Cutaneous haptic feedback for robotics and Virtual Reality

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Habilitation à diriger des recherches

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Contents

1 Introduction and overview of my research work

I defended my PhD in December 2014 at the University of Siena (UNISI, Siena – Italy), Italy. After that, I was a postdoctoral researcher in the Department of Advanced Robotics at the Italian Istitute of Technology (IIT, Genova – Italy) until December 2016, when I joined IRISA-CNRS. This document summarizes my scientific contributions to the fields of haptics, robotics, and virtual interaction since my PhD thesis, i.e., between the years 2015 and 2021.

After my doctorate, during my postdoc years at the Italian Institute of Technology, I worked on the design of haptic assistance and contact feedback techniques for robotic teleoperation. I studied how cutaneous and kinesthetic feedback techniques can be successfully employed to render forbidden-region active constraints, guidance active constraints, and contact sensations in applications of needle insertion [1], microrobotics [2], [3], robot-assisted medical palpation [4], teleoperation with communication delays [5], and laser microsurgery [6], [7]. I also worked on the development of ungrounded/wearable haptic interfaces [8], [9], [10], [11, 12] and cutaneous rendering algorithms [13].

When I started at IRISA, I moved to Rennes to be part of the Lagadic team. There, I continued my research on haptic rendering and interfaces, integrating more and more with the expertise in the team (shared control, mobile robotics, crowd simulation, visual servoing) and at IRISA in general (virtual reality, encounter-haptics, visuohaptic perception). I worked on haptic feedback and shared control for robotic cutting [14], manipulation [15], [16], [17], [18], [19], [20], [21], [22], [23], needle insertion [24], microrobotics [25], mobile robotics [26, 27], [28], [29], crowd simulation [30], [31, 32], navigation assistance for sensory-impaired people [33, 34, 35], laser surgery [36], teleoperation with communication delays [37], [38], [39], as well as in using cutaneous haptics for virtual and augmented reality [40], [41], [42], [43], [44], [45], [46], [47], [48], [49]. In parallel, I continued my research on the development of haptic interfaces and rendering algorithms [50], [51], [52], [53], [54], [55], [56], [57], [58], [59], starting new interesting lines of research on haptics personalization [60], [61] and ultrasonic haptics [62, 63], [64], [65], [66].

Generally speaking, my research efforts have been guided by the vision that in the future robots will seamlessly cooperate with humans in shared or remote spaces, thus becoming an integral part of our daily life. For instance, robots are expected to relieve humans from monotonous and physically demanding tasks, assist them in dealing with complex/dangerous situations, as well as enable natural interactions with digital contents. This attitude has motivated my main research achievements within the scope of shared control of single/multiple fixed/mobile robots as well as in the design of natural haptic interaction paradigms and interfaces. To address these complex issues, I have been mainly relying on the tools of robotics, systems and control theory, computer science, mechatronics, and psychophysics. All my research work has been carried out in collaboration with a wonderful group of students and colleagues, as reported in the authors list of each work.

In a continued effort for supporting open-source science, all the papers I have ever published are freely available online. In this respect, since joining CNRS, I have been using the HAL resource portal for sharing all my contributions.

The remainder of this document is organized in the following way. Section 2 presents my work on the development of new haptic interfaces and rendering techniques, Sec. 3 addresses haptic teleoperation of robotic manipulators, Sec. 4 haptic control of mobile robots, Sec. 5 haptic feedback and rendering systems for medical applications, and Sec. 6 haptic rendering and interaction techniques for Virtual and Augmented Reality scenarios. Finally, Secs. 7 discusses the perspectives of my research work and the questions that are still open, while Sec. 8 draws the conclusions and potential future impact of the field at large.

2 Development of haptic interfaces and rendering techniques

Conceiving and designing haptic interfaces, mostly wearable, has been one of my most prominent and fruitful line of research since the end of my Ph.D.

Wearable haptics is a hot topic in the field, and it has attracted the interest of the international community as well as that of large companies. For example, the 2018 edition of IEEE Haptics Symposium dedicated its first day to this very topic, and Facebook has organized a workshop on wearable haptics during the 2019 edition of IEEE World Haptics. The primary advantage of wearable haptics is the reduced form factor compared to grounded solutions, a feature that opens the possibility of easily engaging in multi-point (or multi-contact) interactions. With such devices, multi-point haptic feedback does not require cumbersome and complex systems anymore, but rather multiple instances of smaller and simpler devices, spread throughout the user's body.

This Section reports on works directly addressing the design of haptic devices and rendering algorithms, while their applications and use in different domains is reported in later Sections.

2.1 Haptic devices for the finger

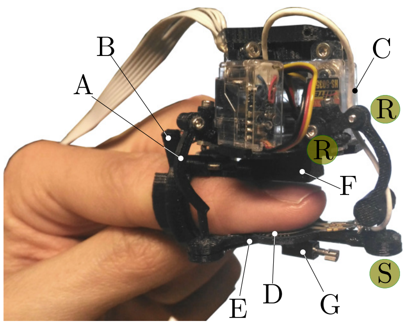


Figure 1: The Revolute-Revolute-Spherical fingertip device presented in [51].

Wearable devices often focus their attention on the fingertip, since it is the most sensitive part of our body and the one that is most often used for grasping, manipulation, and probing the environment. In 2017, I have written a paper presenting the taxonomy and review of wearable haptic systems for the fingertip and the hand, especially focusing on those systems directly addressing wearability challenges [41].

We also directly worked on developing a new set of fingertip haptic devices able to apply cutaneous sensations through an end-effector placed in contact with the fingerpad [10, 51, 67]. They are composed of a static upper body (F in Fig. 1) and a mobile platform (E): the body is located above the nail, supporting three servo motors (C), while the mobile platform contacts the finger pulp. Three legs (A) connect the mobile platform with the static body. Each leg is composed of two rigid links connected to each other and then with the body and the mobile platform, according to a Revolute-Revolute-Spherical (RRS) kinematic chain. The three upper revolute joints are actuated by the servo motors, and a piezoresistive sensor (D) measures the force applied by the mobile platform to the fingertip. A vibrotactile motor (G), attached below the platform, provides additional vibrotactile stimuli. Finally, a clamp (B) enables the user to easily wear the device on the finger. The end-effector can move toward the user's fingertip and rotate it to simulate contacts with arbitrarily-oriented surfaces (video available here).

This design was also extended to integrate a small finger 1-DoF exoskeleton [54]. The 1-DoF finger exoskeleton provides kinesthetic force to the proximal and distal interphalangeal finger articulations using one servo motor grounded on the proximal phalanx. The fingertip device and finger exoskeleton can be used either together or separately as two different systems (see Fig. 2, video available here). We used this composite device for tasks

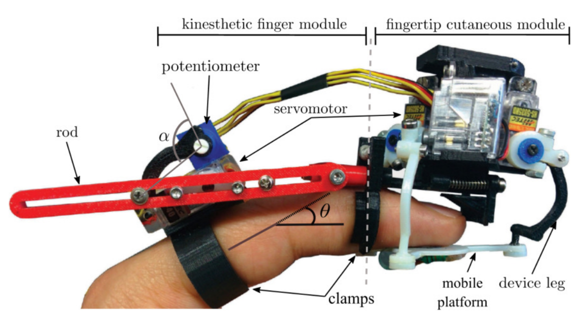


Figure 2: The combined kinesthetic-cutaneous device presented in [54].

of curvature discrimination task, robot-assisted palpation, and immersive Virtual Reality (VR) experiences.

While fingertip devices are great for interacting with remote and virtual environments, they of course prevent the fingertip from interacting with any real/tangible object. At the same time, fingertip devices also make it difficult for markerless trackers, such as the LeapMotion, to correctly track the fingers, as they of course rely on a device-free model of the human hand. For these reasons, we developed a 2-DoF pressure and skin stretch device for the finger [9] (called "hRing", see Fig. 3). It consists of two servo motors positioned in front of each other that move a belt placed in contact with the user's finger skin. When the motors spin in opposite directions, the belt presses into the user's finger, while when the motors spin in the same direction, the belt applies a shear force to the skin. We placed the device on the proximal finger phalanx and not on the fingertip, so as to enable a more effective tracking when using markerless tracking systems. This feature has made this device very useful for Virtual and Augmented Reality applications (see Sec. 6).

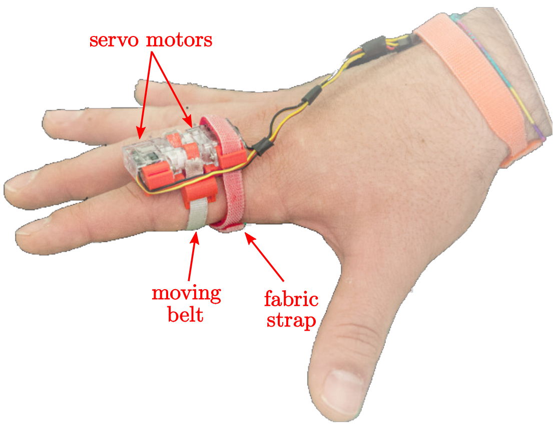


Figure 3: The hRing device [9]. A moving belt, driven by two servo motors, provides skin stretch and normal stimuli to the finger skin.

We also got very interested in the issue of *personalization* of fingertip devices. In fact, designing fingertip interfaces that fit all users is challenging; many studies have indeed highlighted large differences in the fingertip's size across the human population [68, 69, 70]. We tackled this problem both from a rendering and a mechanical design point of view. In the rendering approach, we used the same fingertip device and optimized the rendering algorithm for different fingertips. We started with an existing data-driven haptic rendering algorithm that ignores fingertip size, and then developed two software-based approaches to personalize this algorithm for fingertips of different sizes using either fingertip-specific additional data or geometry [61]. A video of this study is available here. To improve the rendering quality, we can also study how the device end-effector actually deforms the finger pulp and use this information to improve the rendering model [71], [72]. We have also dealt with the same personalization issue from an hardware/design point of view [73]. In this case, we modified the design of a fingertip device to match a specific fingertip. To do so, starting from the user's fingertip characteristics, we define a numerical procedure that best adapts the dimension of the device to: (i) maximize the range of renderable haptic stimuli; (ii) avoid unwanted contacts between the device and the skin; (iii) avoid singular configurations; and (iv) minimize the device encumbrance and weight. Together with the mechanical analysis and evaluation of the adapted design, we presented a MATLAB script that calculates the device dimensions customized for a target fingertip as well as an online CAD utility for generating a ready-to-print STL file of the personalized design. This work enables anyone to measure their fingertips, input these values in the proposed numerical procedure, and generate a personalized fingertip device ready to print. A video showing this hardware personalization procedure is available here.

The same personalization idea can be extended to designing task-specific devices, i.e., devices optimized for certain tasks. Indeed, devices can and should be adapted for the range of stimulation provided, so as to keep their form factor as compact as possible. Given one (or more) target tactile interactions to render and a cutaneous device to optimize, we evaluated the minimum number and best configuration of the device's actuators to minimize the estimated haptic rendering error [60].

First, we calculated the motion needed for the original cutaneous device to render the considered target interaction. Then, we ran a principal component analysis to search for possible couplings between the original motor inputs, looking also for the best way to reconfigure them. If couplings exist, we can redesign our cutaneous device with fewer motors, optimally configured/positioned to render the target set of tactile sensations. A video of this work is available here.

2.2 Haptic devices for the hand

After the fingers, the hands are another popular location to deliver haptic sensations [41].

In this respect, we have worked to combine two promising concept in haptic interaction, tangible objects and wearable haptics. We developed a combined solution called "WeATaViX," at the interface between encounter-type haptic display (ETHDs) and passive tangible haptics, in the form of a wearable encounter-type device whose end-effector is a tangible object [58, 74] (see Fig. 4). It aims to provide physical presence for virtual objects while remaining as simple and unobtrusive as possible. The device is composed of a 3D-printed structure to be placed on the back of the hand. Its profile is slightly curved to fit the shape of the hand. On the internal side, it is anchored in an adhesive silicone skin, guaranteeing good adherence, comfort, and adaptability to different hand morphologies and skin properties. A HTC Vive Tracker can be attached on the external side. The distal side of the 3D-printed structure houses a servomotor which controls the motion of a rigid link holding the tangible object. By moving the rigid link, the motor brings the tangible object toward or away from the user's palm. The tangible object is equipped with capacitive sensors to detect contacts with the hand. The device is designed with wearability in mind, weighing under 90 g without the tracker, and keeping the palm and fingers completely free of any straps thanks to the adhesive silicone fixation. The silicone layer is capable of securely attaching the device during prolonged use (>45 min) and throughout multiple attaching/detaching cycles (>30). A video of this device is available here.

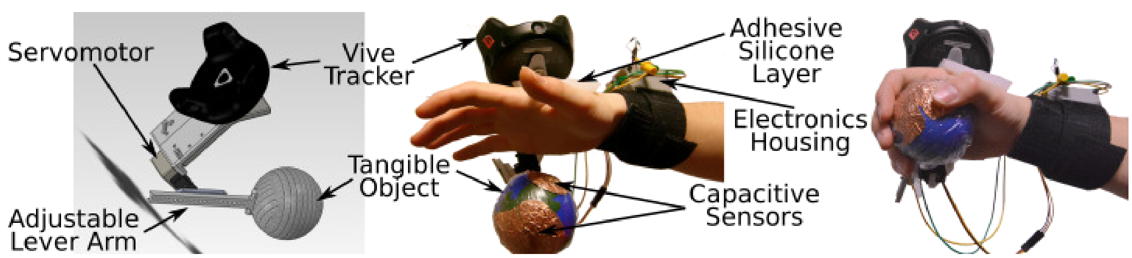
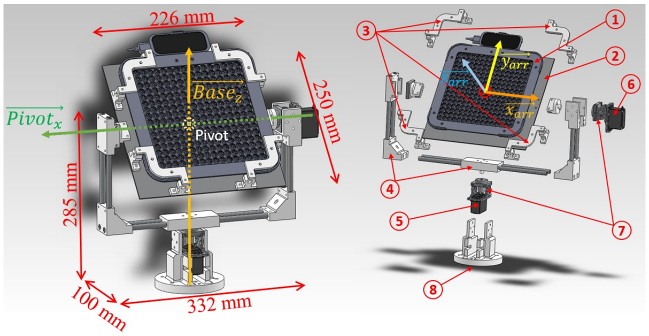


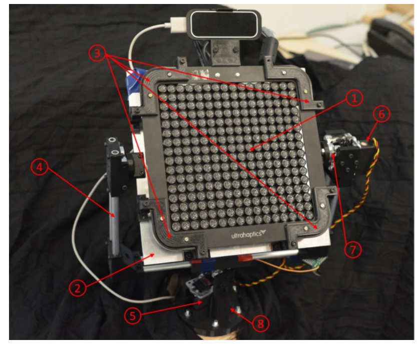
Figure 4: WeATaViX [58]. The device is composed of a 3D-printed static part anchored to an adhesive silicone layer attached to the hand. Two capacitive sensors cover the tangible object, respectively facing the palm and the fingers during grasp closure. The hands-on demonstration of this device won the Best Demonstration award at Eurohaptics 2020 and IEEE World Haptics 2021.

A very different approach to providing haptic sensations to the hand is through mid-air haptics, which consists in conveying haptic sensations without any direct physical contact with the interface creating the stimuli. Several physical principles can be used to provide mid-air haptic stimuli: magnetism, acoustics, electric arcs, optics, and aerodynamics. Among these technologies, the currently most mature one uses focused airborne ultrasound. Arrays of ultrasonic transducers produce phase-shifted acoustic waves which constructively interfere at points in space called focal points and destructively interfere elsewhere, conveying sensations by varying acoustic radiation pressure on the skin [75, 76].

In this respect, we started by investigating important perceptual aspects related to the rendering of 2D shapes through an ultrasound haptic interface [64], evaluating (i) the absolute detection



(a)



(b)

Figure 5: Assembled and exploded view of the PUMAH system design [62], [66]. The array (1) is mounted on an aluminum holding plate (2) using 3D-printed ABS clips at the corners (3). The plate rotates around the Pivot x-axis (tilt) within an aluminium tubing and ABS frame (4), which itself rotates around the device vertical axis Base z (pan). The axes are driven by HiTec HS645-MG (5) and HS625-MG (6) servomotors. They are mounted on bearings held within aluminium chassis (7), relieving the motor shafts of any radial loads. The complete system is mounted on a 3D-printed ABS foot (8), which can be screwed to a supporting structure or mounted on a tripod using M6 screws.

threshold for a static focal point rendered via amplitude modulation, (ii) the absolute detection and identification thresholds for line patterns rendered via spatiotemporal modulation, (iii) the ability to discriminate different line orientations, and (iv) the ability to perceive virtual bumps and holes. Similarly, we analyzed the possibility of rendering stiffness sensations through ultrasound stimuli [65], identifying the differential threshold for stiffness perception when using a focused ultrasound array to render objects in VR. We found JNDs of 17%, 31%, and 19% for three reference stiffness values of 7358 Pa/m, 13242 Pa/m, 19126 Pa/m (sound pressure over displacement), respectively.

While carrying out these studies, we realized that these ultrasound arrays feature a reasonably large vertical workspace but they are not capable of displaying stimuli far beyond their horizontal limits, severely limiting their workspace in the lateral dimensions. To overcome this limitation, we developed a low-cost solution for enlarging the workspace of focused ultrasound arrays, called PUMAH (see Fig. 5). It features two degrees of freedom, rotating the array around the pan and tilt axes, thereby significantly increasing the usable workspace and enabling multi-directional feedback. Results show a 14-fold increase in workspace volume, with focal point repositioning speeds over 0.85 m/s while delivering tactile feedback with positional accuracy below 18 mm [62, 66, 77]. We tested it in a set of VR use cases, that can be seen here. More recently, we released a software library that allows the study of the impact of rendering parameters on perceived ultrasound stimulus properties [63]. This platform-agnostic framework standardizes ultrasound stimulus descriptions, enables reproduction of stimuli between perceptual experiments, and ensures stimuli used in applications correspond to those evaluated in prior perceptual studies.

2.3 Haptic devices for the rest of the body

While the fingers and hand have been the most popular place for designing haptic interfaces, there is an increasing attention to other parts of the body. Indeed, differently from other senses, our sense of touch is spread throughout our body, enabling to design distributed interfaces. This concept of distributed haptics is mentioned as one of the main axes of my future research (see Sec. 7).

