model of contact interaction. In fact, a complete one requires six degrees of freedom and it is very complex to design a wearable or hand-held interface able to implement it. The study "Implementation of a 6-DOF Parallel Continuum Manipulator for Delivering Fingertip Tactile Cues" by Eric M. Young and Katherine J. Kuchenbecker makes it possible thanks to six DC motors, six flexible Nitinol wires, and a parallel continuum manipulator. This novel device is capable of controlling the position and orientation of a flat platform, such that any combination of normal and shear force can be delivered at any location on the fingertip, as effectively shown in their user studies.

B. Perceptual Illusions

The second set of papers concerns the perceptual illusions enabled by wearable and hand-held devices. The illusions presented here are the out-of-body touch illusion, the apparent motion illusion, and the embodiment of virtual limbs.

The study "Power Law based Out of Body Tactile Funneling for Mobile Haptics" by Payal Patel, Rahul Kumar Ray, and Muniyandi Manivannan describes how wearable haptics can be used to exploit the limitations of human perception with the aim of augmenting the perpetual information provided to the human. This research establishes a psychophysics-based mathematical relationship between the intensity of physical and phantom stimulus rendered out of the body. Results show the potential applications of this out-of-body illusion in designing compact wearable and hand-held interfaces.

The second study on out-of-body illusions, by Mar Gonzalez-Franco and Christopher Berger, uses hand-held devices to simulate the action of holding a virtual stick and is entitled "Avatar embodiment enhances haptic confidence on the out-of-body touch illusion" . The authors elaborate on how the presence of a virtual body, the avatar, affects the perceived haptic experience. The rich set of experiments and their results suggest that an out-of-body illusion is much more evident for those subjects who had an avatar in the virtual reality experience.

The study "Tactile Apparent Motion between Individuals with Smart Bracelets" by Taku Hachisu and Kenji Suzuki presents a novel interaction approach for connecting two subjects wearing vibrotactile bracelet devices. By controlling the vibrations, the pair of bracelets induces a tactile apparent motion representing the direction of the touch interaction between the users' hands. The paper aims to inspire researchers of human-human tactile interaction to augment physical touch communication between humans.

The last paper of the special issue is a study on "Can Wearable Haptic Devices Foster the Embodiment of Virtual Limbs?" by Jakob Frohner, Gionata Salvietti, Philipp Beckerle, and Domenico Prattichizzo. The main scientific question addressed is understanding what is the role played by wearable haptics in the immersiveness of users in virtual environments. To answer this question, the authors study the embodiment of a virtual hand equipping the user with or without wearable haptics. Results show that wearable haptic feedback significantly improves the subjective embodiment of a virtual hand. The paper provides useful guidelines for wearable haptic designers and represents a basis for further research concerning human body experience, in real, virtual, and augmented environments.

C. Human-Robot Interaction

The last group of papers of the special issue describes how wearable haptics enables novel forms of interaction of humans with robotic manipulators and mobile robots.

The study "Human-Robot Team Interaction Through Wearable Haptics for Cooperative Manipulation" by Selma Music, Gionata Salvietti, Pablo Budde Genannt Dolman, Francesco Chinello, Domenico Prattichizzo, and Sandra Hirche shows how a human operator can teleoperate three robotic arms that collaboratively manipulate heavy and large objects with a single hand equipped with wearable haptic thimbles. The main control challenge is the asymmetry of the interaction, arising because robot teams have a relatively high number of controllable degrees of freedom compared to the human operator. The proposed solution by the authors is based on a reduction of dimensionality that focuses on the most important information needed to remotely control the manipulation of objects more than guaranteeing the realism of the interactions at the remote contact points between the robots and the manipulated object.

In the study "SwarmTouch: Guiding a Swarm of Micro-Quadrotors with Impedance Control using a Wearable Tactile Interface" by Evgeny Tsykunov, Ruslan Agishev, Roman Ibrahimov, Luiza Labazanova, Akerke Tleugazy, and Dzmitry Tsetserukou, the context is teleoperation of a swarm of quadrotors enabled by advanced impedance control and wearable vibrotactile feedback. The users feel the state of the swarm at their fingertips and receive valuable information to improve the controllability of the quadrotors team. The proposed approach has an impact on the human-swarm interaction, providing a higher level of intuitiveness and immersion into swarm navigation.

The last study of our special issue, "Haptic Feedback Perception and Learning with Cable-Driven Guidance in Exosuit Teleoperation of a Simulated Drone" by Carine Rognon, Vivek Ramachandran, Amy Wu, Auke Ijspeert, and Dario Floreano concludes the special issue on novel forms of interaction with robots, presenting an intuitive wearable exosuit to teleoperate aerial robots. Motor learning studies reveal that this form of haptic guidance improves user performance in training, but this improvement is not retained when subjects are then re-evaluated without guidance.

