Wearability in Robotics: Developing Cutaneous Devices for Haptic Stimuli

Francesco Chinello

Advisor: Prof. D. Prattichizzo
Co-Advisor: Prof. A. Vicino

Committee members: Prof. M. Casini, Prof. K. J. Kuchenbecker, Prof. M. Santello

Tesi di Dottorato

UNIVERSITÀ DEGLI STUDI DI SIENA
DIPARTIMENTO DI INGEGNERIA DELL’INFORMAZIONE E SCIENZE MATEMATICHE

DOTTORATO DI RICERCA IN INGEGNERIA E SCIENZE DELL’INFORMAZIONE
– CICLO XXVI –
Wearability in Robotics: Developing Cutaneous Devices for Haptic Stimuli

Francesco Chinello,
© Ph.D. Thesis, University of Siena,
February, 2014.

A digital version of the thesis can be obtained by e-mail on request from the author:
chinello@dii.unisi.it
To: my family and my friends
Acknowledgements

This thesis is the result of the work performed in the Siena Robotics and Systems Labs directed by prof. Domenico Prattichizzo, the ADVanced Robotics Department (Istituto Italiano di Tecnologia, Genova, IT) directed by prof. Darwin Caldwell, and the School of Biological and Health System Engineering (Phoenix, AZ) directed by prof. Marco Santello. I wish to thank the professors and their laboratory groups who helped realize the experiments and the devices presented in this research activity.
## Contents

1 Introduction ................................................. 1  
  1.1 Motivations of this research .......................... 1  
  1.1.1 Applicative scenario for wearable haptic devices ... 3  
  1.2 Contribution ............................................. 4  
  1.3 Related works ............................................ 5  
    1.3.1 Wearability for haptic devices .................... 5  
    1.3.2 Cutaneous haptic displays in surgery ............... 8  
    1.3.3 Wearable haptic devices for guidance ............... 9  
    1.3.4 Wearable haptic devices for human-to-human interaction . 11  

2 Wearable tactile display ................................... 13  
  2.1 The device model ....................................... 13  
    2.1.1 General description and characteristics .......... 13  
    2.1.2 Kinematics and modelling ......................... 15  
    2.1.3 Contact model ..................................... 17  
    2.1.4 Control model ..................................... 19  
  2.2 Experimental evaluation ............................... 22  
    2.2.1 Experiment 1: curvature discrimination .......... 22  
    2.2.2 Results of the experiment 1 ....................... 23  
    2.2.3 Experiment 2: exploring spherical curvature ....... 24  
    2.2.4 Results of the experiment 2 ....................... 27  

3 Two fingers cutaneous displays ............................. 31  
  3.1 Robotics in surgery .................................... 31
## Contents

3.2 2-DoF cutaneous device for teleoperated needle insertion .......................... 32
  3.2.1 Device design and performance .............................................. 32
  3.2.2 Experimental evaluation .................................................... 34
3.3 3-DoF cutaneous device for virtual interaction ................................. 40
  3.3.1 Device structure and specifications ....................................... 40
  3.3.2 Experimental evaluation .................................................... 44

4 Wearability for guidance ............... 49
  4.1 The vibrotactile device .......................................................... 49
  4.2 Mobile robot guidance though vibrotactile feedback ......................... 50
  4.3 Experimental evaluation ....................................................... 51

5 Using wearable devices for communication: the RemoTouch project ......... 53
  5.1 Toward wearable devices for communication: RemoTouch ................. 53
  5.2 Experimental evaluation ....................................................... 57
    5.2.1 Experiment 1: the father and the remote family ....................... 57
    5.2.2 Experiment 2: play a remote piano .................................... 58

6 Conclusion and future works .......... 59

Bibliography ......................... 63
Introduction

The touch is the not said part of what is thought.