In this respect, we designed a wearable skin stretch device for the forearm [8], [52]. It is composed of four cylindrical end effectors (indicated as "C" in Fig. 6), that accommodate four servomotors (B), and eight ergonomic pads (A), one in the rear and one in the front of each end effector. The end effectors are evenly distributed around the user's forearm. To improve grip and reduce slippage while contacting the skin, the end effectors are covered with rubber. The bracelet is wired to an arm band on the upper arm, that hosts the necessary electronics and two batteries. The arm band is in charge of providing the required power to the device and manage the wireless communication between the device and an external computer. The device itself weighs 95 g, while the arm band equipped with the batteries and control system weighs 280 g. This cutaneous device can generate independent skin stretch stimuli at the palmar, dorsal, ulnar, and radial sides of the arm. When the four end effectors rotate in the same direction, it provides cutaneous stimuli about a desired pronation/supination of the forearm. On the other hand, when two opposite end effectors rotate in different directions, it provides cutaneous stimuli about a desired translation of the forearm. We used this forearm device to provide navigation information in two experiments. In the first one, subjects were asked to translate and rotate the forearm toward a target position and orientation, respectively. In the second one, subjects were asked to control a 6-DoF robotic manipulator to grasp and lift a target object. Haptic feedback provided by our wearable device improved the performance of both tasks with respect to providing no haptic feedback. A video presenting the device is available here.

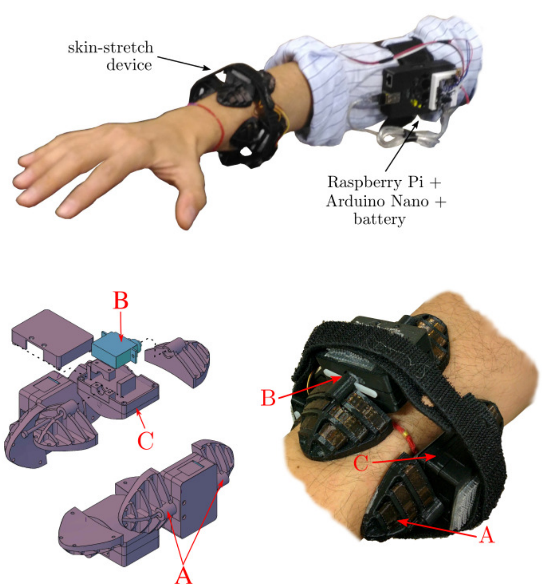
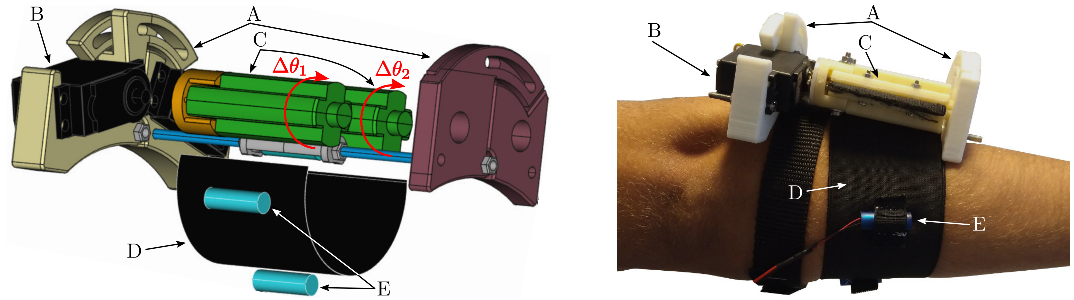


Figure 6: The skin stretch device for the forearm presented in [52].

At the intersection between the above device and the 2-DoF skin stretch device for the finger described in the previous Section, the "hRing" [9], we designed a haptic display for the forearm able to provide skin stretch, pressure, and vibrotactile stimuli [53] (see Fig. 7). Two servo motors, housed in a 3D printed lightweight platform, actuate an elastic fabric belt, wrapped around the arm. When the two servomotors rotate in opposite directions, the belt is tightened (or loosened), thereby compressing (or decompressing) the arm. On the other hand, when the two motors rotate in the same direction, the belt applies a shear force to the arm skin. Moreover, the belt houses four vibrotactile motors, positioned evenly around the arm at 90° from each other. The device weights 220 g for 115×122×50 mm of dimensions, making it wearable and unobtrusive. A video of this device is available here. We used it during the teleoperation of a robotic manipulator for grasping an object as well as to teleoperate the motion of a quadrotor fleet along a given path. In both scenarios, the wearable device provided feedback information about the status of the remote robot(s) and of the given task.

Finally, we have also recently worked on two wearable vibrotactile haptic system: a full-body vibrotactile vest for monitoring the health status of the elderly population [50], capable of alerting the wearer of a possibly-dangerous health condition (e.g., sustained hearth rate); and a vibrotactile glove for transmitting simple remote touch sensations and events [56].



(a) CAD design. (b) Device worn on the forearm.

Figure 7: The proposed wearable device for the arm [53]. It consists of a static platform (A) that accommodates two servomotors (B) and two pulleys (C), a fabric belt (D), and four vibrotactile motors (E). The device is able to provide skin stretch, pressure, and vibrotactile stimuli to the arm.

3 Haptics for ground robotic manipulation

In the last decade, remote telemanipulation has shown significant advancements in several fields such as minimally-invasive robotic surgery [78], telemaintenance [79], dangerous waste management [80, 81], and micromanipulation [82, 83]. However, current telerobotic systems provide teleoperation capabilities through extremely primitive consoles (e.g., passive joystick or teach pendants), making these operations prohibitively slow to process large amounts of material in a reasonable time. Besides being time demanding, these tasks usually require highly-skilled human operators. Indeed, steering a remote manipulator toward, e.g., a desired grasping pose, is a quite complex task for an operator directly controlling the 6-degrees-of-freedom (DoF) pose of a ground manipulator end-effector. This is due to (i) the complexity of regulating both the end-effector position and orientation at the same time and (ii) the presence of several constraints (e.g., collisions, joint limits, singularities) that further limit the operator's maneuvering dexterity (but of which the operator has no direct or intuitive awareness). To overcome these limitations, the user needs to constantly pay close attention to the status of the robotic system, which can be sometimes difficult and cognitively demanding (e.g., for singularity or joints limit avoidance). A possible way to reduce the operator cognitive and physical workload is to exploit the sensory information collected at the remote side to design haptic-guided and shared-control teleoperation systems. Shared control allows a human operator and an autonomous controller to simultaneously and collaboratively control the robotic system to achieve a common goal [84, 85]. Shared-control strategies are devised to reduce the human operator's workload when performing a difficult task (requiring skills/precision that may exceed those of a human operator) through a robotic system [86]. Examples range from grasping and manipulating objects using remote manipulator arms [87] (possibly accounting for post-grasping objectives [81]), to collaborative transportation of large objects using a team of mobile robots [88]. Employing shared-control techniques is particularly useful when dealing with complex tasks and/or many degree-of-freedom (DoF) robotic systems, as direct control would result in cumbersome, time-consuming, and cognitively-demanding task execution, as I mentioned above.

Indeed, a large part of my research work focused on devising haptic (shared-)control techniques for improving the telemanipulation capabilities of ground robots, e.g., robotic arms. Most of my work in this topic has been carried out in the framework of the H2020 European collaborative project "RoMaNS", that tackles "sort and segregation" applications for the decommissioning of nuclear sites. Within the project, we studied the case of the Sellafield (UK) nuclear site. Only there, 69,600 m^3 of legacy intermediate level waste need to be placed into 179,000 storage containers. It stores nearly all the radioactive waste generated by the UK's 15 operational nuclear reactors, including 140 tonnes of civil plutonium and 90,000 tonnes of radioactive graphite. To avoid wastefully filling expensive high-level containers with low-level waste, many old legacy containers must be cut open, and their contents "sorted and segregated". An estimation of the remaining cost of decommissioning and clean-up of the Sellafield site alone amounts to 47.9 billions GBP, with an increase of 90% from 2010. However, current robotic systems designed for such a task provide teleoperation capabilities through extremely primitive master consoles (e.g., passive joystick or teach pendants), making the task prohibitively slow for processing large amounts of material in a reasonable time. Our work aims at improving the effectiveness of such telerobotic systems for manipulation, of course also beyond their application to the nuclear industry.

3.1 Haptic shared control for improving robotic telemanipulation

We started by proposing haptic guidance methods for dual-arm telerobotic manipulation systems, which are able to deal with several different constraints, such as collisions, joint limits, and singularities. In [15], we considered the case of two manipulators (one of which controlled by the operator) sharing the workspace and having independent and sometimes conflicting tasks (see Fig. 8). We combine haptic guidance rendering with shared-control algorithms for autonomous orientation control and collision avoidance meant to further simplify the execution of grasping tasks. In that case, the human operator controlled one robotic arm, equipped with a gripper, through a 6-DoF grounded haptic interface. Haptic guidance provided the operator with information about joint and workspace limits as well as about the presence of singular configurations and imminent collisions. The shared-control algorithm autonomously controlled 2-DoF of the robotic manipulator, orienting the gripper toward the object to grasp. The other robotic arm was equipped with a camera and moved autonomously to track a second object, placed near the one to grasp. A human subjects study enrolling 20 participants showed that haptic shared control improves the grasping performance with respect to using classic human-in-the-loop teleoperation.

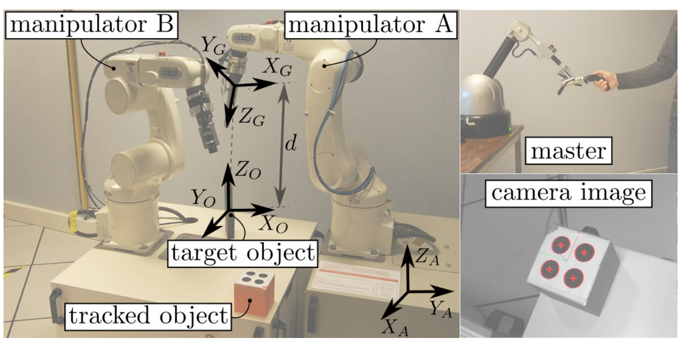
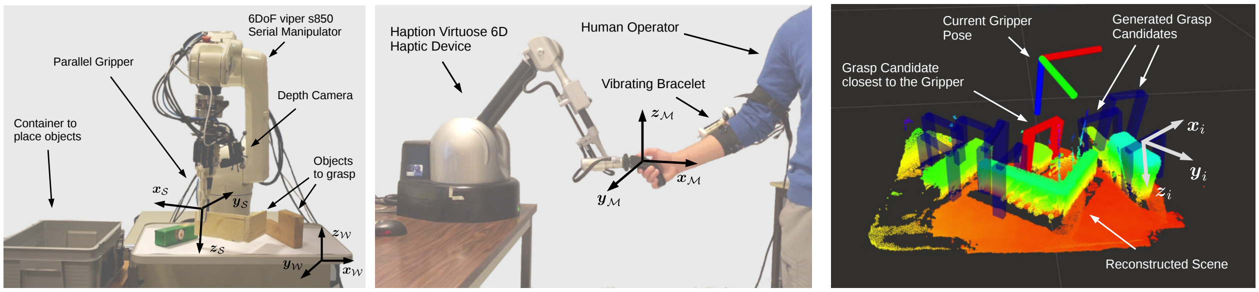


Figure 8: Haptic-enabled shared control enables one operator to control a robotic system composed of two arms. [15].

On a similar line, we designed a haptic shared-control approach for assisting a human operator in the sort and segregation of different objects in a cluttered and unknown environment [16]. A three-dimensional scan of the scene is used to generate a set of potential grasp candidates on the objects at hand. These grasp candidates are then used to generate guiding haptic cues, which assist the operator in approaching and grasping the objects. The haptic feedback is designed to be smooth and continuous as the user switches from a grasp candidate to the next one, or from one object to another one, avoiding any discontinuity or abrupt changes (see Fig. 9). A human subjects study registered an average improvement of 20.8%, 20.1%, and 32.5% in terms of completion time, linear trajectory, and perceived effectiveness, respectively, between the haptic shared control approach and standard teleoperation. A video of this work is available here.

Another important task for robot-assisted waste sorting is cutting through the old containers. To speed up this part of the process, we designed two haptic shared-control approaches. They



(a) (b) (c)

Figure 9: From [16]. (a)–(b) The experimental setup showing the slave robotic arm on the top and the master haptic arm on the bottom. (c) A screenshot of the visual feedback. A point cloud that was generated by an automated scanning routine serves as 3D reconstruction of the scene. The grasp candidates produced by the custom grasp pose detection (GPD) algorithm are shown in blue, except for the one that is currently used for computing the haptic feedback, which is drawn in red. The current pose of the end-effector is indicated by a coordinate frame.

assisted the human operator by enforcing different nonholonomic-like constraints representative of the cutting kinematics [14]. The first shared-control technique resembled the behavior of a unicycle. We imposed nonholonomic constraints on the robotic motion such that the translation of the cutting tool was limited to its cutting direction (forward/backward) and its vertical direction (up/down). These constraints prevented the operator from inadvertently applying high lateral forces during the cutting, which would result in dangerous ruptures of the environment. Although effective, in this condition the operator was still able to rotate the tool in place, which could also lead to significant damage. For this reason, we considered a second shared-control techniques, enforcing an additional constraint on the unicycle motion that ensured the tool rotation was always coupled with a linear motion. Results showed that the proposed shared-control approaches significantly outperform standard teleoperation in most of the considered metrics. Of course, such shared-control techniques for cutting can also be used in other applications, e.g., surgical robotics.

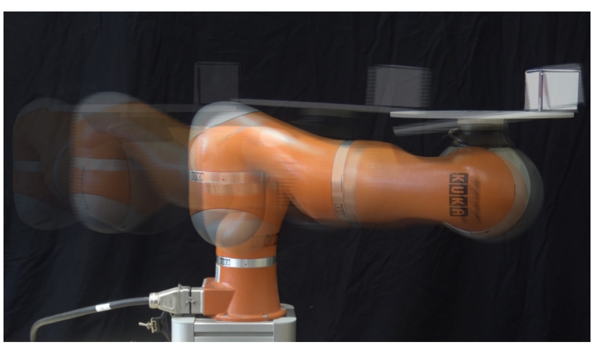


Figure 10: A teleoperated robot manipulator transports an object grasped in a nonprehensile configuration while autonomously modulating the user-specified inputs and the object orientation to prevent it from sliding and possibly falling under the action of gravity [89].

Finally, we have recently presented a work addressing the problem of semi-autonomously transporting an object manipulated by a tray mounted on a remote robotic arm, preventing any relative movement during the motion [89]. Transporting an object in a nonprehensile configuration (i.e., without any form- or force-closure grasp) is representative of many situations in which the robot cannot firmly hold the object and constrain its motion induced by inertial/external forces. In these cases, the object is free to slide or break contact with the robot end-effector, which may sometimes lead to a complete failure of the task. A solution to such a nonprehensile manipulation problem is known as *dynamic grasp*, formally defined in [90] as the condition in which friction forces prevent the object from moving relative to the manipulator. This is achieved by regulating the robot motion such that the object remains stationary with respect to the end-effector despite the action of external forces (such as gravity) or inertial forces due to the object acceleration.

Along this line of research, we proposed a shared-control teleoperation architecture able to alter the operator's commands to prevent the transported object from sliding relative to the manipulator. Besides altering the user's commands, the proposed shared-control architecture autonomously regulates the object orientation for both increasing the performance, in terms of user's commands tracking, and being more robust with respect to any uncertainty in the friction parameter. In addition, information about the discrepancy between the user's commands and those actually applied to the remote robot are provided to the user via haptic feedback. Force cues convey high-level information and can be used by the operators to infer the state of the system, helping them to specify motion commands which comply with the non-sliding constraints. A video of this work is available here.

Similar approaches we developed use haptic shared-control guidance and contact rendering techniques to prevent the operator from hitting robot's singularities and workspace boundaries [20, 23], render collisions with the environment [19, 21], fulfill task-related constraints [91], and design haptic-centered autonomous grasping approaches [18].

3.2 Haptic shared control for improving the operator's comfort

Haptic shared control can also be used to guide the user into completing a task while minimizing his or her effort, which is important when carrying out long telerobotic manipulations, e.g., during robotic surgery. In this respect, we presented a haptic-enabled shared-control approach aimed at minimizing the user's workload during a teleoperated manipulation task [17, 22]. Using an inverse kinematic model of the human arm and the rapid upper limb assessment (RULA) metric, the proposed approach estimates the current user's comfort online. From this measure and an a priori knowledge of the task, we then generate dynamic active constraints guiding the users toward a successful completion of the task, along directions that improve their posture and increase their comfort. Studies with human subjects show the effectiveness of the proposedapproach, yielding a 30% perceived reduction of the workload withrespect to using standard guided human-in-the-loop teleoperation. A video summarizing this work is available here.

3.3 Haptic shared-control for guaranteeing the interaction safety

Finally, one of the paramount objectives in the control of any haptic-enabled teleoperated robotic systems is of course to ensure a stable and transparent implementation. Indeed, it is well-known that haptic (kinesthetic) feedback can lead to an unstable and therefore possibly unsafe behaviour of the overall system. This can be due to factors such as very rigid contacts, delays in the communication, and a relaxed grasp by the user. These behaviors must be prevented, especially in fields where safety is a paramount and non-negotiable requirement, such as medical robotics. On the other hand, transparency is also important as it represents the match between the impedance perceived by the user and that of the teleoperated environment. In this respect, starting from some previous insights on the topic [92, 93], we worked on a novel optimization-based passivity control algorithm for haptic bilateral teleoperation systems involving multiple degrees of freedom [37], [38], [39]. In particular, in the context of energy-bounding control, the contribution focused on the implementation of a passivity layer for an existing time-domain scheme, ensuring optimal transparency of the interaction along subsets of the environment space which are preponderant for the given task, while preserving the energy bounds required for passivity. The involved optimization problem is convex and amenable to real-time implementation. For example, during a robot-assisted remote medical palpation task, we might want to privilege the stiffness/force information along the perpendicular to the object's surface with respect to the other directions.

Another interesting approach is to modulate the haptic information sent through the communication channel taking into consideration their perceptual relevance [5], i.e., we can try to reduce/adapt the haptic flow of data considering their perceptual importance with respect to the current task.

4 Haptics for mobile robotic operation

Mobile robotics applications can be useful in the entertainment industry (e.g., for monitoring sport or performing-arts events, or wildlife scenarios), in telepresence, meteorology, surveillance, search and rescue, inspection of damaged buildings and dangerous materials, and so on. Furthermore, livestock monitoring will be in the future a fundamental asset for developing an economically and sustainable progress. A clear trend looking into the near future is for mobile robots, both ground and aerial, to become smaller and more agile, which will make the use of multi-robot systems (robotic "teams") more and more feasible [94, 95]. Another straightforward application is in cooperative monitoring, data collecting, and mapping by means of a group of "actuated sensors" such as small drones. This expected improvement in smart surveillance and monitoring can have a significant impact in disaster preparedness, mitigating the tragic aftermaths of these events.