V. Conclusions

The contributions presented in this special issue reflect several key directions in current research on Wearable and Hand-held Haptics. Researchers and engineers are devising new ways to better overcome the intrinsic limitations of these types of haptic interfaces, exploiting a renewed understanding of the perceptual basis of haptics and an improvement in the available design and manufacturing techniques. We expect knowledge in this area to continue to grow, thanks to the fertile interactions between activities in mechatronics, ergonomics, robotics, and haptics, as well as for the need for wearable and hand-held haptics driven by fast-growing applications such as gaming, rehabilitation, training, and medicine.

References

[1] C. Pacchierotti, S. Sinclair, M. Solazzi, A. Frisoli, V. Hayward, and D. Prattichizzo, "Wearable haptic systems for the fingertip and the hand: taxonomy, review, and perspectives," *IEEE transactions on haptics*, vol. 10, no. 4, pp. 580–600, 2017.

[2] D. Wang, M. Song, A. Naqash, Y. Zheng, W. Xu, and Y. Zhang, "Toward whole-hand kinesthetic feedback: A survey of force feedback gloves," *IEEE transactions on haptics*, 2018.

[3] V. Yem and H. Kajimoto, "Wearable tactile device using mechanical and electrical stimulation for fingertip interaction with virtual world," in *Proc. IEEE Virtual Reality (VR)*, March 2017, pp. 99–104.

[4] D. Prattichizzo, F. Chinello, C. Pacchierotti, and M. Malvezzi, "Towards wearability in fingertip haptics: a 3-dof wearable device for cutaneous force feedback," *IEEE Transactions on Haptics*, vol. 6, no. 4, pp. 506–516, 2013.

[5] G. Robles-De-La-Torre and V. Hayward, "Force can overcome object geometry in the perception of shape through active touch," *Nature*, vol. 412, no. 6845, p. 445, 2001.

[6] C. Pacchierotti, E. M. Young, and K. J. Kuchenbecker, "Task-driven pca-based design optimization of wearable cutaneous devices," *IEEE Robotics and Automation Letters*, vol. 3, no. 3, pp. 2214–2221, 2018.

[7] A. G. Perez, D. Lobo, F. Chinello, G. Cirio, M. Malvezzi, J. San Martín, D. Prattichizzo, and M. A. Otaduy, "Optimization-based wearable tactile rendering," *IEEE Transactions on Haptics*, vol. 10, no. 2, pp. 254–264, 2016.

[8] T. d'Aquino, *Sentencia Libri De anima*, 1268.

[9] F. A. Geldard, "Some neglected possibilities of communication," *Science*, 1960.

[10] J. Pasquero, "Survey on communication through touch," *Center for Intelligent Machines-McGill University, Tech. Rep. TR-CIM*, vol. 6, 2006.

[11] T. B. Sheridan, "Further musings on the psychophysics of presence," in *Proc. IEEE Int. Conf. on Systems, Man, and Cybernetics*, vol. 2, 1994, pp. 1073–1077.

[12] C. Pacchierotti, *Cutaneous haptic feedback in robotic teleoperation*, ser. Springer Series on Touch and Haptic Systems. Springer, 2015.

[13] W. K. Larkin, "Miniature headset-microphone adapted for use with a mask," U.S. Patent 3,184,556, 1965.

[14] M. Bergamasco, A. Frisoli, and C. A. Avizzano, "Exoskeletons as man-machine interface systems for teleoperation and interaction in virtual environments," in *Advances in Telerobotics*, 2007, pp. 61–76.

[15] D. Prattichizzo, C. Pacchierotti, and G. Rosati, "Cutaneous force feedback as a sensory subtraction technique in haptics," *IEEE Transactions on Haptics*, vol. 5, no. 4, pp. 289–300, 2012.

[16] F. Chinello, M. Malvezzi, D. Prattichizzo, and C. Pacchierotti, "A modular wearable finger interface for cutaneous and kinesthetic interaction: control and evaluation," *IEEE Transactions on Industrial Electronics*, 2019.

[17] A. Casalino, C. Messeri, M. Pozzi, A. M. Zanchettin, P. Rocco, and D. Prattichizzo, "Operator awareness in human-robot collaboration through wearable vibrotactile feedback," *IEEE Robotics and Automation Letters*, vol. 3, no. 4, pp. 4289–4296, October 2018.

[18] X. De Tinguy, C. Pacchierotti, M. Marchal, and A. Lécuyer, "Enhancing the stiffness perception of tangible objects in mixed reality using wearable haptics," in *Proc. IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 2018, pp. 81–90.

[19] I. Bortone, D. Leonardis, N. Mastronicola, A. Crecchi, L. Bonfiglio, C. Procopio, M. Solazzi, and A. Frisoli, "Wearable haptics and immersive virtual reality rehabilitation training in children with neuromotor impairments," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 26, no. 7, pp. 1469–1478, 2018.

[20] A. Al Maimani and A. Roudaut, "Frozen suit: designing a changeable stiffness suit and its application to haptic games," in *Proc. CHI Conference on Human Factors in Computing Systems*, 2017, pp. 2440–2448.

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