Henry van Dyke

1.1 Motivations of this research

The sense of touch develops before all other senses in embryos, and it is the main way in which children begin to explore their environment and bond with other people. Throughout life people use their sense of touch to learn, protect themselves from harm, relate to others, and communicate [1]. Compared to other senses, touch does not have a specific locus because tactile sensory information enters the nervous system from every part of the body.

There is still a lot of work to do in developing technologies for this sense: haptic interfaces are widely used in laboratories and research centers, the research in this field is growing very fast and interesting applications are presented in the literature. However, haptics in everyday life remains largely under-exploited even though digital 3D contents are becoming more and more common and there is a need to provide a way to haptically interact with them.

This doctoral thesis aims to deeply study the current knowledge, proposing different devices that can provide haptic feedback. Some of the devices presented in thesis can be defined wearable in the sense that the system is easily integrated with the human body and ergonomic: a wearable interface should not constantly demand attention and interrupt everyday activities.

A crucial study in this work is the design of a new concept interface which exploit the concept of wearability. We believe that wearability tasks will be one of the key elements to enabling the use of haptics in every day task. We envision haptic devices transitioning from grounded, fully actuated haptic devices, to a small, body grounded, distributed system of underactuated robots. This vision implies different research directions, and
1. Introduction

Several open problems, spanning many research fields, e.g., physiology, neuroscience, cognitive science and robotics.

Crossing traditional boundaries between robotics and neuroscience, this interdisciplinary research is driven by the design for wearability, which imposes strict restrictions on weight, volume, shape and form factor of the system to be worn [2]. In grounded haptics, the contact interaction is simulated through an external robot as shown in Fig. 1.1a. In exoskeletons, the haptic system is body-grounded [3, 4]. The robotic system applying forces to simulate contact interaction is worn by the human operator, who feels both the contact force simulating the interaction and the reaction force counterbalancing the first one, as in Fig. 1.1b.

A promising design principle of wearable haptic systems looks at cutaneous perception and stimulation as a direct consequence of improved wearability in haptics. In Fig. 1.1b, an exoskeleton, for the human hand is sketched [4]. Its wearability is poor because of the presence of the external mechanics grounded to the forearm.

In this work we want to go beyond exoskeletons reducing the mechanical complexity of the system for the sake of wearability. To tackle this idea, it is evident that the more intuitive approach to re-design the wearable robot is to move the base as close as possible to the point of application of the force simulating the interaction, as sketched in Fig. 1.1c: the body-grounded base is moved from the forearm to the back of the finger. This simple and efficient principle of moving the body-grounded base as close as possible to the application point of the force is absolutely essential to simplify the mechanical design of the wearable haptic system and improve wearability.

Figure 1.1: Grounded haptics (a), exoskeletons (b) and wearable haptics (c). In (c) the exoskeleton is removed and the wearability is improved at the cost of losing most of the kinesthetic component of the interaction.
1.1 Motivations of this research

1.1.1 Applicative scenario for wearable haptic devices

Wearable haptics offers exciting new ways of interaction and cooperation with augmented or remote environments populated by robots, other humans, and digital contents. Some of these scenario are described below.

**Wearable haptics for human-robot interaction and cooperation**

The efficient and seamless cooperation of humans and robots in a team plays an important role in many application fields such as search & rescue, human-robot cooperative production systems, machine-based rehabilitation, and service robotics. Due to its particularly high requirements in terms of cooperation efficiency and societal impact, we selected search & rescue as a representative scenario to highlight the benefits of using wearable devices. The deployment of robotic systems is desirable for tasks such as moving obstacles out of the way and the search/transport of humans/objects. However, purely autonomous systems will fail as there are still substantial limits to robotic perception, decision making, and manipulation in unstructured environments. Depending on the situation and task, human input will still be required. Therefore it is desirable to dynamically change the level of autonomy of the robotic partner. Wearable haptic systems offer the opportunity to seamlessly switch between different levels of autonomy from pure teleoperation to fully autonomous modes. In teleoperation mode wearability offers super mobility to the user and allows seamless changes between teleoperated modes (bilateral, semi-autonomous, shared control, autonomous) including teaching of the robot. As a completely new interaction paradigm, the robot partner may also haptically guide the human through the system, e.g. in low visibility environments.