Indeed, the use of robots in disastered environments has rapidly increased in the last decade, thanks to their expendability, flexibility, and ability to adapt to different situations and tasks and to exploit the onboard sensors for obtaining information (e.g., 3D maps) of the surroundings. In this respect, ground Urban Search-And-Rescue (USAR) mobile robots are already widely used, while aerial solutions are only recently gaining interest [96]. For example, since 2011, there have been more than fifty documented ground robot deployments in disaster relief scenarios in more than fifteen countries. Notable examples are the USAR operations at the World Trade Center site [97] and during Hurricane Katrina [98]. Unfortunately, natural disasters are frighteningly on the rise [99], doubling over the past forty years. It is therefore vital to work on solutions able to mitigate the tragic aftermaths of these events. In fact, potentially hazardous events do not always need to end badly. Disasters occur due to the combination of an hazard with exposed people and assets vulnerable to the hazard. They are characterized by a lack of resilience and poor ability to cope and respond in the affected area. Another relevant application for robotic teams is surveillance and patrolling. Counter terrorism, border control, and city surveillance are indeed top priorities of several governments nowadays, and they have played a significant role in many recent political campaigns. Notable commercial solutions for robotic surveillance are provided by SMP Robotics (Canada), Knightscope (USA), and OTSAW (Singapore). Also in this context, most of the robots employed are grounded, while aerial solutions are far less common [100, 101].

As these scenarios are generally highly dynamic and unstructured, it is often important to enable human operators to control the robotic systems in a reactive, effective, and intuitive manner. For example, most USAR robots are nowadays fully teleoperated [102] while autonomous solutions are scarce. On the other hand, autonomous surveillance robots are more common. However, also in this case, a human operator can usually remotely access the robots. While these solutions are already widely employed, having the expert operator present *in* the target environment has been proven to significantly improve the response time and effectiveness with respect to remotely teleoperated solutions [103]. Indeed, sharing the environment with the robots provides the human operator with a level of situational awareness that no teleoperation technology can match as of today.

Our work in this respect aims at improving the applicability of such mobile robotics system as well as at enriching the amount and quality of information provided to the controlling human operator(s).

4.1 Haptics for aerial robotics

We designed a decentralized connectivity-maintenance algorithm for the teleoperation of a team of multiple UAVs [28]. The proposed connectivity-maintenance algorithm enhances earlier works carried out in the team (mostly by Paolo Robuffo Giordano) by improving their applicability, safety, effectiveness, and ease of use. We included: (i) an airflow-avoidance behavior that avoids stack downwash phenomena in rotor-based aerial robots; (ii) a consensus-based action for enabling fast displacements with minimal topology changes by having all follower robots moving at the leader's velocity; (iii) an automatic decrease of the mini-mum degree of connectivity, enabling an intuitive and dynamic expansion/compression of the formation; and (iv) an automatic detection and resolution of deadlock configurations, i.e., when the robot leader cannot move due to counterbalancing connectivity-and external-related inputs. Results of two human subject experiments show that the proposed algorithm is effective in various situations. Moreover, using haptic feedback to provide information about the team connectivity outperforms providing both no feedback at all and sensory substitution via visual feedback. A video showing the different improvements is available here.

We have also worked on extending this framework to heterogeneous teams composed of humans and mobile robots that work together in the same environment [104], [105]. Differently from other works on the subject, here the human user physically becomes part of the team, moving in the same environment of the robots and receiving information about the team through wearable haptics and other types of ubiquitous feedback (see the concept idea in Fig. 11).

In [104], we presented a distributed algorithm able to manage a team composed of an arbitrary number of mobile robots (drones and ground robots in our case) and humans, for collaboratively achieving exploration and patrolling tasks. While the humans explore the environment, the robots move so as to keep the team connected via a connectivity-maintenance algorithm; at the same time, each robot can also be assigned with a specific target to visit. The operator is provided with information about the status of the team and tasks via two wearable vibrotactile bracelets (see a video here). Similarly, in [105], we presented a decentralized haptic-enabled multi-robot framework able to control the coordinated motion of a team consisting of mobile robots and one human, for collaboratively achieving SAR tasks. As in [104], also here the human operator moves in the same environment of the robots, while receiving rich haptic feedback about the team status and the direction toward a safe path. A video showing the details of this work is available here.

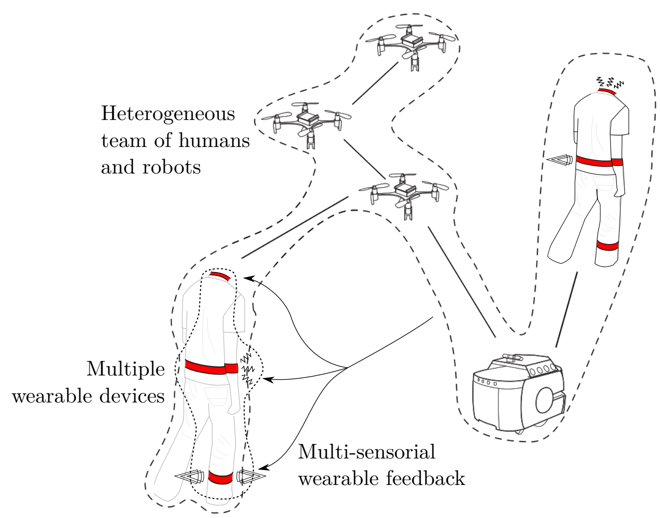


Figure 11: A team composed of two human operators, three drones, and one ground mobile robot explores the environment. The human control the coordinated motion of the team while receiving wearable vibrotactile and skin stretch haptic feedback on the status of the team and task.

4.2 Haptics for ground mobile robotics

Along a similar line, we also worked on devising a shared control and active perception framework combining the skills of a human operator with the capabilities of a mobile robot in autonomously maximizing the information acquired by the on board sensors for improving its state estimation [26],

[29]. The human operator modifies at runtime some suitable properties of a persistent cyclic path followed by the robot so as to achieve the given task (e.g., explore an environment). At the same time, the path is concurrently adjusted by the robot with the aim of maximizing the collected information. This combined behavior enables the human operator to control the high-level task of the robot while the latter autonomously improves its state estimation. The user's commands are included in a task priority framework together with other relevant constraints, while the quality of the acquired information is measured by the Shatten norm of the Constructibility Gramian. The user is also provided with guidance feedback pointing in the direction that would maximize this information metric. A video showing two teleoperation experiments carried out using this framework is available here.

We also started to study control-based techniques for trajectory optimization of mobile robots for environmental monitoring applications [27], which we plan to couple with haptic-enabled human-centered approaches in the next future.

5 Haptics for medical and assistive robotics

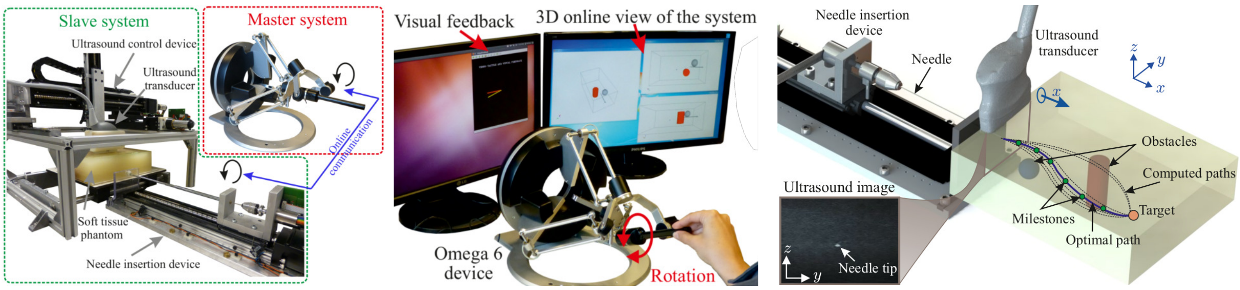
Haptic feedback has been historically used to provide information about the contact forces exchanged between the remote robot and environment, but it is also very effective in providing assistance information regarding the actions a supervisor controller considers best for the task and system at hand. Both forms of haptic feedback are particularly important for medical applications, where it is paramount to provide the clinician/surgeon the richest information possible about the remote environment and the status of the robot and task. Nowadays, despite the many expected and anticipate benefits, commercially-available medical robots provide very limited haptic sensations [106]. Among many others, Lanfranco et al. [107] and the SAGES-MIRA Robotic Surgery Consensus Group [108] indicate the lack of haptic feedback as one of the main limitations of nowadays robot-assisted surgery. This is due to different reasons, including the fact that outputting grounded forces may lead to undesired and abrupt oscillations of the system in the presence of communication delays or stiff environments, interfering with the operation and being possibly dangerous for the remote environment (see also Sec. 3). This limitation is of course extremely problematic wherever safety is paramount, such as in medical robotics [109].

In this respect, our work aims at studying how to provide rich haptic information in the most safe and effective way, especially focusing on cutaneous haptic feedback. Indeed, as cutaneous feedback provides ungrounded sensations, it does not affect the stability and safety of the teleoperation loop, making it very promising for this application.

5.1 Haptic feedback for needle insertion

Needle insertion into soft-tissue is a minimally invasive procedure used for diagnostic and therapeutic purposes. Examples of diagnostic needle insertion procedures are liver, kidney and lung biopsies to detect tumors [110]. Therapeutic applications of needle insertion include brachytherapy of cervical, prostate, breast cancers [111], and also thermal ablation therapies such as cryotherapy. Inaccurate placement of the needle may result in misdiagnosis or unsuccessful treatment. While autonomous needle insertion exists, for reasons of safety and acceptance, keeping the physician tightly in the loop is highly preferable.

Toward this objective, we tried to combine the advantages of manual steering with the high accuracy of autonomous (robotic) needle insertion. The system uses ultrasound imaging, path planning, and control to compute the desired needle orientation during the insertion and intuitively passes this information to the operator, who teleoperates the motion of the needle's tip [1, 112] (see Fig. 12). Navigation cues about the computed orientation are provided through vibrotactile haptic and/or visual feedback to the operator steering the needle.



(a) (b) (c)

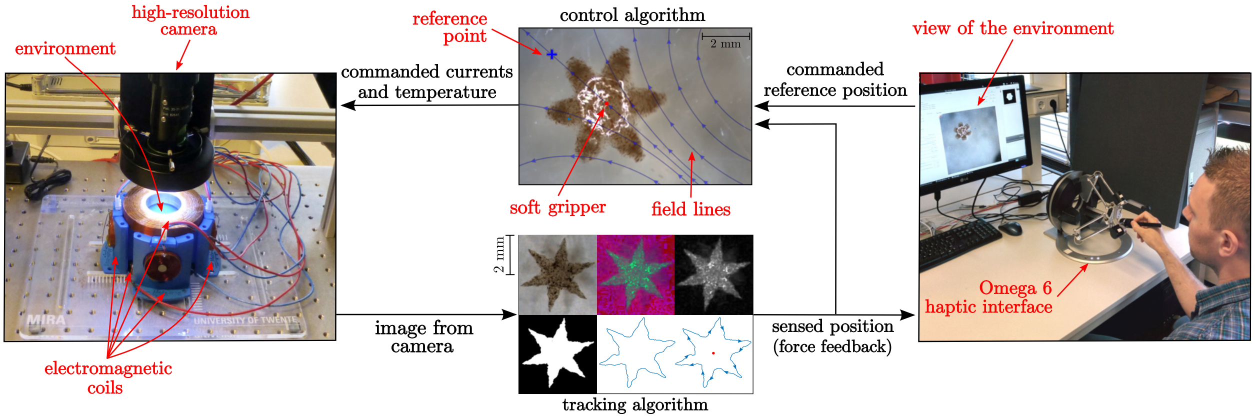
Figure 12: From [1]. (a),(b) The remote system includes the needle control device and the ultrasound tracking system. The master system includes the haptic device that allows the operator to control the needle. (c) The needle tip pose is determined using a two-dimensional ultrasound transducer. The path planning algorithm generates a feasible path by exploring the state space using a rapidly exploring random tree. The path planner generates milestones along the path, and the control algorithm steers the needle using the milestones to move along the planned trajectory.

Very recently, we started to work again on this problem, using a combination of wearable cutaneous interfaces and grounded kinesthetic interfaces to provide navigation information during needle insertion as well as cutting/insertion force [113]. Similarly to [1], the needle is tracked during the insertion using a 3D ultrasound probe. A friction estimation algorithm then extracts salient information about the cutting force at the needle tip from a force sensor placed at the needle base. A grounded haptic interface enables natural 6-DoF control of the needle motion while providing kinesthetic feedback, and a wearable cutaneous interface on the forearm provides distributed vibrotactile sensations. A video is available here.

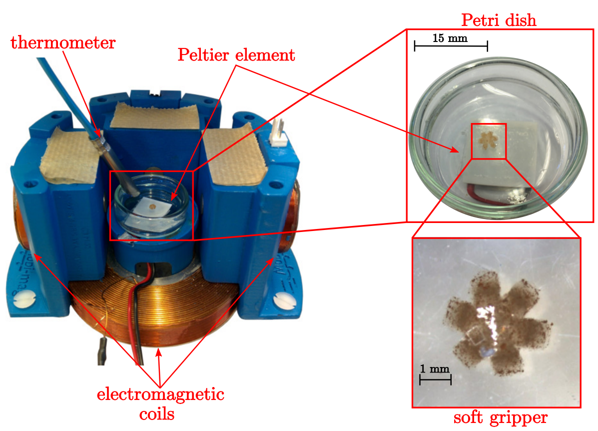
Finally, we also worked on the experimental design and evaluation of a teleoperation system for robot-assisted medical procedures providing *magnified* haptic sensations. It addresses the safety challenges of providing magnified haptic feedback in three different scenarios: stiffness discrimination during palpation, stiffness discrimination during needle insertion, and guidance during needle insertion [24]. (Magnified) haptic feedback can enable surgeons to deliver better care in procedures they are already performing robotically, and it could also broaden the range of operations that can be done with a robotic surgical system. A video of this system is available here.

5.2 Haptic feedback for microrobotics

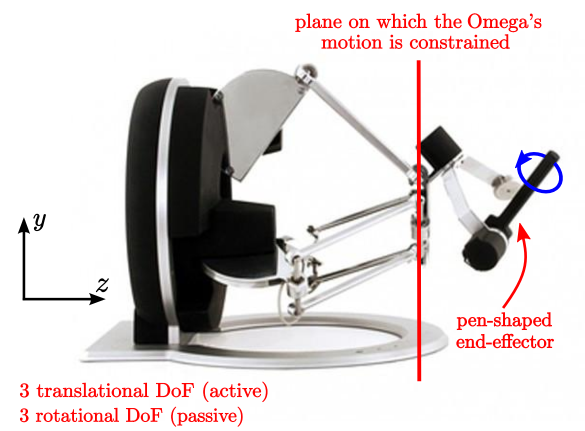
Microrobotics systems are showing promising results in several applications and scenarios, such as targeted drug delivery and screening, biopsy, environmental control, surgery, and assembly [114]. While most of the systems presented in the literature consider autonomous techniques, there is a growing interest in human-in-the-loop approaches [2]. As in the previous Section, for reasons of responsibility, safety, and public acceptance, it is in fact beneficial to provide a human with intuitive and effective means for directly controlling these microrobotic systems. In this respect, haptic feedback is once again widely believed to be a valuable tool in human-in-the-loop teleoperation systems. One of the main challenges for an effective implementation of haptic teleoperation of microrobots is stability control [115]. In fact, the high scaling factors introduced to match variables in the macro and the micro worlds may introduce instabilities. Another challenge lies in the measurement of position and force signals in the remote environment. The integration of microsized sensors may significantly increase the complexity and cost of tools fabrication. To overcome the lack of force-sensing, vision seems a promising solution [116, 117].



(a) Interconnected haptic-enabled micro teleoperation system.



(b) Detail of the remote system.



(c) Detail of the local system.

Figure 13: Haptic-enabled micro teleoperation system [3], [25]. The image-guided algorithm tracks the position of the miniaturized soft gripper in the remote environment using a high-resolution camera and a Fourier-descriptors-based algorithm. A 6-DoF grounded haptic interface then provides the human operator with haptic stimuli about the interaction of the gripper with the remote environment. At the same time, it enables the operator to intuitively control the reference position of the gripper. Finally, the magnetic control algorithm steers the gripper toward the reference position defined by the operator, and a Peltier element regulates the temperature of the distilled water where the gripper is floating.

In this respect, starting from our previous contributions on the topic [118], we worked on a teleoperation system with haptic feedback for the control of untethered soft grippers. The system is able to move and open/close the grippers by regulating the magnetic field and temperature in the workspace [3], [25]. The soft grippers can be wirelessly positioned using weak magnetic fields and opened/closed by changing their temperature. A particle-filter-based image-guided algorithm tracks the position of the controlled miniaturized gripper in the remote environment. A haptic interface provides the human operator with compelling haptic sensations about the interaction between the gripper and the environment as well as enables the operator to intuitively control the target position and grasping configuration of the gripper. Finally, magnetic and thermal control systems regulate the position and grasping configuration of the gripper (see Fig. 13). Results show that providing haptic stimuli elicited statistically significant improvements in the performance of navigation and micromanipulation tasks. A video summarizing this work and showing three use cases is available here.

5.3 Haptic feedback for robot-assisted medical palpation

As mentioned already, despite its expected clinical benefits, current teleoperated surgical robots do not provide the surgeon with haptic feedback. This is also due to the fact that grounded kinesthetic forces can destabilize the system's closed-loop controller. For this reason, we focused our research on ungrounded cutaneous solutions, able to provide rich haptic information while guaranteeing the safety of the system even in presence of delays or stiff contacts [109, 119, 120, 121, 122, 123].

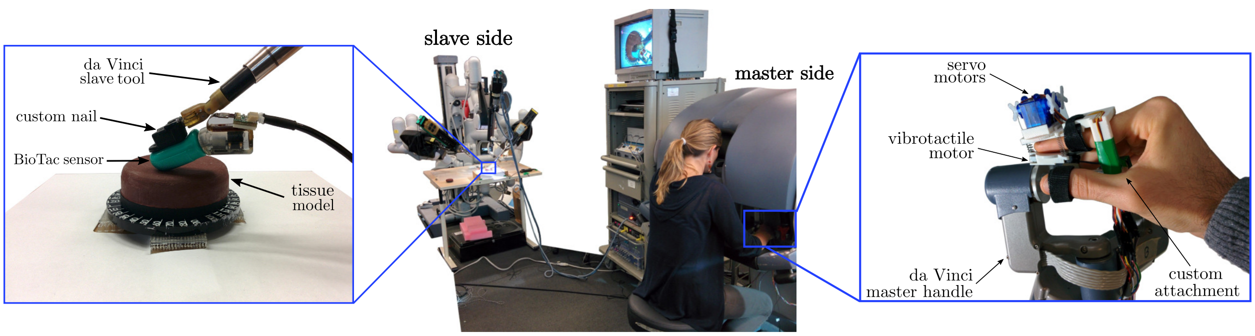


Figure 14: Cutaneous robot-assisted palpation system [4]. A BioTac tactile sensor (left) measures contact deformations and vibrations at the operating table, and a custom cutaneous feedback device (right) applies those deformations and vibrations to the surgeon's fingertip. The BioTac is attached to a da Vinci slave tool, and the cutaneous feedback device is attached to the robot's corresponding master controller. The BioTac follows the motions of the operator's finger.

We worked on the adaptation of the cutaneous fingertip devices described in Sec. 2.1 for use with the da Vinci Surgical robot. We designed an approach that enables the surgeon to feel fingertip contact deformations and vibrations while guaranteeing the teleoperator's stability [4]. We implemented our cutaneous feedback solution on an Intuitive Surgical da Vinci Standard robot by mounting a SynTouch BioTac tactile sensor to the distal end of a surgical instrument and a custom cutaneous display to the corresponding master controller. As the user probes the remote environment, the contact deformations, DC pressure, and AC pressure (vibrations) sensed by the BioTac are directly mapped to input commands for the cutaneous device's motors using a model-free algorithm based on look-up tables [124, 125]. The cutaneous display continually moves, tilts, and vibrates a flat plate at the operator's fingertip to optimally reproduce the tactile sensations experienced by the BioTac (see Fig. 14). This mapping between the sensations registered by the BioTac and the motor actuation of the cutaneous device is performed using a machine-learning-like approach. In fact, rather than attempting to create an accurate mechanical model of the actuation and sensing systems from first principles, we solved this problem with a data-driven approach that uses look-up tables of fingertip deformation recordings vs. motor commands and vibration recordings vs. motor commands. Specifically, we placed the BioTac *inside* the cutaneous device and tested how the motion of the mobile platform affects the fingertip deformation and vibration readings. During teleoperation, these recorded data are used to map contact deformations and vibrations sensed by the BioTac to input commands for the cutaneous device's servo motors and vibrotactile motor, respectively. A video summarizing this work is available here. An extension of this approach for pinching palpation has been presented in [13].

5.4 Haptic feedback for laser microsurgery

Transoral Laser Microsurgery (TLM) is a suite of minimally invasive surgical techniques for the management of minuscule laryngeal tumors [126, 127]. In these interventions, a carbon dioxide (CO_2) laser is used as a cutting tool to perform incisions in soft tissue. The execution of such accurate tumor resections requires precise control of the laser incisions. However, nowadays, laser incisions are performed manually. Surgeons control the laser aiming using a joystick-like device, called laser micromanipulator, while the laser activation/deactivation is controlled with a footswitch [128, 129]. While rather popular, such approach provides the surgeon with little feedback about the depth of the incision. As the CO_2 laser operates in a contactless (vaporisational) fashion [130], surgeons cannot use their sense of touch to estimate the depth of the incisions they make, as it would happen if cutting with a scalpel. Furthermore, state-of-the-art technology for TLM does not include any support to accurately measure the depth of laser cuts. As a result, the accuracy of incisions can only be estimated visually. For all these reasons, surgical precision in TLM procedures largely depends on the dexterity and experience of the operating surgeon, which require extensive training.

We worked on a laser microsurgery control interface that uses haptic feedback to provide real-time laser incision depth information to the surgeon [6]. The depth information is rendered to the surgeon through a grounded haptic device, using both kinesthetic and vibrotactile haptic feedback. We aimed at evaluating (i) the level of laser cutting accuracy enabled by the use of haptic feedback, and (ii) the users' confidence in using the proposed system. Furthermore, we provide a comparison with the existing system based on visual feedback and the traditional feedback-less laser cutting method. Results show that haptic feedback can significantly improve the level of surgical precision of laser interventions (see Fig. 15). Further refinements of this approach aimed at increasing the operator dexterity in operating the laser have been presented in [7], [36].

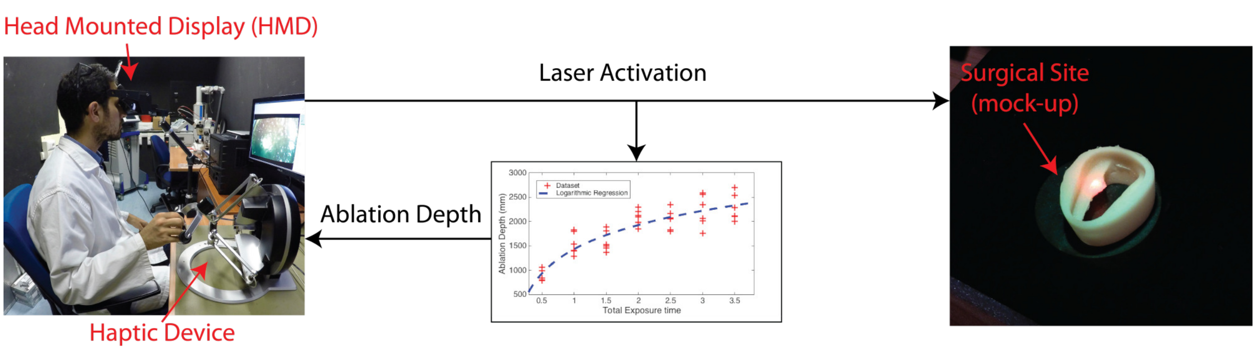
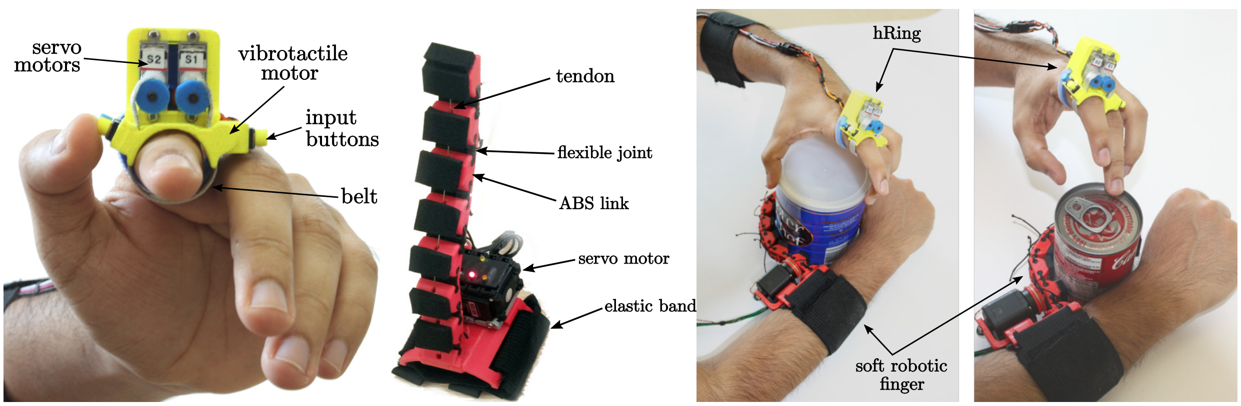


Figure 15: Haptic-enabled laser ablation system [6]. The surgeon views the surgical site through a stereoscopic display while using the Omega 6 haptic interface to control the laser aiming and its activation. A mathematical model is used to map the total time of laser activation to the resulting laser ablation depth. This information is rendered to the surgeon through kinesthetic and vibrotactile feedback provided by the Omega haptic interface.

5.5 Haptic feedback for rehabiliation

Long-term disabilities of the upper limb affects millions of stroke survivors, with more than 80% of individuals who experience severe hemiparesis after stroke that cannot completely recover hand and arm use [131]. The improvement of the paretic hand functionality plays indeed a key role in the functional recovery of stroke patients with a paretic upper limb [132]. Different motor impairments can affect the hand both at motor execution and motor planning/learning level, including weakness of wrist/finger extensors, increased wrist/finger flexors tone and spasticity, co-contraction, impaired finger independence, poor coordination between grip and load forces, inefficient scaling of grip force and peak aperture, and delayed preparation, initiation, and termination of object grip [133].

To compensate for the missing motor functions, my former group at the University of Siena (Prof. Prattichizzo) developed a series of robotic devices for the compensation of hand functions in chronic stroke patients, including a wearable robotic supernumerary finger that can be used as an active compensatory tool for grasping objects (see Fig. 16). The supernumerary finger is controlled by only one motor, and its soft structure enables it to adapt to the object being grasped, resulting in a gentle but stable grasp. The device consists of two main parts: a modular flexible finger and a support base, as shown in Fig. 16b. The flexible finger is composed of seven identical modules. Each module consists of an ABS part that acts as a rigid link and a 3D printed TPU (thermoplastic polyurethane) part that acts as a flexible joint. The servomotor drives the flexion/extension of the finger by pulling/releasing the tendon. Inspired from some previous work on the topic [134], we coupled this supernumerary flexible finger with a wearable haptic interface, presented in [9] and described in Sec. 2.1, to provide normal, skin stretch, and vibrotactile stimuli at the wearer's finger, relying rich information about the forces exerted by the supernumerary finger on the environment [11, 12], [55], [57]. The device enabled the patients to easily control the motion of the robotic finger while being provided the haptic feedback about the status of the grasping action. A video is available here.



(a) hRing haptic interface. (b) Supernumerary finger. (c) Opening a jar of coffee (left) and tomato (right).

Figure 16: The robotic system for rehabiliation presented in [11], [55], [57]. It is composed of a supernumerary robotic finger and a wearable cutaneous finger interface, called hRing [9]. The picture shows the integrated system used by a patient in Activities of Daily Living (ADL). The hRing controls the opening/closing motion of the robotic finger and provides the wearer with information about the forces exerted by the robotic finger.

5.6 Haptic feedback for mobility assistance

People with severe disabilities often rely on power wheelchairs for moving around. However, if their driving abilities are affected by their condition, driving a power wheelchair can become very dangerous, both for themselves and the surrounding environment.

Inspired by previous work showing that vibrotactile feedback is effective in guiding humans, we proposed the use of wearable vibrotactile haptics for wheelchair navigation assistance [33] (see Fig. 17). Using one or two vibrotactile armbands, we can provide rich guidance feedback while leaving the user free to follow or deviate from the suggested path. Moreover, the armbands are inexpensive, easy to use, and very flexible. They can be worn either on the wrist, upper arm, or legs, depending on the preference and specific condition of the patient. They are also compatible with any wheelchair control system, including but not limited to the joystick controllers of commercially-available power wheelchairs. Each armband is composed of four evenly-spaced vibrotactile actuators, powered by a Li-ion battery and controlled by an embedded wireless electronic board. Drivers receive information regarding the trajectory to follow or the presence of obstacles via vibrotactile stimuli, but they are always the ones in charge of controlling the motion of the wheelchair. Finally, as the feedback and control are decoupled, the teleoperation loop is intrinsically safe. Results of human subjects experiments show that providing information on closest obstacle position improved significantly the safety of the driving task (least number of collisions). Moreover, participants expressed a positive feedback on the use of vibrotactile sensations as well as on the comfort of the armbands. A video summarizing this work is available here.

We are recently working to extend such navigation approach to also use skin stretch [34] and tap stimulation [35].

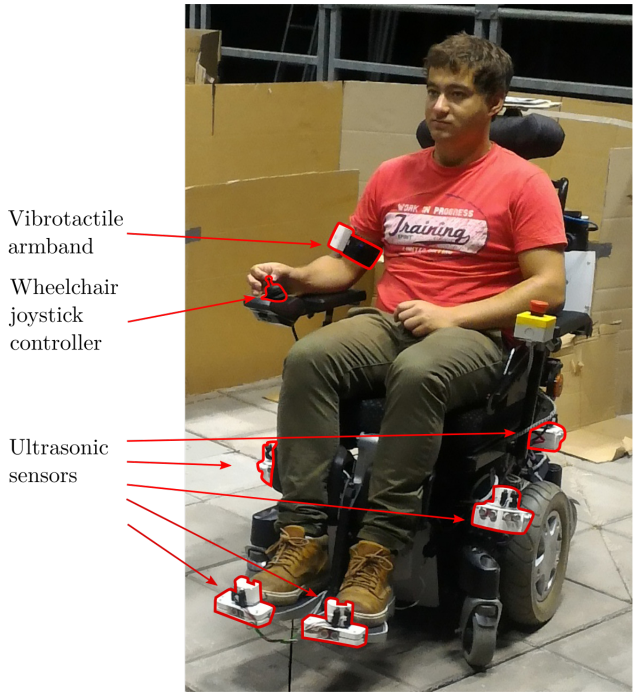


Figure 17: A participant drives a power wheelchair while being equipped with one or two vibrotactile armbands (one in this example). The wheelchair is commanded using a standard 2D joystick, and it is instrumented with 12 ultrasonic sensors to detect obstacles. The armbands provide information either on a trajectory to follow or the presence of obstacles [33].

6 Haptics for Virtual and Augmented Reality

Wearable haptics has a great potential in the fields of Virtual and Augmented Reality. In this respect, as also discussed in [41], gaming and immersive applications represent a fantastic market for wearable haptic technologies. Haptic technologies entered the gaming theater back in 1997, when Sony introduced its DualShock controller for PlayStation and Nintendo its Rumble Pak for the Nintendo 64. Both devices were able to provide a compelling vibrotactile feedback on particular events, such as a race car hitting the retaining wall or a plane crashing on the ground. Wearable haptics can take the immersiveness of such systems to the next level: a haptic vest can replicate the feeling of being hit by bullets in First Person Shooters (FPS) games, vibrotactile bracelets can reproduce the vibrations of the steering wheel of a race car driven in rough terrain, and fingertip devices can relay the feeling of touching in-game objects in action role-playing games (ARPG) and massively multi-player role-playing games (MMRPG). This opportunity is already being exploited by a few start-up companies, such as Immerz (USA), Tesla Studios (UK), and Actronika (FR). More recently, a few start-up companies have also taken up the challenge of designing wearable haptic devices for the fingertips, mainly targeting virtual reality and gaming applications. GoTouchVR (France) developed a 1-DoF wearable device equipped with a mobile platform able to apply pressure and make/break contact with the fingertip. WEART (Italy) is developing a wearable device composed of a static upper body and a mobile end-effector. The device is able to render pressure, texture, and the sensation of making and breaking contact with virtual objects. The development of wearable haptic systems from gaming applications goes of course together with the recent development and commercialization of wearable and unobtrusive virtual reality headsets, such as the Oculus Rift and the HTC Vive. In this respect, there are already some promising examples of applications integrating virtual reality headsets with wearable haptic systems. For example, GoTouchVR and WEART have already been showing demonstrations of their wearable haptics systems featuring immersive environments displayed through these virtual reality headsets.

6.1 Wearable finger haptic devices for immersive environments

We started by combining our wearable haptic interfaces presented in Sec. 2.1 in Virtual Reality environments, inspired by some preliminary work we carried out in the topic [135, 136, 137].

We evaluated the role and effectiveness of wearable haptics in interacting with virtually-augmented world, especially focusing on how the placement of the haptic device can affect the interaction quality [40], [42]. We evaluated two wearable haptic systems for the fingers, [51] and [9], in six representative augmented reality applications. In the first experiment, subjects are requested to write on a virtual board using a real chalk. The haptic devices provide the interaction forces between the chalk and the board. In the second experiment, subjects are asked to pick and place virtual and real objects. The haptic devices provide the interaction forces due to the weight of the virtual objects being picked up. In the third experiment, subjects are asked to balance a virtual sphere on a real cardboard. The haptic devices provide the interaction forces due to the weight of the virtual sphere rolling on the cardboard. In the fourth experiment, subjects are asked to complete a mixed reality "box and block" test, which is a functional test used in upper limb rehabilitation. In the fifth experiment, we considered a guidance task for industrial training, where subjects are asked to place the cube rendered on the subject's finger in a target position. Finally, in the sixth experiment, subjects played the mixed reality first-person shooter RoboRaid game, that consists of defending your home against a (virtual) robot/alien invasion. Results showed that providing haptic feedback through the considered wearable device significantly improved the performance of all the considered tasks with respect to providing no haptic feedback. Moreover, results showed that wearing the device at the fingertip reduces the user's immersiveness when interacting with tangible objects. Videos of these experiments are available here and here.

We presented similar works aimed at employing and evaluating our wearable haptic devices in different immersive virtual reality scenarios and applications in [46], [49], [59].

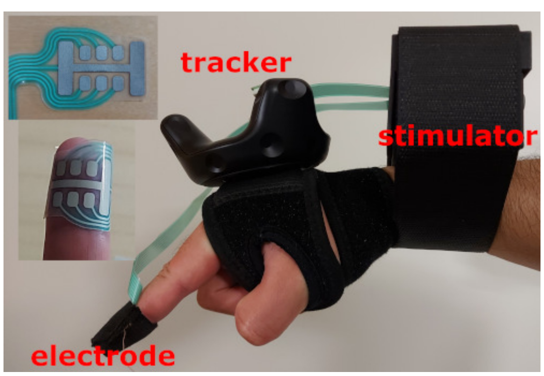


Figure 18: An electrical stimulator is attached to the forearm and the electrode is placed in contact with the finger pad. The user's hand is tracked by a HTC Vive Tracker [138].

Very recently, we have also started working on electrotactile haptics for the fingertip. Electrotactile feedback is provided by a system comprised of electrodes and stimulators (actuators). The electrical current travels through the subdermal area between the anode(s) and cathode(s) and stimulates the nerves endings (i.e., skin's receptors). The area of the skin where the electrode contacts the skin is stimulated, however the sensation may be spread further when the contact point is near nerve bundles [139]. The way electrotactile systems functions is therefore different than mechanical and thermal tactile interfaces, as it is not mediated by any skin receptor. In this respect, we used a wearable electrotactile device for the fingertip to render the interpenetration distance between the user's finger and virtual objects [138] (see Fig. 18). The perceived intensity (frequency and pulse width modulation) of the electrotactile stimuli was modulated according to the registered interpenetration distance. We assessed the performance of four different interpenetration feedback approaches: electrotactile-only, visual-only, electrotactile and visual, and no interpenetration feedback. Results showed that contact precision and accuracy were significantly improved when using interpenetration feedback. Moreover, we found that visual and electrotactile feedback of interpenetration performed similarly, which is a quite interesting result.

6.2 Wearable haptics and tangible objects

Another very fruitful line of research in this field is that of augmenting passive tangible objects, which are known to be very effective at providing global and distributed shape sensations [140, 141]. However, being often passive, tangible objects are usually unable to simulate several varying contact sensations. In this respect, wearable haptics is gaining interest in VR/AR, being unobtrusive, lightweight, inexpensive, and able to display varying touch sensations when interacting with virtual objects. However, wearable devices are usually not able to provide kinesthetic feedback, failing at effectively simulating stiff contacts and global shapes [41].

First, we studied how similar tangible and virtual objects need to be, in terms of haptic perception, to still feel the same [48]. As it is often not possible to create tangible replicas of all the virtual objects in the scene, it is important to understand how different tangible and virtual objects can be without the user noticing. On a similar line, we presented an algorithm able to analyze the available tangible and virtual objects in the considered real and virtual environments to find the best grasps in terms of matching haptic sensations [45]. The algorithm starts by identifying several suitable pinching poses on the considered tangible and virtual objects. Then, for each pose, it evaluates a series of haptically-salient characteristics. Next, it identifies the two most similar pinching poses according to these metrics, one on the tangible and one on the virtual object. Finally, it highlights the chosen pinching pose, which provides the best matching sensation between what users see and touch.