**Wearable haptics for cognitively impaired subjects**

In subjects with severe brain damage, there exist several levels of consciousness ranging from vegetative state to severe disorder of consciousness. At the moment it is not clear which specific stimuli are actually perceived by such subjects and to what extent. No standardized tools are available for a precise assessment of the levels of residual consciousness. In this context haptic stimulation is very promising as touch is a primordial and ancestral sense through which subjects can communicate easily and instantly. Accordingly, touch can be considered a reasonable and effective way to come into contact with these patients. Moreover, the remote bi-directional communication provided with a wearable system will allow the caregivers to keep in touch with the patients continuously and even when they are at home. Advantageously, wearable haptic devices can be
customized in size and shape, easily placed wherever on the body, and can be flexible, unobtrusive, small and lightweight. Other important health sciences applications include navigation of blind people, post-stroke rehabilitation, surgical training, and tumor detection training.

Wearable haptics for communication and media

Videogames have become a multi-billion industry, with players of all ages, both male and female. In addition, “serious games” exploit the entertaining aspects of videogames for professional training. Despite technological advancements in game consoles from hand-held or desktop interfaces to full body motion interfaces like Nintendo’s Wiimote or Microsoft’s Kinect, we are still strongly limited in the ways we can interact with the virtual content in videogames. The interaction is essentially visual and auditory, as we only see and hear the virtual content, but we cannot touch it. Interestingly, much of our interaction with the real world takes place through touch, as we manipulate objects around us. Wearable haptic devices have the potential to enrich videogames by enabling the users to interact directly with the content with our hands and body without workspace restrictions, i.e. the immersion into the game will be drastically increased. The videogame is an intelligent agent with its own cognitive control: it senses the state of the human user, simulates its action in a virtual world, and renders the appropriate multimodal feedback to the user.

1.2 Contribution

The character of the research presented in this thesis is inherently interdisciplinary and involves haptics, robotics, cognitive science and neuroscience. In particular, the main contributions of this thesis are described below:

- **Developing wearable cutaneous displays for haptic interaction.**
  A novel design of a wearable tactile display for virtual interaction and for teleoperation tasks will be introduced. The cutaneous stimulus is performed on the user’s fingertip surface through a mobile platform which is slanted relatively to a virtual surface touched by the user. The device can also generate a normal force compressing the fingertip. The experiments presented show the stable behaviour of the platform and a curvature recognition test performed on different users.

- **Embedding cutaneous devices on an Omega 3 haptic interface.**
  We will introduce a 2-DoF active and a 3-DoF device handle able to generate a
cutaneous feedback independent from the forces delivered by the grounded haptic interface. A peg-in-hole and a needle insertion experiment will be described to analyse the performances of these systems.

- **Introducing a wearable vibrating bracelet for robot guidance.**
  Wearable haptics is particularly suited to guide humans since it allows humans to freely move. Wearable haptics also allows us to improve the interaction and communication between robots and humans. We present a scenario where the human leads a team of robot followers. We introduce wearable vibrotactile feedback to allow the human-leader to easily satisfy the team follower constraints.

- **Using a wearable device system for communication: the RemoTouch project.**
  This part presents some preliminary results on RemoTouch, a system that allows the user to perform experiences of remote touch. The system consists of an avatar equipped with an instrumented glove and a user wearing tactile displays allowing to feel the remote tactile interaction. The main features of RemoTouch are that it is a wearable system in which a human avatar, instead of a robotic or virtual avatar, is remotely used to collect tactile interaction data. New paradigms of tactile communication can be designed around the RemoTouch system. Two simple experiences are reported to show the potential of the proposed remote touch architecture.

1.3 Related works

This section reviews the background for this thesis as follows:

1. wearability for haptic devices;
2. cutaneous haptic displays in surgery;
3. wearable haptic devices for guidance;

1.3.1 Wearability for haptic devices

Wearability will open many opportunities to exploit haptics in everyday life and will improve the way humans interact with each other and the surrounding environment. Think, for instance, about the possibility of taking your haptic interface wherever you
go, use it to get in touch with your family while you are abroad [5], touch the brand-
new sofa you are about to buy, or telemanipulate a remote robotic system [6]. Wearable
haptic systems shall be comfortable to be carried around and well integrated daily life,
with the aim of providing valuable services to the users. Moreover, they shall be in-
trinsically integrated with the human body and fit it without constraining its motion, or
requiring additional voluntary actions to be held. Many haptic devices have been stud-
ied and designed to be portable or wearable, and there are three main approaches used
to generate haptic feedback in wearable devices: (1) systems generating vibrations, (2)
pin-arrays locally deforming the skin to simulate a given shape, and (3) mechanisms
applying three-dimensional vector forces at one or more contact points. Vibrotactile
feedback became popular in the '90s with the advent of mobile phones and the in-
novative DualShock game controller produced by Sony. Nowadays, one of the most
popular portable device providing vibrations is the game interface Wii Remote motion
controller (Nintendo Co. Ltd., Japan). The form factor and weight of this device facil-
itate its portability. However, it can only provide very simple vibrating patterns, limiting
its possibility of properly simulating any rich contact interaction with virtual or remote
objects. In [7], Traylor and Tan presented a vibrating wearable device able to impart di-
rectional information on the user’s back. The tactile display consisted of a single tactor
strapped to the volar side of the user’s forearm. An accelerometer was placed on top of
the tactor to record its displacement during signal delivery. In [8], the authors developed
a 5-DoF arm suit able to guide the motion of the wearer by providing solely vibrotactile
feedback. The suit was composed by eight vibrotactile actuators distributed throughout
the right arm, whose frequency and amplitude were independently controlled. In [9],
Kim et al. developed a vibrotactile display to provide safety information to drivers. The
device was placed on top of the foot and was composed by a 5x5 array of vibrating
motors.

For all these wearable devices, the stimuli applied to the user consisted of sinusoidal
signals varying in their intensity and frequency. Although these haptic devices can be
considered wearable, their force feedback is limited to vibrations, thus limiting their
possibility of simulating richer force patterns.

The second approach for providing haptic force feedback with wearable devices
deals with dynamic pin arrays. In [10], Yang et al. developed a cutaneous display
composed of a 6x5 pin-array, actuated by piezoelectric bimorph actuators. It was able
to display planar and Braille cell patterns to the fingertips. Pin-arrays are also employed
in [11], where the authors used a solenoid, a permanent magnet and an elastic spring to
develop a miniature cutaneous module. Although this kind of display is very flexible
and effective, it usually employs a large number of actuators, which compromises the
1.3. Related works

overall wearability and portability of the system. For this reason, Sarakoglou et al. [12] proposed a compact 4x4 tactors array, remotely actuated through a flexible tendon transmission. Their implementation achieved a compact design, but it still required an external drive unit for the actuation system, thus compromising portability.

The third approach to wearable haptics consists of applying three-dimensional force vectors at given points on the human body. These devices are the closest, in terms of interaction modality, to grounded haptic interfaces, since both are able to apply forces at one contact point. Glove-type haptic displays, such as the CyberGrasp (CyberGlove Systems LLC, San Jose, CA, USA), are the most popular devices of this type; they can provide force vectors to all five fingers of the hand simultaneously. However, the mechanics of these displays is usually rather complex, thus compromising their wearability and portability.