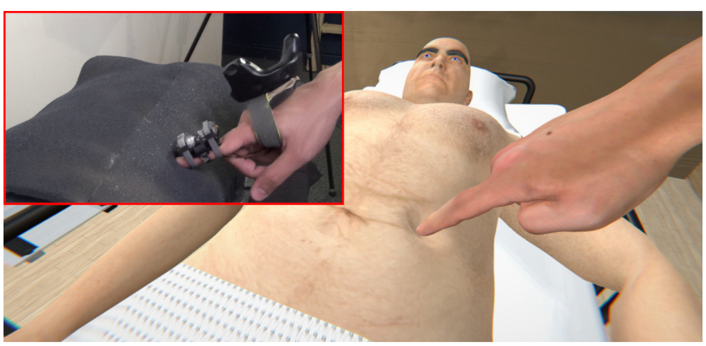


Figure 19: Use case from [43]. A human user wearing a finger device interactswith a tangible object that resembles the abdomen of a virtual human patient.Providing timely cutaneous stimuli via the wearable haptic device, we can alterthe stiffness and shape perception of passive tangible objects. For example, inthe context of medical palpation, we can simulate the presence of a tender bodypart or of a small bump representing a cyst.

From these results, to improve the range and effectiveness of haptic sensations in virtual environments, we studied the effect of combining tangible objects (for simulating the global and distributed shape/percept of the virtual object) together with wearable haptics (for dynamically changing the mechanical properties of the object). By applying timely cutaneous sensation through wearable devices, we tested the possibility of altering the sensation of stiffness/elasticity [43], [47], shape [43], and friction [43] of virtual/tangible objects. Results confirm that we can increase and decrease the perceived compliance of a tangible object by varying the pressure applied through a wearable device. We were also able to simulate the presence of bumps and holes by providing timely pressure and skin stretch sensations. Altering the friction of a tangible surface showed recognition rates above the chance level, albeit lower than those registered when altering the other characteristics. Finally, we showed the potential of our techniques in an immersive medical palpation use case in VR, shown in Fig. 19. Videos of these experiences are available here and here.

Finally, while working with tangible objects, we realized that one of the biggest issue lies in the tracking of the user. Indeed, one important factor to achieve an immersive VR experience is the synchronization of motion and sensory feedback between the human users and their virtual avatars. Whenever one user moves a limb, the same motion should be replicated by the avatar; similarly, whenever the avatar touches a virtual object,the user should feel the same haptic experience. To ensure a good match between the motion of the users with respect to their avatars, commercial VR systems already provide vision-based solutions able to track the headset or a dedicated active prop (e.g., the HTC Vive tracker). Other more advanced approaches consist in tracking a set of markers constellations worn directly by the user (e.g., Vicon and Optitrack systems). However, they require a clear line of sight and their performance significantly degrades in the presence of, e.g., occlusions, calibration and modeling errors, suboptimal light conditions or positioning of the markers. This limitation leads to mismatches in the relative positioning of the virtual hand with respect to the virtual object, i.e., a negative or positive virtual gap upon contact, breaking the synchronicity of the virtual and tangible contacts. To address these issues, we worked on a new approach to rendering of contacts with tangible objects in VR, compensating such relative positioning error to achieve a better visuohaptic synchronization upon contact and preserve immersion during interaction in VR. We employed one tangible object to provide distributed haptic sensations. It is equipped with capacitive sensors to estimate the proximity of the user's fingertips to its surface. This information is then used to retarget, prior contact, the fingertips position as obtained from a standard vision tracking system, so as to achieve better synchronization between virtual and tangible contacts [44] (see Fig. 20). A video of the system is available here. Results of a human subjects study show that our approach significantly increased the perceived coherency and synchronicity of the VR experience, correcting common relative positioning errors related to the use of optical tracking systems and tangible objects.

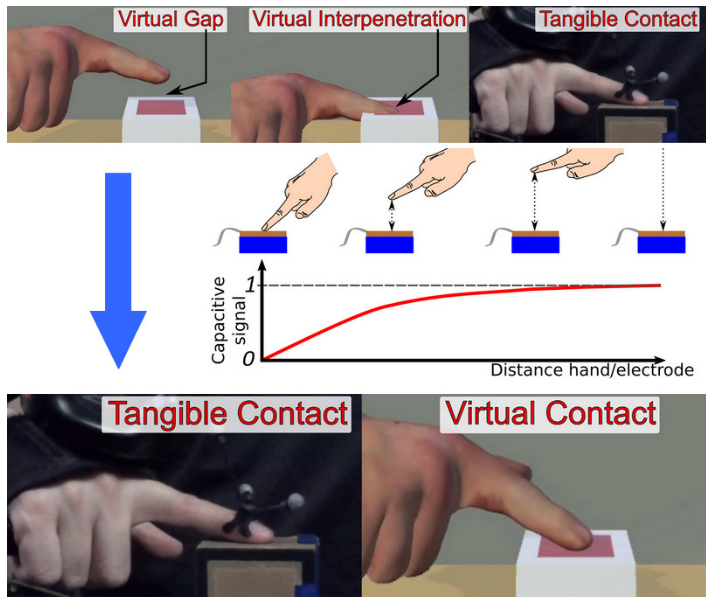


Figure 20: Representative issues while using standard optical tracking systems (up) vs. our integrated capacitive-based approach (bottom) [44]. By combining tracking information from standard optical tracking systems with proximity information from a capacitive sensor, we can re-target the virtual fingertip toward the virtual surface, achieving a better synchronization between tangible and virtual contacts.

6.3 Wearable haptics for crowd simulation

Virtual reality is a valuable experimental tool for studying human movement, including the analysis of interactions during locomotion tasks for developing crowd simulation algorithms. However, most VR experiences still lack of any haptic sensation, which is of course of paramount importance when studying crowd behavior and interactions. For example, if we are unable to render the sensation of bumping into virtual characters when navigating in a crowded environment, participants might stop avoiding collisions, leading to data that does not capture well how humans truly behave.

Figure 21: The objective of [30] is to understand whether and to what extent providing haptic rendering of collisions during navigation through a virtual crowd (right) makes users behave more realistically. Whenever a collision occurs (center), armbands worn on the arms locally vibrate to render this contact (left).

For this reason, we explored the role of contact interactions (collisions) during navigation in a crowded environment [30]. To do so, we employed a set of wearable haptic interfaces able to provide compelling vibrotactile sensations of contact to the user's arms. Our objective was to investigate whether and to what extent the rendering of contacts influences the user's behavior in this context, as well as limits the occurrence of certain well-known artifacts, such as when the user's virtual avatar interpenetrates other virtual characters. We conducted an experiment where participants were equipped with four wearable haptic interfaces (two on each arm), and asked to navigate in a densely-crowded virtual train station (see Fig. 21). We evaluated objective metrics related to the user's behavior with respect to the crowd, as well as subjective metrics related to the user's sense of presence and embodiment. First, we carried out the experiment without haptic rendering of contacts, then with haptic rendering,and finally once again without haptic rendering. This experimental design enabled us to register the difference in user's behavior when activating the haptic feedback as well as the persistence of any relevant after-effect. Results showed that providing haptic feedback improved the overall realism of the interaction, as participants more actively avoided collisions. We also noticed a significant after-effect in the users' behavior when haptic rendering was once again disabled in the third part of the experiment. Nonetheless, haptic feedback did not have any significant impact on the users' sense of presence and embodiment. This experiment is shown here.

Insights from this work were later on used to define a user-friendly approach to sketch interactions for defining collective behaviors [31] as well to drive the motion of reactive virtual agents [32].

7 Future work and open questions

7.1 Motivation

Robotics has created huge opportunities in a broad range of industries and applications, ranging from space and deep ocean exploration to search-and-rescue, robot-assisted surgery, and manipulation of hazardous materials. Teleoperated and (semi-)autonomous robots are already exploring the surface of Mars, they help our public forces during natural calamities, perform over 700,000 surgeries per year, navigate our oceans, and sort our waste. The medical robotics market alone is projected to reach USD 16.74 billion by 2023, from an estimated USD 6.46 billion in 2018, at a compound annual growth rate (CAGR) of 21%. On-orbit teleoperation between a manned spacecraft and the planet's surface is already considered the most promising way of exploring far planets, and the years 2020s are expected to see several new teleoperated surgical platforms, including Verb Surgical by Johnson&Johnson and Alphabet.

In this respect, as seen in the first part of this document, haptic feedback has been widely proven to be a valuable tool for robotics at large, spanning a great range of high-impact scenarios, including surgical robotics, microrobotics, needle insertion, manipulation, human-robot interaction, and immersive environments. The benefits of haptic feedback in such scenarios include increased manipulation and perception accuracy, decreased completion time, decreased peak and mean force applied to the remote/virtual environment, increased immersion and user's experience. One of the most prominent features of haptic feedback systems is that they can provide several pieces of information at once (e.g., force/torque contact sensations, stiff/compliant active constraints, information on the presence of singularities, workspace limitations, and dangerous areas to avoid). This is possible because our sense of touch is spread across our body and it is composed of different receptors (kinesthetic, tactile/cutaneous, thermal). The same result cannot be achieved using, e.g., the visual or audio modality. This important characteristic has made haptic feedback one of the most anticipated and wanted feature in many fields, including robotics, promising steep performance increases in a wide range of scenarios – however, this is not currently the case.

However, despite these well-proven benefits, current commercial robotic systems provide very limited haptic feedback. This surprising omission and mismatch between good research/lab results and poor industry/field adoption is due to three main barriers (b):

b1. the challenge of devising effective, viable, and general haptic rendering policies	
What we HAVE	Haptic feedback can convey **contact feedback** (multi-directional force/torque sensations) and **haptic assistance** (navigational/forbidden-region, stiff/compliant constraints), using a wide set of haptic sensations, i.e., **grounded (kinesthetic) and ungrounded (cutaneous) stimuli.** It is however challenging to understand how to convey all this information at once, in a way that it is effective and applicable to a wide range of scenarios. Currently, **empirical choices based on personal experience are the standard**, leading to suboptimal policies that convey a limited number of information using only **single-point** kinesthetic feedback, **forcing engineers to devise ad-hoc methods for each task.** This limitation is extremely daunting, as robotic and immersive systems are often targeted to serve multiple purposes and should not need to be reprogrammed for every task.

What we NEED	⟹ **There is a need for a unified approach able to combine all the above haptic techniques and sensory delivery methods.** Such unified framework should detect the situation at hand (task, environment, robotic system, operator) and **provide all the relevant feedback information** (contact, assistance) **through an effective set of multi-point multi-sensory interfaces** (kinesthetic, cutaneous, visual, audio), transparently with respect to the user. This technique should also be as general as possible, easily applicable to a wide range of interaction scenarios with minimal adjustments.
b2. the negative effect grounded kinesthetic feedback has on the safety of the system	
What we HAVE	Although kinesthetic feedback is the current standard, **outputting grounded forces may lead to undesired and abrupt oscillations of the system** in the presence of communication delays or stiff environments, interfering with the operation and being possibly dangerous for the remote environment [142]. This limitation is extremely problematic wherever safety is paramount, such as in medical robotics or in the handling of dangerous materials. Even though safety control techniques exists, they severely affect the system's performance [143, 144].
What we NEED	⟹ **There is a need for safe yet effective and rich haptic solutions.** We need ground-breaking haptic techniques combining multiple sensory stimuli and devices, **interleaved at runtime to achieve higher safety while guaranteeing good performance and user's experience**. An autonomous supervisor should understand when and where to modulate kinesthetic feedback to guarantee stability and safety, and then act to compensate for this reduction of feedback through other sensory systems (cutaneous) **which are known to be safe** [109].
b3. the high cost and complexity of currently-available haptic-enabled consoles	
What we HAVE	The market of haptic systems is currently dominated by single-point grounded kinesthetic interfaces. **Such devices are rather complex and expensive**, costing up to EUR 100,000. They usually only provide kinesthetic feedback at one contact point (e.g., the hand), **severely limiting the richness of the feedback information.** This limitation is extremely discouraging for most industries, as including haptic feedback means significantly increasing the system's price, especially if multi-point feedback is required (e.g., bi-manual consoles for telerobotic surgery).
What we NEED	⟹ **There is a need for an innovative set of haptic interfaces able to provide rich, distributed, safe, and cost-effective feedback information.** These new haptic interfaces should provide a wide set of haptic sensations applied to multiple parts of the body, as to provide multiple pieces of feedback information at once. This feedback should come across as easy to understand and pleasant to receive for a long period of time. Finally, these devices should also be relatively inexpensive, as to enable easy replication and everyday use.

Research around these three barriers will steer my future objectives, knowing that the above are three important limitations nowadays preventing haptics from being broadly available in robotic and immersive systems. In the following, I will detail a bit more these future directions of research, highlight three main axes of research: design of haptic interfaces and rendering techniques, haptics for multi-robot teaming, and haptics for Mixed Reality. Of course, my future research will not be limited to these three topics.

7.2 Future research directions

7.2.1 Design of (wearable) haptic interfaces and rendering policies

Creating new haptic interfaces is always exciting. Although I have already worked considerably on this topic in the past, I believe there is still a lot to do in terms of science (understanding haptic perception, combining multiple types of stimulation), technology (creating compact yet effective devices, experimenting with new materials), and application (using haptic devices in new scenarios), especially when considering the design and development of wearable haptic interfaces.

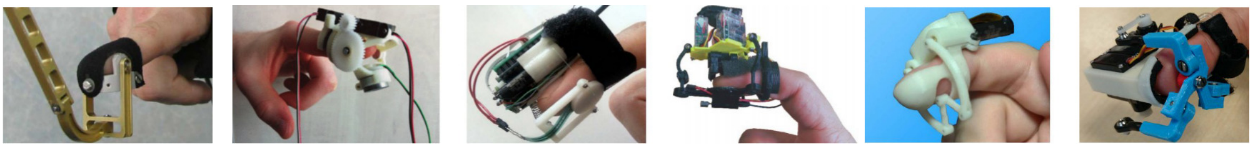


Figure 22: Six representative examples of wearable devices for the fingertip. From left to right, the devices of the CEA (2005 - 16 years ago!), Scuola Superiore Sant'Anna (2016), Univ. Siena (2014), Italian Institute of Technology (2015), Keio University (2007), Skoltech (2014 & 2019), Scuola Superiore Sant'Anna (2015).

Wearable devices have been proposed for different parts of the body, providing kinesthetic, pressure, skin stretch, and vibration stimuli to the fingers, hand, and forearm. However, it is rare to find devices designed to provide more than one type of haptic sensation. This is mostly due to form factor, size, and weight constraints: developing a device able to provide multiple sensations means including more actuators, resulting in bulkier structures. Moreover, most devices are designed for the fingers and hand, and it is less common to find devices designed to be worn elsewhere. This is mostly due to the fact that the hand is the most sensitive parts of our body and, since most devices apply sensations at only one point, the hand is a good choice. Finally, researchers tend to design wearable interfaces as smaller versions of more classic kinesthetic desktop interfaces, using the same rigid materials (hard plastic, aluminum), end-effectors (a platform, a pin) and kinematics (parallel or articulated configuration). This is due to the simple fact that these are the most popular and established methods/techniques for designing any robotic structure. Indeed, how we design most wearable haptic interfaces has not fundamentally changed in the past two decades (see Fig. 22).

Using smart, flexible, and soft materials and electronics, coupled with the latest low-latency wireless technology, it is possible to design innovative multi-point multi-type cutaneous feedback systems, i.e., small, connected, distributed, modular interfaces able to provide different types of cutaneous sensations in multiple parts of the body. These devices should be comfortable to wear, lightweight [41], and able to combine multiple haptic sensations at once, applied throughout the user body. Each module could be wireless and independent, constantly coordinating and communicating with the others. Integrating data transfer and wireless powering into one miniature flexible device can significantly reduce its weight by removing bulky batteries and make it compact and lightweight. By combining different modules, we can imagine building rich multi-type cutaneous systems, easy to configure and re-configure into, e.g., bracelets, armbands, fingertip devices, or belts, according to the system's requirements. Users can wear these cutaneous devices through garments (e.g., an elastic cloth). For attaining increased wearability, attaching the cutaneous units directly on the skin using a layer of adhesive silicone is also a promising approach, as we already successfully tested on the back of the hand [58]. This approach enables to attach the haptic units wherever needed on the body, without being limited to locations where we can fit a band or a belt, e.g., a skin-stretch module can go on the chest, a vibration one on the torso. To convey a coherent sensory feedback to the user, these devices should communicate and interoperate with each other as well as with any other part of the feedback system (e.g., a grounded kinesthetic interface, the visual feedback). Similarly to an Internet-of-Things mesh network, they can communicate in a distributed and stand-alone manner through low-latency wireless connections, making the system unobtrusive and easily reconfigurable. Efficient cutaneous radiating structures will ensure reliable wireless link, maximize the data rate, and reduce the power budget. In this respect, wireless communication and powering/recharge of the modules can be enabled by custom radiating structures to direct the Radio frequency (RF) energy energy in a desired way. Such structures can be based on conformal antenna arrays in industrial, scientific and medical (ISM) frequency bands (including 5G bands) decoupled from the human body to reduce losses, maximize the radiation efficiency, improve robustness, and reduce exposure of users. Multiband and reconfigurable solutions can also be employed to maximize the robustness of links considering the dynamic spatial behavior of the system. Finally, exposure reduction techniques should be implemented to minimize the user exposure and ensure the compliance with exposure regulations, e.g., near-field shaping, feeding type optimization, use of EBG structures and/or electrotextile. Indeed, the study of the effect of wearing these devices onto the body is another interesting area of research.

The modularity of such wearable haptic devices also opens a new direction for their personalization. In addition to hardware- [73] and rendering-based [61] personalization techniques, we can also optimize the placement of the modules according to the specific characteristics of the user, his or her preference, as well as the nature of the task.

Below I briefly discuss three possible areas of application for this technology, although it is clear that such systems might be employed well beyond these scenarios.

Application in healthcare. We are seeing a rapid increase in the number of tissue-implantable devices able to monitor different health-related parameters (e.g., insulin sensors implanted under skin). Nowadays, these devices provide information and alerts about the current health status of the user via, e.g., audio alerts, provided through an external system, e.g., a smartphone. Using flexible wearable haptic modules to provide such information would represent a more private (e.g., only the wearer will feel the alerts) and reliable (e.g., no risks if the smartphone is out of battery or not with the wearer) solution.

Application in robotics. Most robotic applications use desktop kinesthetic interfaces or single-point cutaneous devices for controlling, e.g., a remote manipulator. Being able to easily and comfortably distribute the feedback coming from the remote environment throughout the operator's body will enable richer interactions, e.g., we could provide contact feedback at the fingertips via pressure stimuli, guidance feedback along the arm via skin stretch, and alerts on collisions on the shoulders via vibratory sensations (see Fig. 23).