Wearability of this kind of device has been dramatically improved in [13], where Minamizawa et al. presented a wearable and portable ungrounded haptic display able to apply cutaneous forces to simulate weight sensations of virtual objects. The approach was based on the novel insight that cutaneous sensations make a reliable weight illusion, even when the kinesthetic information is absent. The device consisted of two motors and a belt able to deform the fingertip. When the motors spin in opposite directions, the belt applies a force perpendicular to user’s fingertip, while if the motors rotate in the same direction, the belt applied a shear force to the skin. That device was also used in [14] to examine the role of cutaneous and kinesthetic feedback in weight sensations, and in [5] for experiences of remote tactile interaction. However, the device proposed by Minamizawa et al. was able to render forces in only two directions, the force control was open loop, and it was not very accurate. The main issue was that its control accuracy largely depended on the visco-elastic parameters of the fingerpad, which change with different subjects [15].

More recently, Solazzi et al. developed an effective 3-DoF wearable cutaneous display [16], but the portability and wearability of the device were limited by its mechanical structure. The motors were placed on the forearm and two cables for each actuated finger were necessary to transmit the motor torque. Provancher et al. proposed a fingertip device with two degrees of freedom [17]. The device used two RC servo motors and a compliant flexure stage to create planar motion. The servos could operate simultaneously, allowing motion along any path in a plane. Another interesting device has been developed in [18], where the authors presented a fingertip device which provided the user with the cutaneous sensation of making and breaking contact with virtual surfaces. However, this display had no actuation and relied on the haptic feedback provided by the haptic device it was attached to.
1.3.2 Cutaneous haptic displays in surgery

Shibata et al. in [19] demonstrated the relevance of tactile stimuli in finger coordination for grasping interaction. This results are visible in cutaneous haptic grounded devices performing grasping tasks in virtual environment [6]. To render a realistic representation of the remote environment, haptic displays use active input devices, such as electric motors, to generate the forces fed back to the operator. Stability and transparency of such systems can be significantly affected by communication latency, reducing their applicability and effectiveness in case of stiff remote environments [20, 21]. This limitation can be alleviated by designing proper control systems [22–24], but these approaches do not address an intrinsic issue affecting the haptic loop design: in case of serious failure of the haptic device’s actuators, the teleoperation loop can experience problems that cannot be managed by control and may cause an abrupt change in the behaviour of the remote robot.

This is a serious problem in surgical robotics as, for example, in needle insertion tasks. One way to address this issue is to modify on the hardware design, substituting master actuation with passive components such as brakes [25]. However, passive input devices have rendering limitations and may lead to large steady-state errors in teleoperation tasks [26]. Another interesting approach is to remove the actuator from the haptic device and replace haptic feedback with other forms of feedback, such as vibrotactile, auditory, and/or visual feedback [27, 28]. This approach is referred as sensory substitution. When employing this technique, the haptic device could be substituted with a device able to track the position of the operator’s hand, without any active component, since haptic feedback is missing.

Using sensory substitution techniques in medical surgery dramatically reduces the risk of producing uncontrollable displacement of the robotic tool and, consequently, it increases the safety of the overall teleoperation loop [29]. Cutaneous feedback is important to simulate interactions with objects in a virtual environment. Single-contact haptic devices, such as the Omega devices (Force Dimension, CH), provide haptic feedback, consisting of both cutaneous and kinesthetic forces, to the user. The complete haptic feedback allows users to better understand the relative position of neighboring parts of the body by means of sensory organs in muscles and joints [30]. Watanabe et al., in [31], developed a system for controlling cutaneous sensations of surface roughness by applying ultrasonic vibration to the surface. In [32] the authors proposed an approach to provide human cutaneous sensation using surface acoustic wave. A pulse-modulated driving voltage excited temporal distribution of shear force on the surface acoustic wave substrate. The force-friction distribution was perceived as cutaneous sensations at re-
1.3. Related works

A widely-used approach for providing cutaneous sensations is employing dynamic pin-matrices. Ikei et al., in [33], developed a cutaneous display which has 50 vibrating pins. The vibratory pin array included 5x10 contact piano-wires 0.5 mm in diameter, aligned in a 2 mm pitch with a vibration frequency of 250 Hz.

The elastic springs in the actuators were separated into several layers to minimize the conductor’s gap. In [11] the authors used electrostatic force and friction control to render surface roughness sensations. The display consisted of stator electrodes and a thin film slider, on which an aluminium conductive layer was deposited. Minamizawa et al., in [34],[35], presented a wearable and ungrounded haptic display able to simulate weight sensations of virtual objects. That device was used in [36] to provide cutaneous feedback in an industrial application involving heavy duty machines, and in [5] for experiences of remote cutaneous interaction. A similar device has been also used in [37], where the authors presented a new approach to sensory substitution in haptics called sensory subtraction. They substituted haptic feedback, consisting of both cutaneous and kinesthetic forces, with cutaneous feedback only, in order to achieve the stability of the system and outperform other conventional sensory substitution techniques.

A similar device has been presented in [38], where the authors developed a system, named VerroTouch, for providing cutaneous feedback to surgeons during telerobotic surgery. VerroTouch measured the vibrations caused by tool contact and recreates them on the master handles for the surgeon.

More recently, Bau et al. developed in [39] a technology to provide cutaneous sensation while moving fingers on touch screens. The touch panel presented has a conductive layer coated with an insulating layer, which the finger rests upon. When voltage difference was applied between the finger and the conductive layer, a normal attractive force was induced. By alternating the voltage, it was possible to modulate the friction force felt by the moving finger.

1.3.3 Wearable haptic devices for guidance

Robots can support humans in complex everyday tasks, such as indoor and outdoor navigation, information supplying, or carrying heavy objects. In the last decade, formation control has become one of the leading research areas in mobile robotics since multiple mobile robots can achieve a given task, faster, more robustly and more accurately than a single unit. In addition, a growing interest in human-robot interaction led recent studies [40, 41] explore new strategies in mixed human-robot formation control. However these works as well as other recent researches, [42–45] provided only the possibility to send...
information from the human to the robot, in terms of gesture recognition and human pose estimation and tracking.

The solution proposed in [46] allows the robot to send information to the human by using simple signals that are easy to process. This can be achieved via a wearable haptic device which provides suitable vibrotactile feedback. As with sound, a tactile stimulus is made up of a signal with varying frequency and amplitude, but, differently from the auditory feedback which needs a mental model in order to parse the information, tactile feedback directly engages our motor learning system. Moreover, differently from cutaneous feedback, technologies for generating kinesthetic stimuli are typically cumbersome, have limited ranges of motion and although they can typically generate strong forces and realistically guide a human motion, they are typically designed only for some special applications [47].

Most of the research on cutaneous feedback has focused on providing stimuli on human finger pads, due to the high number of receptors located there. Recent works have started to explore other body parts for information display, mostly for navigation purposes and instruction of motor tasks.

In [48], the authors studied the possibility of presenting navigation information on a vibrotactile waist belt. Results indicated the usefulness of tactile feedback for navigation and, eventually, situational awareness in multitask environments. A similar device was proposed in [49], where a haptic belt was integrated with a directional sensor and a GPS system, and used as an intuitive navigation system.

In [50] the authors developed a robotic suit for improved human motor learning. The suit provides vibrotactile feedback proportional to the error between the effective and the learned motion. Strictly related are the works in [51, 52]. In [52] a set of user-worn bands that provide vibrotactile guidance for static pose was presented, while in [51] the authors presented the design of a wearable robotic teacher for forearm movement guidance. The system provides vibrotactile stimulations through a bracelet composed of four vibration motors disposed in quadrants. A vibrotactile orientation guidance device was also proposed in [53]. The authors mainly focused on the layout of the device as well as on the generation of different vibrating patterns.