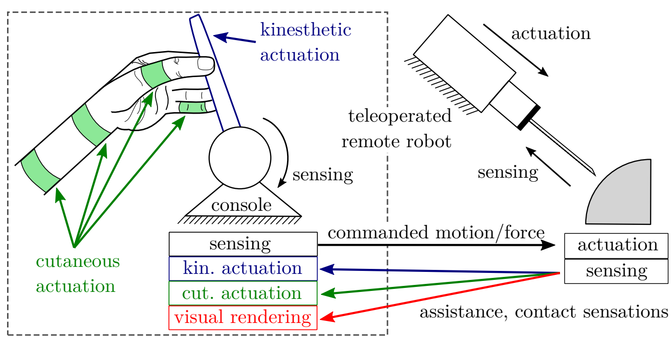


Figure 23: In a robotic teleoperation scenario, we can complement standard kinesthetic and visual feedback with distributed wearable cutaneous interfaces.

Application in Virtual Reality. Currently-available interactions with virtual objects lack haptic sensations. Depending on the VR scenario at hand, users can attach distributed haptic modules on their body, receiving, e.g., soothing vibrations to render drops of rain on their back, sharp contacts to render gunshots on their chest.

7.2.2 Haptic shared control for heterogeneous human-robot teams

Teams of coordinated robots have been successfully used in a plethora of different applications, including disaster response, exploration, patrolling, and surveillance. As already mentioned in Sec. 4, the use of mobile robots for disaster response is on the rise, with a promising attention toward human-centered solutions. Another promising application is that of robotic agriculture, where mobile robots can be used to monitor the cultures and optimize human interventions. In all these situations, it is important to keep the human operators in the loop, sharing the same environment as the robots. Indeed, having one or more expert operators present in the target environment can significantly improve the response time and effectiveness with respect to remotely teleoperated solutions, providing the operator with a level of situational awareness that no teleoperation technology can match.

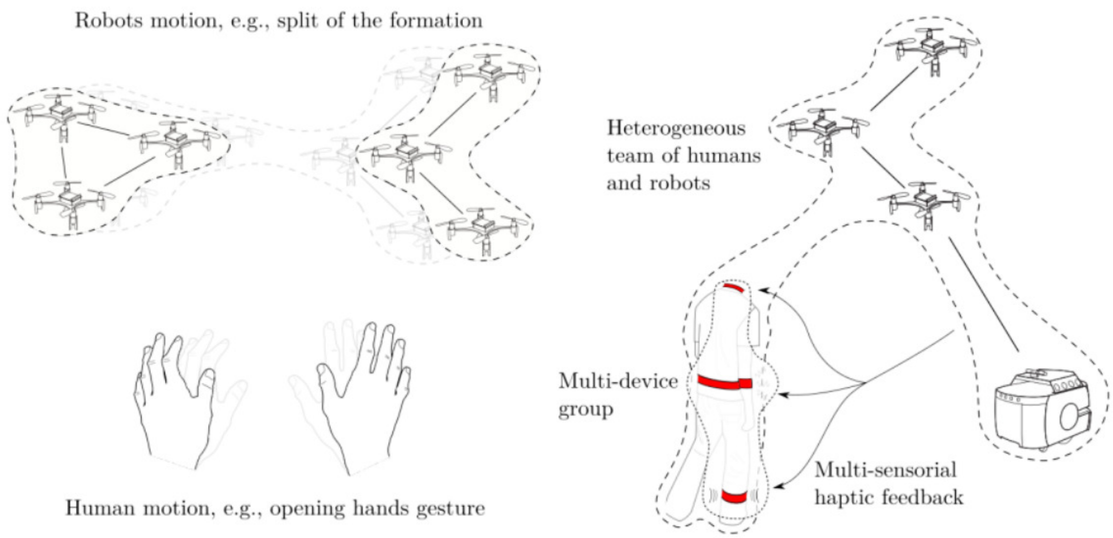


Figure 24: Representative scenario. (Left) A user controls the motion of six drones in a shared environment, splitting - with an opening-hands gesture - a connected team of drones in two so as to cover more ground. (Right) He receives vibrotactile and skin stretch feedback spread throughout the body - through a multi-device group, informing him about the status of the team(s), of the environment, and the task.

In this context, it would be very exciting to continue our research beyond [104, 105], pursuing novel paradigms for the (shared) control of a heterogeneous team composed of both robots and humans, suitable for applications involving exploration, mapping, patrolling, surveillance, agriculture, environmental monitoring, and USAR operations. Similarly to [104, 105], one or more human operators move in the same environment of the robotic team, composed of multiple aerial and grounded mobile robots. Each unit in the team needs to share information with its neighbor, process these pieces of information in a distributed way, and carry out certain tasks according to its specific function. To achieve such a level of team integration so as to carry out meaningful collaborative tasks, it is important to advance the state of the art in human-robot communication and interaction, formation control, and multi-robot systems.

Following this idea, I see two main research objectives to pursue.

The first one deals with enabling humans to intuitively and naturally control the motion of diverse multiple robots (e.g., a team of grounded and aerial robots coordinated by humans), by finding novel theoretical approaches and scientific solutions advancing the state-of-the-art toward new shared-control operation systems (i.e., where the control of the robot is shared between users and an autonomous control algorithm). To do so, we should unobtrusively track the human body and then map its motion to the robots, studying how to link the motion of systems which are kinematically very different, e.g., five or ten fingers vs. a fleet of UAVs. A promising approach is to employ techniques nowadays used for the control of robotic hands with dissimilar kinematics [145]. From there, we can design semi-autonomous shared-control solutions, where controlled points at the remote side are represented by multiple robots (and their tools). Sensor-based techniques can be used to enable the remote robots to deviate from the commands imparted by the operator, so as to ease their control (e.g., while the operator commands a desired trajectory, the robots may autonomously avoid collisions). Similarly, we can also study how the human operator can impart commands deviating from what the autonomous controller expects. For example, considering a connected team of aerial and ground mobile robots exploring a disaster area, the human should be able to split the team in two, temporarily breaking the team to cover a wider area (see Fig. 24). Such command, although useful to the task, requires understanding how to handle a controlled disconnection of the team and how to manage eventual reconnections, which is not trivial. The second research objective deals with the ability of providing the human operator with rich feedback information in a comfortable, unobtrusive, and ubiquitous way, by advancing the state-of-the-art toward the development of effective multimodal and multi-point wearable haptic feedback systems. This objective fits perfectly the research already described in Sec. 7.2.1, that can be seen as an input for this line of research. However, it is important to understand what is needed to best fit this specific scenario. Using distributed cutaneous modules, we should study which pieces of information are most important to provide to the operator for the selected tasks, e.g., mechanical properties of the environment, presence of obstacles and other robots, trajectory guidance, so as to achieve the best outcome. These devices can be seen as part of a larger "multi-device" (cyberphysical) system, resembling that of a multi-robot one.

Below I briefly discuss possible areas of application for this technology.

Application in USAR. Field USAR scenario are high-impact applications that can greatly benefit from this type of human-robot team collaboration. In this respect, we could consider the haptic-enabled control of a heterogeneous human-robot team, composed of multiple humans, aerial robots, and mobile grounded robots. For example, we can address tasks of multi-robot surveillance, mapping, and exploration of dangerous environments, combining decentralized topological motion control with the proposed heterogeneous human-robot approach. Imagine a heterogeneous team composed of one expert rescuer, one doctor, three recon drones, and one ground mobile robot carrying medical supplies. The team has just accessed a neighborhood hit by a earthquake. Through cameras, one of the drones quickly identifies a group of injured survivors gathered in front of a residential building. This information is relayed to the rescuers, who start to move in their direction. While this happens, one drone analyzes the area around the survivors, assessing the structural quality of neighboring buildings and their risk of collapse; another drone flies directly to the survivors, putting them in contact with the doctor and indicating a safer location to wait. Few minutes later, the doctor arrives in place and starts attending the injured survivors using the medical supplies carried by the ground mobile robot. The expert rescuer, from the information gathered by the drones, draws the safest path out of the disastered area and communicate it to the doctor. Finally, the group splits in two: the survivors join the doctor, one drone, and the ground mobile robot in a new heterogeneous team that moves out of the area; on the other hand, the expert rescuer and the remaining two drones continue their task. Once the survivors are secured, the heterogeneous team led by the doctor joins again the rescuers and the drones, bringing new supplies.

Application in indoor inspection. Another interesting scenario can be the disinfection of indoor spaces, which has recently shown a great importance. Few human operators, aided by a coordinated robotic team, can direct the sanitation of large environments.

7.2.3 Haptics for Mixed Reality

Haptic feedback is an essential component of the user's immersive experience when interacting in Mixed Reality (MR). Many ways of simulating haptic sensations in virtual and remote scenarios exist, e.g., using dedicated and actuated such as force feedback or tactile interfaces, using passive props such as tangible objects, or even exploiting perceptual phenomena with cross-modal effects or sensory substitutions. Every approach has its drawbacks and advantages, but none of them succeeds in reproducing, all-in-one, the complex richness of real haptic exploration, and especially not in a simple, cost-effective, rich, and portable manner. The challenge of developing effective portable haptic interfaces and rendering techniques for MR is one of the most researched in the fields of haptics and immersive environments, as being able to provide compelling haptic sensations in a comfortable and easy-to-carry way would pave the way for evolving from currently-available grounded/desktop haptic interactions to ubiquitous/wearable ones. Of course, the devices and rendering techniques I mentioned in Sec. 6 as well as the perspectives of Sec. 7.2.1 are good starting points, but it is important to tackle the specificity of MR vs. more standard interaction scenarios, e.g., the co-existence and interaction between physical and digital objects, which introduces a series of very specific challenges. Indeed, most currently-available haptic devices are designed to interact with virtual or remote objects.

Figure 25: Distributed wearable haptic interfaces can provide the user with the feeling of interacting with a mixture of virtual and real objects, haptically augmenting the world around us. This technology can be applied to gaming, industry training, data physicalization and rendering, CAD design, office productivity.

Along this line of research, I see three main research objectives to pursue.

The first objective deals with the study of how immersive audio-visual stimulation can coexist with (wearable) haptic sensations. It is paramount to advance our understanding on how to provide multiple types of haptic sensations in a natural and effective way as well as how to best combine them with visuo-audio stimuli, which are of course still paramount in any human-machine interaction. For this application, it is of course important to design wearable haptic interfaces able to provide haptic sensations while leaving the user free to also interact with the real environment, which is a rather new approach to wearable haptics. This objective fits again perfectly the line of research described in Sec. 7.2.1, although some additional constraints need to be considered. As MR requires the user to interact both with virtual and real environments, it is important that these devices do not prevent the user from touching real objects (e.g., by using rigid end-effectors at the fingertips). While we carried out some preliminary research on this topic (see Sec. 6), soft and reconfigurable materials might open new interesting avenues for the developed of such interfaces. Finally, there is a need for human-computer interaction techniques specifically adapted to these augmented interactions. Existing graphical user interfaces (GUIs) are bound to 2D screens, and controlled via conventional inputs (e.g., keyboard). Future haptic-enabled applications will require new UIs and input techniques. We should re-imagine gesture-controlled UIs to exploit fully-immersive MR environments, delivering abstracted interaction techniques and analyzing the known limitations of current haptic systems due for instance to their size, their actuation capabilities (e.g. under-actuation of wearables), their limited range of forces, their workspace, and/or the potential visual occlusions (important in MR). Solutions based on pseudo-haptic effects exploiting visual feedback and cross-modal illusions can also be useful to overcome some of the abovementioned limitations of haptic interfaces.

Below I briefly discuss possible areas of application for this technology.

Application in industrial training. Standard industrial panels (e.g., a flight cockpit) can be augmented with new hardware (e.g., different buttons and levels) and software features (e.g., alerts). These items can be visually augmented through standard AR headset as well as haptically augmented thanks to the above haptic rendering approaches.

Application in augmented desktops. Imagine sitting at your desk. There are few pens, a notebook, a large screen, a keyboard, and other everyday objects. Through a AR headset, the surrounding gets visually augmented by a plethora of virtual objects grounded on the real, tangible environment, e.g., the notebook gets augmented with buttons and control knobs, the pens become drum sticks, and the keyboard turn into a large drum cymbal. Through wearable haptics, the surrounding gets haptically augmented so as to match the expected physical characteristics anticipated by the above visual augmentation, e.g., you can now feel the reliefs of the button and knobs on the notebook, perceive the weight of the drum sticks, and experience the vibrations when hitting the cymbal.

8 Conclusions and perspectives

It is an exciting moment to be working in the field of haptics. The community is growing strong and the technology is getting ready to enable the design of unobtrusive yet effective displays, ready to revolutionize how we interact with virtual, augmented, and remote environments in a wide range of applications. These advancements enable researchers and engineers to finally apply haptic feedback to a plethora of new scenarios that, until now, have mostly benefited from audio and visual stimuli only, e.g., medical robotics, VR/AR interaction, human-robot interaction.

The wearability/portability of haptic interfaces is one of the most promising technological advancements in the field. Wearable devices naturally fit the human body without constraining it, and they can function without requiring any additional voluntary action. In this way, users can seamlessly perceive and interact with the surrounding environment in a natural yet private way. The variety of new opportunities wearable haptics can bring in social interaction, health-care, virtual reality, remote assistance, and robotics are huge and exciting. The primary advantage of wearable haptic devices is their reduced form factor compared to grounded devices, a feature that opens the possibility of easily engaging in multi-contact interactions. With wearable haptics, multi-contact haptic feedback does not require anymore cumbersome and complex systems, but rather multiple instances of similar designs (see Sec. 7.2.1). Together with the multi-contact revolution, recent advancements in actuation and power technologies enable researchers to make wearable haptic devices wireless and in need of low power. In fact, many wearable devices can run on a standard lithium-ion battery and communicate wirelessly with the external computer unit. This feature is particularly promising for consumer applications, such as gaming and immersive environments, and assistive technologies, such as guidance for the visually-impaired. In this respect, gaming applications represent a fantastic market for cutaneous haptic technologies. Haptic technologies entered the gaming theater back in 1997, when Sony introduced its DualShock controller for PlayStation. It was able to provide a compelling vibrotactile feedback on particular events, such as a race car hitting the retaining wall or a plane crashing on the ground. By 2013, more than 400M units had been sold. In 2006, Nintendo released the game interface Wii Remote motion controller, which provides a similar feature, but wirelessly. Cutaneous haptics can take the immersiveness of such systems to the next level: a haptic vest can replicate the feeling of being hit by bullets in First Person Shooters (FPS) games, vibrotactile bracelets can reproduce the vibrations of the steering wheel of a race car driven in rough terrain, and fingertip devices can rely the feeling of touching in-game objects in action role-playing games (ARPG) and massively multi-player role-playing games (MMRPG). This opportunity is already being exploited by a few startup companies. Immerz (USA) raised USD 183,449 on Kickstarter for their "KOR-FX" gaming vest. It converts audio signals coming from the game into vibrotactile haptic stimuli that allow the wearer to feel in-game events such as explosions and punches. A similar experience is promised by the full-body suit "Teslasuit" by Tesla Studios (UK) and the "3RD Space Vest" by TN Games (USA). More recently, Actronika (France) presented their "Skinetic" vest, which is equipped with 20 voice-coil motors all over the torso, driven taking into account the sensitivity of different parts of the human body. In addition to vibrotactile systems, the hand-held "Reactive grip" controller by Tactical Haptics (USA) provides relative tangential motion and skin stretch to the hand. A similar haptic device for gaming, called "Hapto", is also developed by Intellect Motion (SG). Such interfaces have the potential of making the next generation of haptically-enhanced Sony DualShock or Nintendo Wii controllers. The development of cutaneous haptic systems from gaming applications goes naturally together with the recent fast-growing development and commercialization of wearable and unobtrusive virtual reality headsets, such as the Oculus Rift and the HTC Vive. In this respect, we see a growing set of works combining cutaneous haptics with such head-mounted displays, as also shown in Sec. 6.

Robotic teleoperation and telepresence are other promising fields for cutaneous haptic technologies. Being able to reproduce haptic stimuli safely, in different parts of the body, can significantly improve the performance, applicability, and illusion of telepresence of teleoperation systems. The low cost of cutaneous devices might even take teleoperation and telepresence applications to the consumer market. For example, we could improve the experience of online shopping. Think of being able to feel, from home, the fabric of a new piece of clothing you are about to buy on Ebay, the softness of a pillow you are getting shipped from Amazon, or being able to gently squeeze a vegetable on Ocado to check its ripeness.

The multi-robot systems we considered in Sec. 4 can find application in domains as agriculture, livestocks monitoring, security, 3D movies and television, immersive systems, production lines, handling of dangerous materials, safe and rescue, gaming, and so on. Providing humans with effective means to control and interact with robots enable to exploit the great capabilities of robotics while keeping humans at the center, which is a topic of great importance nowadays, as world leaders talk more and more about the "re-industrialization" of western countries [146].

Another robotic application cutaneous haptics can positively impact is telecommuting, which has gained enormous importance during the COVID-19 pandemic. In 2015, 37% of U.S. workers have worked remotely, 7% more than in 2007 and 28% more than in 1995 [147]. According to a recent study from the OECD, in Australia, France, and the United Kingdom, 47% of employees teleworked during lockdowns in 2020. In Japan, which did not institute a nationwide lockdown, the teleworking rate increased from 10% to 28% between December 2019 and May 2020 [148]. While telecommuting is popular for office workers, it is of course more problematic when dealing with manual workers. However, technological advancements in the field of robotics and haptics can allow a broader range of workers to access the benefits of remote working.

A similar reasoning can be done for haptics for MR applications. Nowadays, while MR is growing exponentially, haptics is still surprisingly missing. For example, MR made the headlines with the smartphone game "Pokemon GO", which renders virtual animated creatures on top of the real world. The application uses the smartphone camera to capture the surrounding environment, to which it adds the fictional pocket monsters. After less than 1 month from its release, the "Pokemon GO" application had been downloaded more than 75 million times. And this success seems only the very first step toward a bright and popularfuture for MR: Apple is reported to be "pouring money into [...] augmented reality", Facebook is "researching AR very seriously", Google is "working on a high-end stand-alone headset-one that mixes features of augmented reality and virtual reality", and Microsoft expects "80 million mixed reality devices to be sold by 2020". Very recently, Facebook even renamed itself "Meta", highlighting its interest in building a metaverse. The research on haptics for MR presents some very specific challenges, as discussed in Sec. 6, but this line of research seems one of the most promising in terms of impact and industrial interest.

I would also like to mention the significant impact that cutaneous haptics technologies can have in assistive applications and, in general, in the delivery of private and effective notifications. While smartphones and smartwatches already deliver notifications through vibrotactile stimuli, more complex haptic devices can improve the range of stimuli we are able to perceive. For example, systems providing wearable haptic guidance can guide firefighters in environments with reduced visibility, help the visually-impaired to walk around in their cities, and warn pedestrians and drivers about imminent dangers. We find skin stretch devices particularly promising for this purpose. By exploiting the high sensitivity of the human skin to tangential stretches, a single tactor can provide effective directional and torsional information with very small movements. For example, we could safely provide drivers with directional information by using a simple skin stretch haptic band fastened to their leg or arm. In this respect, we are recently focusing on endowing mobility aids such as power wheelchairs, white canes, and walkers, with hand-held cutaneous devices able to provide navigation guidance through a rich combination of cutaneous sensations. The flexibility and low cost of cutaneous technologies is expected to significantly expand the number of people that can have access to haptic-enabled solutions for rehabilitation and navigation aid.