Finally, it is worth mentioning the vibrotactile device presented in [54] where the authors presented a deep study on the bracelet wearability, usability and capability of displaying vibrotactile stimuli.
1.3.4 Wearable haptic devices for human-to-human interaction

Humans have always attempted to extend their perception abilities to enlarge the workspace of the human body. Consider, for instance, the role played by mobile phones for audio interactions. If one thinks about technology for recording and playback of audio and video, portable devices come to mind. It isn’t so for touch modality. Technology for touching remote objects has typically been used in robotics for teleoperation and the devices used are very far from being portable. In telepresence, a robot is used as a slave in the remote scenario and a haptic interface or an exoskeleton feeds back contact forces letting the user perceive the remote environment [4]. Current technology for telepresence is very advanced but it is not portable and is not low energy consumption thus compromising the possibility to be used in everyday life. In Fig. 1.2 an example of a telepresence system developed at DLR is reported [55].

A different approach to remote tactile perception is presented in this work. It involves replacing the slave robot with a human and substituting the exoskeleton, or other haptic interfaces, with a simple and wearable tactile device. In the RemoTouch project the device in charge of recording tactile perception is not a robot, but a human avatar. It is able to collect tactile, audio and video signals to be fed back to the remote user. This is what we refer to as remote perception in Chapter 5. Of course, the main difference with teleoperation is that the human avatar cannot be controlled as a robot but this has nothing to do with RemoTouch, which deals only from the perception of the remote environment through human avatars.
Chapter 2

Wearable tactile display

This chapter focuses on the problem of reproducing realistic contact force sensations generated by contact between fingertip and virtual objects or surfaces, by means of a wearable haptic device. A novel wearable three DoFs haptic is developed. It is able to deliver stimuli to the fingertip by applying forces to the vertices of a rigid platform by means of cables whose lengths are regulated by three small size DC motors.

2.1 The device model

2.1.1 General description and characteristics

The device shown in Fig. 2.1, is mainly composed of two parts: a static nail-side body and an active fingertip-side platform. The contact force between the active part of the device and the fingertip is measured by three force sensors. As the display developed in [35], this system provides tactile cutaneous stimuli only while the kinesthetic stimulus is missing. Since the dimensions are small, it can be easily integrated with other systems that also provide kinesthetic stimuli to the user’s hand and arm. Possible solutions to compensate this lack of information have been presented in [14].

With respect to the device described in [35], the presented in [56] has an additional actuated DoF, that allows to the fingertip shear stimuli in both the tangential, directions a wider applicability. Furthermore, the force sensors on the interface between the skin and the active part of the device are used in a closed loop control of force and position. This control approach allows to increase the precision of the applied forces and to perform tests in which the applied stimulus changes dynamically.

The device is designed for wearability and to be easy portable and light so its structure is very essential. It is composed of two main parts: one part is fixed to the back side of the finger and supports three small size DC electrical motors, while the active
The device is composed of two platforms: one static (B), which supports three motors (A), and one mobile (C), which is in charge of applying the requested force to the finger pad. The actuators tilt the mobile platform by means of three cables (F) and pulleys (E). Moreover, three force sensors (D) make possible to register the force applied to the fingertip.

The actuators used for the device prototype are three 0615S Falhauber motors, with planetary gear-heads having 16:1 reduction ratio. The mobile platform has a Y shape and allows to simulate contacts with generally oriented surfaces. The contact surface orientation can be modified by acting on the forces applied to the platform vertices. Three piezoresistive force sensors (400 FSR™Interlinks Electronics) are placed at the vertices, in contact with the finger, in order to measure the actual normal component of the force applied to the fingertips. The sensors have a 5mm diameter and 3mm thickness so they are very transparent to the user and easily embeddable in the device. The mechanical supports for the actuators and the mobile platform are made using a special type of acrylonitrile butadiene styrene, the ABSPlus™(Stratasys Inc.). The total weight of the whole device, including sensors, actuators, wires, and mechanical supports is
2.1. The device model

Figure 2.2: The 3-DoF device kinematic scheme. Force sensors on the mobile platform measure the normal component of the force applied to the fingertip.

about 30g. The device control is managed by an Atmega 328 microcontroller installed on an Arduino Nano board which can control up to 6 PWM signals and read the outputs of up to 6 analog sensors.