Scientifically, all these line of research will provide a strong push to the state of the art of haptics and robotics. Such research is highly interdisciplinary, requiring knowledge from various fields: human perception, design of physical interfaces, automatic control, mechatronics, human-robot interaction. All these disciplines must be contemplated from an integral perspective, leading to insights in each of the separate aspects and feedback between one another, opening interesting opportunities for cross-field collaboration and interaction.

References

[1] M. Abayazid, C. Pacchierotti, P. Moreira, R. Alterovitz, D. Prattichizzo, and S. Misra, "Experimental evaluation of co-manipulated ultrasound-guided flexible needle steering," *The International Journal of Medical Robotics and Computer Assisted Surgery*, vol. 12, no. 2, pp. 219–230, 2016.

[2] C. Pacchierotti, S. Scheggi, D. Prattichizzo, and S. Misra, "Haptic feedback for microrobotics applications: A review," *Frontiers in Robotics and AI*, vol. 3, p. 53, 2016.

[3] F. Ongaro, C. Pacchierotti, C. Yoon, D. Prattichizzo, D. H. Gracias, and S. Misra, "Evaluation of an electromagnetic system with haptic feedback for control of untethered, soft grippers affected by disturbances," in *Proc. IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob)*, 2016, pp. 900–905.

[4] C. Pacchierotti, D. Prattichizzo, and K. J. Kuchenbecker, "Cutaneous feedback of fingertip deformation and vibration for palpation in robotic surgery," *IEEE Transactions on Biomedical Engineering*, vol. 63, no. 2, pp. 278–287, 2016.

[5] A. Tirmizi, C. Pacchierotti, I. Hussain, G. Alberico, and D. Prattichizzo, "A perceptually-motivated deadband compression approach for cutaneous haptic feedback," in *Proc. IEEE Haptics Symposium (HAPTICS)*, 2016, pp. 223–228.

[6] L. Fichera, C. Pacchierotti, E. Olivieri, D. Prattichizzo, and L. S. Mattos, "Kinesthetic and vibrotactile haptic feedback improves the performance of laser microsurgery," in *Proc. IEEE Haptics Symposium (HAPTICS)*, 2016, pp. 59–64.

[7] N. Deshpande, M. Chauhan, C. Pacchierotti, D. Prattichizzo, D. G. Caldwell, and L. S. Mattos, "Robot-assisted microsurgical forceps with haptic feedback for transoral laser microsurgery," in *2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, 2016, pp. 5156–5159.

[8] F. Chinello, C. Pacchierotti, N. G. Tsagarakis, and D. Prattichizzo, "Design of a wearable skin stretch cutaneous device for the upper limb," in *Proc. IEEE Haptics Symposium (HAPTICS)*, 2016, pp. 14–20.

[9] C. Pacchierotti, G. Salvietti, I. Hussain, L. Meli, and D. Prattichizzo, "The hring: A wearable haptic device to avoid occlusions in hand tracking," in *Proc. IEEE Haptics Symposium (HAPTICS)*, 2016, pp. 134–139.

[10] F. Chinello, C. Pacchierotti, M. Malvezzi, and D. Prattichizzo, "A novel 3rrs wearable fingertip cutaneous device for virtual interaction," in *AsiaHaptics*. Springer, 2016.

[11] I. Hussain, G. Spagnoletti, C. Pacchierotti, and D. Prattichizzo, "A wearable haptic ring for the control of extra robotic fingers," *Haptic Interaction: Science, Engineering and Design*, vol. 432, p. 323, 2017.

[12] I. Hussain, L. Meli, C. Pacchierotti, G. Salvietti, and D. Prattichizzo, "Vibrotactile haptic feedback for intuitive control of robotic extra fingers." in *IEEE World Haptics*, 2015, pp. 394–399.

[13] J. D. Brown, M. Ibrahim, E. D. Chase, C. Pacchierotti, and K. J. Kuchenbecker, "Data-driven comparison of four cutaneous displays for pinching palpation in robotic surgery," in *Proc. IEEE Haptics Symposium (HAPTICS)*, 2016, pp. 147–154.

[14] R. Rahal, F. Abi-Farraj, P. Robuffo Giordano, and C. Pacchierotti, "Haptic shared-control methods for robotic cutting under nonholonomic constraints," in *Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2019, pp. 8151–8157.

[15] M. Selvaggio, F. Abi-Farraj, C. Pacchierotti, P. Robuffo Giordano, and B. Siciliano, "Haptic-based shared-control methods for a dual-arm system," *IEEE Robotics and Automation Letters*, vol. 3, no. 4, pp. 4249–4256, 2018.

[16] F. Abi-Farraj, C. Pacchierotti, O. Arenz, G. Neumann, and P. Robuffo Giordano, "A haptic shared-control architecture for guided multi-target robotic grasping," *IEEE Transactions on Haptics*, vol. 13, no. 2, pp. 270–285, 2019.

[17] R. Rahal, G. Matarese, M. Gabiccini, A. Artoni, D. Prattichizzo, P. Robuffo Giordano, and C. Pacchierotti, "Caring about the human operator: haptic shared control for enhanced user comfort in robotic telemanipulation," *IEEE Transactions on Haptics*, vol. 13, no. 1, pp. 197–203, 2020.

[18] A. Lillienskiold, R. Rahal, P. Giordano, C. Pacchierotti, and E. Misimi, "Human-inspired haptic-enabled learning from prehensile move demonstrations," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 2021.

[19] J. Bimbo, C. Pacchierotti, M. Aggravi, N. Tsagarakis, and D. Prattichizzo, "Teleoperation in cluttered environments using wearable haptic feedback," in *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2017, pp. 3401–3408.

[20] F. Abi-Farraj, C. Pacchierotti, and P. Robuffo Giordano, "User evaluation of a haptic-enabled shared-control approach for robotic telemanipulation," in *Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2018, pp. 1–9.

[21] J. Bimbo, C. Pacchierotti, N. G. Tsagarakis, and D. Prattichizzo, "Collision detection and isolation on a robot using joint torque sensing," in *Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2019, pp. 7604–7609.

[22] R. Rahal, G. Matarese, M. Gabiccini, A. Artoni, D. Prattichizzo, P. Robuffo Giordano, and C. Pacchierotti, "Haptic shared control for enhanced user comfort in robotic telemanipulation," in *Proc. IEEE ICRA workshop on Shared Autonomy: Learning and Control*, 2020.

[23] F. Abi-Farraj, C. Pacchierotti, and P. Robuffo Giordano, "Human-subject evaluation of shared-control approaches for robotic telemanipulation," in *2017 IEEE/RSJ IROS Workshop Human in-the-loop robotic manipulation: on the influence of the human role*, 2017.

[24] L. Meli, C. Pacchierotti, and D. Prattichizzo, "Experimental evaluation of magnified haptic feedback for robot-assisted needle insertion and palpation," *The International Journal of Medical Robotics and Computer Assisted Surgery*, vol. 13, no. 4, p. e1809, 2017.

[25] C. Pacchierotti, F. Ongaro, F. Van den Brink, C. Yoon, D. Prattichizzo, D. H. Gracias, and S. Misra, "Steering and control of miniaturized untethered soft magnetic grippers with haptic assistance," *IEEE Transactions on Automation Science and Engineering*, vol. 15, no. 1, pp. 290–306, 2018.

[26] M. Cognetti, M. Aggravi, C. Pacchierotti, P. Salaris, and P. Robuffo Giordano, "Perception-aware human-assisted navigation of mobile robots on persistent trajectories," *IEEE Robotics and Automation Letters*, vol. 5, no. 3, pp. 4711–4718, 2020.

[27] G. Notomista, C. Pacchierotti, and P. Robuffo Giordano, "Online robot trajectory optimization for persistent environmental monitoring," *IEEE Control Systems Letters*, vol. 6, pp. 1472–1477, 2021.

[28] M. Aggravi, C. Pacchierotti, and P. Robuffo Giordano, "Connectivity-maintenance teleoperation of a uav fleet with wearable haptic feedback," *IEEE Transactions on Automation Science and Engineering*, 2020.

[29] M. Cognetti, M. Aggravi, C. Pacchierotti, P. Salaris, and P. Giordano, "Shared control active perception for human-assisted navigation," in *2nd Italian Conference on Robotics and Intelligent Machines (I-RIM)*, 2020.

[30] F. Berton, F. Grzeskowiak, A. Bonneau, A. Jovane, M. Aggravi, L. Hoyet, A.-H. Olivier, C. Pacchierotti, and J. Pettré, "Crowd navigation in VR: exploring haptic rendering of collisions," *IEEE Transactions on Visualization and Computer Graphics*, 2020.

[31] A. Colas, W. van Toll, L. Hoyet, C. Pacchierotti, M. Christie, K. Zibrek, A.-H. Olivier, and J. Pettré, "Interaction fields: Sketching collective behaviours," in *MIG 2020: Motion, Interaction, and Games*, 2020.

[32] P. Raimbaud, A. Jovane, K. Zibrek, C. Pacchierotti, M. Christie, L. Hoyet, J. Pettré, and A.-H. Olivier, "Reactive virtual agents: A viewpoint-driven approach for bodily nonverbal communication," in *Proc. ACM International Conference on Intelligent Virtual Agents*, 2021, pp. 164–166.

[33] L. Devigne, M. Aggravi, M. Bivaud, N. Balix, C. S. Teodorescu, T. Carlson, T. Spreters, C. Pacchierotti, and M. Babel, "Power wheelchair navigation assistance using wearable vibrotactile haptics," *IEEE Transactions on Haptics*, vol. 13, no. 1, pp. 52–58, 2020.

[34] L. Kuang, M. Aggravi, P. Giordano, and C. Pacchierotti, "Wearable cutaneous device for applying position/location haptic feedback in navigation applications," in *Proc. IEEE Haptics Symposium (HAPTICS)*, 2022.

[35] I. Lacôte, C. Pacchierotti, M. Babel, M. Marchal, and D. Gueorguiev, ""tap stimulation": An alternative to vibrations to convey the apparent haptic motion illusion," in *Proc. IEEE Haptics Symposium (HAPTICS)*, 2022.

[36] M. Chauhan, N. Deshpande, G. Barresi, C. Pacchierotti, D. Prattichizzo, D. G. Caldwell, and L. S. Mattos, "Design and control of a novel robotic microsurgical forceps for transoral laser microsurgery," in *Proc. IEEE International Conference on Advanced Intelligent Mechatronics (AIM)*, 2017, pp. 737–742.

[37] O. A. Moreno, J. Bimbo, C. Pacchierotti, D. Prattichizzo, D. Barcelli, and G. Bianchini, "Transparency-optimal passivity layer design for time-domain control of multi-DoF haptic-enabled teleoperation," in *Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2018, pp. 4988–4994.

[38] G. Bianchini, J. Bimbo, C. Pacchierotti, D. Prattichizzo, and O. A. Moreno, "Transparency-oriented passivity control design for haptic-enabled teleoperation systems with multiple degrees of freedom," in *Proc. IEEE Conference on Decision and Control (CDC)*, 2018, pp. 2011–2016.

[39] O. A. Moreno, J. Bimbo, C. Pacchierotti, G. Bianchini, and D. Prattichizzo, "Optimizing damping factors in a 3dof passive two-layer approach for bilateral telemanipulation," in *Short paper at the IEEE World Haptics Conference (WHC)*, 2017.

[40] M. Maisto, C. Pacchierotti, F. Chinello, G. Salvietti, A. De Luca, and D. Prattichizzo, "Evaluation of wearable haptic systems for the fingers in augmented reality applications," *IEEE Transactions on Haptics*, vol. 10, no. 4, pp. 511–522, 2017.

[41] 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*, 2017.

[42] L. Meli, C. Pacchierotti, G. Salvietti, F. Chinello, M. Maisto, A. De Luca, and D. Prattichizzo, "Combining wearable finger haptics and augmented reality: User evaluation using an external camera and the microsoft hololens," *IEEE Robotics and Automation Letters*, vol. 3, no. 4, pp. 4297–4304, 2018.

[43] S. V. Salazar, C. Pacchierotti, X. de Tinguy, A. Maciel, and M. Marchal, "Altering the stiffness, friction, and shape perception of tangible objects in virtual reality using wearable haptics," *IEEE Transactions on Haptics*, vol. 13, no. 1, pp. 167–174, 2020.

[44] X. de Tinguy, C. Pacchierotti, A. Lécuyer, and M. Marchal, "Capacitive sensing for improving contact rendering with tangible objects in vr," *IEEE Transactions on Visualization and Computer Graphics*, vol. 27, no. 4, pp. 2481–2487, 2020.

[45] X. De Tinguy, C. Pacchierotti, M. Marchal, and A. Lécuyer, "Toward universal tangible objects: Optimizing haptic pinching sensations in 3d interaction," in *Proc. IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 2019.

[46] G. Gioioso, G. Spagnoletti, L. Meli, T. L. Baldi, C. Pacchierotti, and D. Prattichizzo, "Interacting with the virtual reality: rendering of pressure, textures, and making/break contact sensations via fingertip wearable haptic devices," in *Short paper at the IEEE World Haptics Conference (WHC)*, 2017.

[47] 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.

[48] X. de Tinguy, C. Pacchierotti, M. Emily, M. Chevalier, A. Guignardat, M. Guillaudeux, C. Six, A. Lécuyer, and M. Marchal, "How different tangible and virtual objects can be while still feeling the same?" in *Proc. IEEE World Haptics Conference (WHC)*, 2019, pp. 580–585.

[49] G. Spagnoletti, L. Meli, T. L. Baldi, G. Gioioso, C. Pacchierotti, and D. Prattichizzo, "Rendering of pressure and textures using wearable haptics in immersive vr environments," in *Proc. IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 2018, pp. 691–692.

[50] F. Sanfilippo and C. Pacchierotti, "A wearable haptic system for the health monitoring of elderly people in smart cities," *International Journal of Online Engineering*, vol. 14, no. 08, pp. 1–15, 2018.

[51] F. Chinello, C. Pacchierotti, M. Malvezzi, and D. Prattichizzo, "A three revolute-revolute-spherical wearable fingertip cutaneous device for stiffness rendering," *IEEE Transactions on Haptics*, vol. 11, no. 1, pp. 39–50, 2018.

[52] F. Chinello, C. Pacchierotti, J. Bimbo, N. G. Tsagarakis, and D. Prattichizzo, "Design and evaluation of a wearable skin stretch device for haptic guidance," *IEEE Robotics and Automation Letters*, vol. 3, no. 1, pp. 524–531, 2017.

[53] M. Aggravi, F. Pausé, P. Robuffo Giordano, and C. Pacchierotti, "Design and evaluation of a wearable haptic device for skin stretch, pressure, and vibrotactile stimuli," *IEEE Robotics and Automation Letters*, vol. 3, no. 3, pp. 2166–2173, 2018.

[54] 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.

[55] I. Hussain, L. Meli, C. Pacchierotti, and D. Prattichizzo, "A soft robotic supernumerary finger and a wearable cutaneous finger interface to compensate the missing grasping capabilities in chronic stroke patients," in *2017 IEEE World Haptics Conference (WHC)*, 2017, pp. 183–188.

[56] F. Sanfilippo and C. Pacchierotti, "A low-cost multi-modal auditory-visual-tactile framework for remote touch," in *Proc. 3rd International Conference on Information and Computer Technologies (ICICT)*, 2020, pp. 213–218.

[57] L. Masia, I. Hussain, M. Xiloyannis, C. Pacchierotti, L. Cappello, M. Malvezzi, G. Spagnoletti, C. Antuvan, D. Khanh, M. Pozzi *et al.*, "Soft wearable assistive robotics: exosuits and supernumerary limbs," in *Wearable Exoskeleton Systems: Design, control and applications*, ser. Control, Robotics & Sensors, 2018, pp. 219–254.

[58] X. de Tinguy, T. Howard, C. Pacchierotti, M. Marchal, and A. Lécuyer, "Weatavix: wearable actuated tangibles for virtual reality experiences," in *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer, Cham, 2020, pp. 262–270.

[59] M. Aggravi, T. L. Baldi, C. Pacchierotti, and D. Prattichizzo, "Combined tracking and vibrotactile rendering with a wearable armband," in *Hands-on demostration at IEEE Haptics Symposium (HAPTICS)*, 2020.

[60] 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.

[61] E. M. Young, D. Gueorguiev, K. J. Kuchenbecker, and C. Pacchierotti, "Compensating for fingertip size to render tactile cues more accurately," *IEEE Transactions on Haptics*, vol. 13, no. 1, pp. 144–151, 2020.

[62] T. Howard, M. Marchal, A. Lécuyer, and C. Pacchierotti, "Pumah: Pan-tilt ultrasound mid-air haptics for larger interaction workspace in virtual reality," *IEEE Transactions on Haptics (ToH)*, 2020.

[63] L. Mulot, G. Gicquel, Q. Zanini, W. Frier, M. Marchal, C. Pacchierotti, and T. Howard, "Dolphin: A framework for the design and perceptual evaluation of ultrasound mid-air haptic stimuli," in *ACM Symposium on Applied Perception*, 2021.

[64] T. Howard, G. Gallagher, A. Lécuyer, C. Pacchierotti, and M. Marchal, "Investigating the recognition of local shapes using mid-air ultrasound haptics," in *Proc. IEEE World Haptics Conference (WHC)*, 2019, pp. 503–508.

[65] M. Marchal, G. Gallagher, A. Lécuyer, and C. Pacchierotti, "Can stiffness sensations be rendered in virtual reality using mid-air ultrasound haptic technologies?" in *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer, Cham, 2020, pp. 297–306.

[66] T. Howard, G. Gicquel, M. Marchal, A. Lécuyer, and C. Pacchierotti, "Pumah: Pan-tilt ultrasound mid-air haptics," in *WHC 2021-IEEE World Haptics Conference*, 2021.

[67] F. Chinello, M. Malvezzi, C. Pacchierotti, and D. Prattichizzo, "Design and development of a 3RRS wearable fingertip cutaneous device," in *Proc. IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*, 2015, pp. 293–298.

[68] A. Courtney and M. Ng, "Hong Kong female hand dimensions and machine guarding," *Ergonomics*, vol. 27, no. 2, pp. 187–193, 1984.

[69] O. F. Obi, "Hand anthropometry survey of rural farm workers in south-eastern Nigeria," *Ergonomics*, vol. 59, no. 4, pp. 603–611, 2016.

[70] S. N. Imrhan, M. Sarder, and N. Mandahawi, "Hand anthropometry in Bangladeshis living in America and comparisons with other populations," *Ergonomics*, vol. 52, no. 8, pp. 987–998, 2009.

[71] D. Gueorguiev, D. Tzionas, C. Pacchierotti, M. J. Black, and K. J. Kuchenbecker, "Statistical modelling of fingertip deformations and contact forces during tactile interaction," Extended abstract presented at the Hand, Brain and Technology conference (HBT), 2018.

[72] ——, "Towards a statistical model of fingertip contact deformations from 4D data," Work-in-progress paper (3 pages) presented at the IEEE Haptics Symposium, San Francisco, USA, Mar. 2018.

[73] M. Malvezzi, F. Chinello, D. Prattichizzo, and C. Pacchierotti, "Design of personalized wearable haptic interfaces to account for fingertip size and shape," *IEEE Transactions on Haptics*, 2021.

[74] T. Howard, X. de Tinguy, G. Gicquel, M. Marchal, A. Lécuyer, and C. Pacchierotti, "Weatavix: Wearable actuated tangibles for virtual reality experiences," in *Hands-on demonstration at IEEE World Haptics Conference*, 2021.

[75] T. Iwamoto, M. Tatezono, T. Hoshi, and H. Shinoda, "Airborne ultrasound tactile display," in *ACM SIGGRAPH 2008 new tech demos*, 2008, pp. 1–1.

[76] T. Carter, S. A. Seah, B. Long, B. Drinkwater, and S. Subramanian, "Ultrahaptics: multi-point mid-air haptic feedback for touch surfaces," in *Proc. ACM symposium on User interface software and technology*, 2013, pp. 505–514.

[77] T. Howard, G. Gicquel, M. Marchal, A. Lécuyer, and C. Pacchierotti, "Pumah: Pan-tilt ultrasound mid-air haptics," in *Hands-on demonstration at IEEE World Haptics Conference*, 2021.

[78] C. Freschi, V. Ferrari, F. Melfi, M. Ferrari, F. Mosca, and A. Cuschieri, "Technical review of the da vinci surgical telemanipulator," *Int J Med Robot*, vol. 9, no. 4, pp. 396–406, 2013.

[79] D. Aschenbrenner, M. Fritscher, F. Sittner, M. Krauß, and K. Schilling, *Teleoperation of an Industrial Robot in an Active Production Line*, 2015.

[80] F. Abi-Farraj, N. Pedemonte, and P. Robuffo Giordano, "A visual-based shared control architecture for remote telemanipulation," in *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, 2016, pp. 4266–4273.

[81] E. A. M. Ghalamzan, F. Abi-Farraj, P. R. Giordano, and R. Stolkin, "Human-in-the-loop optimisation: mixed initiative grasping for optimally facilitating post-grasp manipulative actions," in *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2017, pp. 3386–3393.

[82] C. Pacchierotti, F. Ongaro, F. van den Brink, C. Yoon, D. Prattichizzo, D. H. Gracias, and S. Misra, "Steering and control of miniaturized untethered soft magnetic grippers with haptic assistance," *IEEE Trans. Automation Science and Engineering*, vol. 15, no. 1, pp. 290–306, 2018.

[83] C. Pacchierotti, S. Scheggi, D. Prattichizzo, and S. Misra, "Haptic feedback for microrobotics applications: a review," *Frontiers in Robotics and AI*, vol. 3, no. 53, 2016.

[84] A. Franchi, C. Secchi, M. Ryll, H. H. Bulthoff, and P. Robuffo Giordano, "Shared control : Balancing autonomy and human assistance with a group of quadrotor uavs," *IEEE Rob. Aut. Mag.*, vol. 19, no. 3, pp. 57–68, 2012.

[85] K. Hauser, "Recognition, prediction, and planning for assisted teleoperation of freeform tasks," *Auton. Robot.*, vol. 35, no. 4, pp. 241–254, Nov 2013.

[86] H. Boessenkool, D. A. Abbink, C. J. M. Heemskerk, F. C. T. van der Helm, and J. G. W. Wildenbeest, "A task-specific analysis of the benefit of haptic shared control during telemanipulation," *IEEE Trans. Haptics*, vol. 6, no. 1, pp. 2–12, 2013.

[87] D. Rakita, B. Mutlu, M. Gleicher, and L. M. Hiatt, "Shared control–based bimanual robot manipulation," *Sci. Robot.*, vol. 4, no. 30, 2019.

[88] S. Musić and S. Hirche, "Control sharing in human-robot team interaction," *Annu. Rev. Control*, vol. 44, pp. 342 – 354, 2017.

[89] M. Selvaggio, J. Cacace, C. Pacchierotti, F. Ruggiero, and P. Giordano, "A shared-control teleoperation architecture for nonprehensile object transportation," *IEEE Transactions on Robotics*, 2021.

[90] M. T. Mason and K. M. Lynch, "Dynamic manipulation," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, vol. 1, 1993, pp. 152–159.

[91] Y. Michel, R. Rahal, C. Pacchierotti, P. Robuffo Giordano, and D. Lee, "Bilateral teleoperation with adaptive impedance control for contact tasks," *IEEE Robotics and Automation Letters*, vol. 6, no. 3, pp. 5429–5436, 2021.

[92] C. Pacchierotti, A. Tirmizi, G. Bianchini, and D. Prattichizzo, "Enhancing the performance of passive teleoperation systems via cutaneous feedback," *IEEE Transactions on Haptics*, vol. 8, no. 4, pp. 397–409, 2015.

[93] ——, "Improving transparency in passive teleoperation by combining cutaneous and kinesthetic force feedback," in *Proc. IEEE/RSJ Int. Symp. Intelligent Robots and Systems (IROS)*, 2013, pp. 4958–4963.

[94] R. Mendonça, M. M. Marques, F. Marques, A. Lourenco, E. Pinto, P. Santana, F. Coito, V. Lobo, and J. Barata, "A cooperative multi-robot team for the surveillance of shipwreck survivors at sea," in *Proc. MTS/IEEE OCEANS*, 2016, pp. 1–6.

[95] R. R. Murphy, K. L. Dreger, S. Newsome, J. Rodocker, E. Steimle, T. Kimura, K. Makabe, F. Matsuno, S. Tadokoro, and K. Kon, "Use of remotely operated marine vehicles at minamisanriku and rikuzentakata japan for disaster recovery," in *IEEE International Symposium on Safety, Security, and Rescue Robotics*, 2011, pp. 19–25.

[96] L. Marconi, C. Melchiorri, M. Beetz, D. Pangercic, R. Siegwart, S. Leutenegger, R. Carloni, S. Stramigioli, H. Bruyninckx, P. Doherty *et al.*, "The sherpa project: Smart collaboration between humans and ground-aerial robots for improving rescuing activities in alpine environments," in *Proc. IEEE International Symposium on Safety, Security, and Rescue Robotics*, 2012, pp. 1–4.

[97] J. Casper and R. R. Murphy, "Human-robot interactions during the robot-assisted Urban Search and Rescue response at the World Trade Center," *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)*, vol. 33, no. 3, pp. 367–385, 2003.

[98] L. E. Davis, J. Rough, G. Cecchine, A. G. Schaefer, L. L. Rohn, and L. L. Zeman, *Hurricane Katrina: Lessons for army planning and operations*, 2007.

[99] D. Guha-Sapir, R. Below, and P. Hoyois, "The OFDA/CRED International Disaster Database. Université Catholique de Louvain, Belgium," 2016.

[100] S. J. Kim and G. J. Lim, "Drone-aided border surveillance with an electrification line battery charging system," *Journal of Intelligent & Robotic Systems*, vol. 92, no. 3-4, pp. 657–670, 2018.

[101] R. L. Finn and D. Wright, "Unmanned aircraft systems: Surveillance, ethics and privacy in civil applications," *Computer Law & Security Review*, vol. 28, no. 2, pp. 184–194, 2012.

[102] M. Zucker, S. Joo, M. X. Grey, C. Rasmussen, E. Huang, M. Stilman, and A. Bobick, "A General-purpose System for Teleoperation of the DRC-HUBO Humanoid Robot," *Journal of Field Robotics*, vol. 32, no. 3, pp. 336–351, 2015.

[103] T. Tomic, K. Schmid, P. Lutz, A. Domel, M. Kassecker, E. Mair, I. L. Grixa, F. Ruess, M. Suppa, and D. Burschka, "Toward a fully autonomous UAV: Research platform for indoor and outdoor urban search and rescue," *IEEE Robotics & Automation Magazine*, vol. 19, no. 3, pp. 46–56, 2012.

[104] M. Aggravi, G. Sirignano, P. Robuffo Giordano, and C. Pacchierotti, "Decentralized control of a heterogeneous human-robot team for exploration and patrolling," *IEEE Transactions on Automation Science and Engineering*, 2021.

[105] M. Aggravi, A. A. S. Elsherif, P. Robuffo Giordano, and C. Pacchierotti, "Haptic-enabled decentralized control of a heterogeneous human-robot team for search and rescue in partially-known environments," *IEEE Robotics and Automation Letters*, vol. 6, no. 3, pp. 4843–4850, 2021.

[106] A. Marbán, A. Casals, J. Fernández, and J. Amat, "Haptic feedback in surgical robotics: Still a challenge," in *ROBOT2013: First Iberian Robotics Conference*, 2014, pp. 245–253.

[107] A. R. Lanfranco, A. E. Castellanos, J. P. Desai, and W. C. Meyers, "Robotic surgery: a current perspective," *Annals of surgery*, vol. 239, no. 1, p. 14, 2004.

[108] D. Herron and M. Marohn, "A consensus document on robotic surgery," *Surgical endoscopy*, vol. 22, no. 2, pp. 313–325, 2008.

[109] C. Pacchierotti, *Cutaneous Haptic Feedback in Robotic Teleoperation.* Springer International Publishing, 2015.

[110] E. M. Boctor, M. A. Choti, E. C. Burdette, and R. J. Webster Iii, "Three-dimensional ultrasound-guided robotic needle placement: an experimental evaluation," *The International Journal of Medical Robotics and Computer Assisted Surgery*, vol. 4, no. 2, pp. 180–191, 2008.

[111] P. Beddy, R. D. Rangarajan, and E. Sala, "Role of MRI in intracavitary brachytherapy for cervical cancer: What the radiologist needs to know," *American Journal of Roentgenology*, vol. 196, no. 3, pp. 341–347, 2011.

[112] C. Pacchierotti, M. Abayazid, S. Misra, and D. Prattichizzo, "Teleoperation of steerable flexible needles by combining kinesthetic and vibratory feedback," *IEEE Transactions on Haptics*, vol. 7, no. 4, pp. 551–556, 2014.

[113] M. Aggravi, D. A. Estima, A. Krupa, S. Misra, and C. Pacchierotti, "Haptic teleoperation of flexible needles combining 3d ultrasound guidance and needle tip force feedback," *IEEE Robotics and Automation Letters*, vol. 6, no. 3, pp. 4859–4866, 2021.

[114] N. Chaillet and S. Régnier, *Microrobotics for micromanipulation.* John Wiley & Sons, 2013.

[115] A. Bolopion and S. Régnier, "A review of haptic feedback teleoperation systems for micromanipulation and microassembly," *IEEE Transactions on automation science and engineering*, vol. 10, no. 3, pp. 496–502, 2013.

[116] Z. Ni, A. Bolopion, J. Agnus, R. Benosman, and S. Régnier, "Asynchronous event-based visual shape tracking for stable haptic feedback in microrobotics," *IEEE Transactions on Robotics*, vol. 28, no. 5, pp. 1081–1089, 2012.

[117] A. Bolopion, Z. Ni, J. Agnus, R. Benosman, and S. Régnier, "Stable haptic feedback based on a dynamic vision sensor for microrobotics," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2012, pp. 3203–3208.

[118] C. Pacchierotti, V. Magdanz, M. Medina-Sánchez, O. G. Schmidt, D. Prattichizzo, and S. Misra, "Intuitive control of self-propelled microjets with haptic feedback," *Journal of micro-bio robotics*, vol. 10, no. 1, pp. 37–53, 2015.

[119] C. Pacchierotti and D. Prattichizzo, "Sensory subtraction via cutaneous feedback: a novel technique to improve the transparency of robotic surgery," in *Proc. 4th Joint Workshop on Computer/Robot Assisted Surgery (CRAS)*, 2014.

[120] L. Meli, C. Pacchierotti, and D. Prattichizzo, "Sensory subtraction in robot-assisted surgery: fingertip skin deformation feedback to ensure safety and improve transparency in bimanual haptic interaction," *IEEE Transactions on Biomedical Engineering*, vol. 61, no. 4, pp. 1318–1327, 2014.

[121] 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.

[122] L. Meli, C. Pacchierotti, and D. Prattichizzo, "Sensory subtraction with cutaneous feedback to ensure safety in bimanual robot-assisted surgery," in *Proc. Medical and Service Robotics Conference (MESROB)*, 2014.

[123] ——, "Sensory subtraction via cutaneous feedback in robot-assisted surgery," in *New Trends in Medical and Service Robots*. Springer International Publishing, 2015, pp. 121–130.

[124] C. Pacchierotti, D. Prattichizzo, and K. J. Kuchenbecker, "Displaying sensed tactile cues with a fingertip haptic device," *IEEE Transactions on Haptics*, vol. 8, no. 4, pp. 384–396, 2015.

[125] ——, "A data-driven approach to remote tactile interaction: From a biotac sensor to any fingertip cutaneous device," in *Haptics: Neuroscience, Devices, Modeling, and Applications*. Springer Berlin Heidelberg, 2014, pp. 418–424.

[126] C. A. Rosen and C. B. Simpson, *Operative techniques in laryngology*. Springer Science & Business Media, 2008.

[127] M. Rubinstein and W. B. Armstrong, "Transoral laser microsurgery for laryngeal cancer: a primer and review of laser dosimetry," *Lasers in medical science*, vol. 26, no. 1, pp. 113–124, 2011.

[128] M. Remacle, G. Lawson, M.-C. Nollevaux, and M. Delos, "Current state of scanning micromanipulator applications with the carbon dioxide laser," *Annals of Otology, Rhinology & Laryngology*, vol. 117, no. 4, pp. 239–244, 2008.

[129] J. Lin and E. Prisman, "Transoral laser microsurgery for early glottic carcinoma," *Surgery Current Research*, vol. 4, no. 5, 2014.

[130] M. Niemz Niemz and H. Markolf, "Laser-tissue interactions: fundamentals and applications. third," 2013.

[131] H. Nakayma, H. S. Jørgensen, H. O. Raaschou, and T. S. Olsen, "Compensation in recovery of upper extremity function after stroke: the copenhagen stroke study," *Archives of physical medicine and rehabilitation*, vol. 75, no. 8, pp. 852–857, 1994.

[132] I. Faria-Fortini, S. M. Michaelsen, J. G. Cassiano, and L. F. Teixeira-Salmela, "Upper extremity function in stroke subjects: relationships between the international classification of functioning, disability, and health domains," *Journal of Hand Therapy*, vol. 24, no. 3, pp. 257–265, 2011.

[133] S. Balasubramanian, J. Klein, and E. Burdet, "Robot-assisted rehabilitation of hand function," *Current opinion in neurology*, vol. 23, no. 6, pp. 661–670, 2010.

[134] I. Hussain, G. Salvietti, L. Meli, C. Pacchierotti, D. Cioncoloni, and D. Prattichizzo, "Using the robotic sixth finger and vibrotactile feedback for grasp compensation in chronic stroke patients," in *Proc. IEEE/RAS-EMBS International Conference on Rehabilitation Robotics*, 2015.

[135] S. Scheggi, L. Meli, C. Pacchierotti, and D. Prattichizzo, "Using the Leap Motion controller for hand tracking and wearable haptic devices for contact rendering," in *IEEE World Haptics*, 2015, pp. 22–26.

[136] L. Meli, S. Scheggi, C. Pacchierotti, and D. Prattichizzo, "Using the leap motion controller for hand tracking and wearable haptic devices for contact rendering," in *Proc. ACM Special Interest Group on Computer Graphics and Interactive Techniques Conference (SIGGRAPH)*, 2015, p. 31.

[137] ——, "Wearable haptics and hand tracking via an rgb-d camera for immersive tactile experiences," in *Proc. ACM Special Interest Group on Computer Graphics and Interactive Techniques Conference (SIGGRAPH)*. ACM, 2014, pp. 56–1.

[138] S. Vizcay, P. Kourtesis, F. Argelaguet, C. Pacchierotti, and M. Marchal, "Electrotactile feedback for enhancing contact information in virtual reality," in *ICAT-EGVE 2021-International Conference on Artificial Reality and Telexistence and Eurographics Symposium on Virtual Environments*, 2021.

[139] U. Ghafoor, S. Kim, and K.-S. Hong, "Selectivity and longevity of peripheral-nerve and machine interfaces: a review," *Frontiers in Neurorobotics*, vol. 11, p. 59, 2017.

[140] A. D. Cheok, X. Yang, Z. Z. Ying, M. Billinghurst, and H. Kato, "Touch-space: Mixed reality game space based on ubiquitous, tangible, and social computing," *Personal and ubiquitous computing*, vol. 6, no. 5, pp. 430–442, 2002.

[141] M. Billinghurst, H. Kato, and I. Poupyrev, "The magicbook-moving seamlessly between reality and virtuality," *IEEE Computer Graphics and applications*, vol. 21, no. 3, pp. 6–8, 2001.

[142] N. Diolaiti, G. Niemeyer, F. Barbagli, and J. K. Salisbury, "Stability of haptic rendering: Discretization, quantization, time delay, and coulomb effects," *IEEE Transactions on Robotics*, vol. 22, no. 2, pp. 256–268, 2006.

[143] J.-H. Ryu, D.-S. Kwon, and B. Hannaford, "Stable teleoperation with time-domain passivity control," *IEEE Transactions on robotics and automation*, vol. 20, no. 2, pp. 365–373, 2004.

[144] C. Pacchierotti, L. Meli, F. Chinello, M. Malvezzi, and D. Prattichizzo, "Cutaneous haptic feedback to ensure the stability of robotic teleoperation systems," *International Journal of Robotics Research*, 2015.

[145] G. Gioioso, G. Salvietti, M. Malvezzi, and D. Prattichizzo, "Mapping synergies from human to robotic hands with dissimilar kinematics: an approach in the object domain," *IEEE Transactions on Robotics*, vol. 29, no. 4, pp. 825–837, 2013.

[146] Financial Associated Press. (2021) France announced to invest 800 million euros to develop robot industry. [Online]. Available: https://equalocean.com/briefing/20211026230089858

[147] Gallup. (2015) Gallup social series: Work and education. [Online]. Available: http://www.gallup.com/poll/184649/telecommuting-work-climbs.aspx

[148] Organisation for Economic Co-operation and Development (OECD). (2021) Teleworking in the covid-19 pandemic: Trends and prospects. [Online]. Available: https://www.oecd.org/coronavirus/policy-responses/teleworking-in-the-covid-19-pandemic-trends-and-prospects-72a416b6/