2.1.2 Kinematics and modelling

The mobile platform is actuated by three cables connecting its vertices to three actuators. The kinematic scheme of the device is shown in Fig. 2.2. $B_1$, $B_2$, and $B_3$ are the points, on the platform, are connected. The cables link the mobile patch to the actuators. $S_1 = \langle x, y, z \rangle$ is a reference frame fixed to the mobile platform whose origin $P_1$ is placed at

<table>
<thead>
<tr>
<th>ver.</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>ver.</th>
<th>x</th>
<th>y</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_1$</td>
<td>-8</td>
<td>13</td>
<td>0</td>
<td>$B_1$</td>
<td>-9</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>$A_2$</td>
<td>-8</td>
<td>-13</td>
<td>0</td>
<td>$B_2$</td>
<td>-9</td>
<td>-6</td>
<td>0</td>
</tr>
<tr>
<td>$A_3$</td>
<td>13</td>
<td>0</td>
<td>0</td>
<td>$B_3$</td>
<td>6</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2.1: Point coordinates on the two platforms: points $A_i$ on the fixed platform are expressed with respect to $S_0$ (mm), points $B_i$ on the mobile platform are expressed with respect to $S_1$ (mm).
the platform’s geometric center, conventionally, chosen in the center of mass of the triangle defined by the points $B_i$. Let $A_1, A_2,$ and $A_3$ be the vertices of the fixed platform and $S_0 = \langle X, Y, Z \rangle$ a reference frame on the fixed platform whose origin is located at $P_0$. $A_i$ and $B_i$ coordinates, expressed, respectively, in $S_0$ and $S_1$ reference frames are summarized in Tab. 2.1.

The transformation from frame $S_1$ to the fixed frame $S_0$ can be described by a vector

$$p = P_0 - P_1$$

and a $3 \times 3$ rotation matrix $R_1$, a defined as a function of the yaw ($\gamma$), pitch ($\beta$) and roll ($\alpha$) angles. Let $a_i, i = 1, 2, 3$ represent the coordinates of point $A_i$, with respect to the frame $S_0$. Let $b^0_i, i = 1, 2, 3$ be the coordinates of point $B_i$, with respect to the same frame, that can be expressed as

$$b^0_i = p + R^0_1 b^1_i$$

where $b^1_i$ represent the coordinates of the same points expressed with respect to frame $S_1$. $A_i$ and $B_i$ coordinates, expressed in the base and platform frame respectively, are summarized in Tab. 2.1. The inverse kinematics problem consists of finding the distance between the platforms’ vertices

$$d_i = B_i - A_i$$

for a given displacement $p$ and an angular configuration $\alpha, \beta$ and $\gamma$. The solution in this case is straightforward:

$$q_i = ||d_i|| = \sqrt{a_i^2 + b_i^2 - 2a_i b_i}, \ i = 1, ..., 3$$

(2.1)

where $q_i = d_i$ is the distance between the $i$th vertices. From the distance between the points on the fixed and mobile platform, and from the finger curvature radii $R_i$ (that can be approximately considered constant), we can evaluate the actual length of the cables $l_i$ as

$$l_i = 2R_i \arcsin \left( \frac{q_i}{2R_i} \right)$$

(2.2)

Concerning the velocity analysis, following the standard procedure described for instance in [57], we can express the joint variable time

$$\dot{q}_i = J_p \dot{v}_p$$

(2.3)

where $J_p \in \mathbb{R}^{3 \times 6}$ is the Jacobian matrix, and $v_p = [p \ \omega_p]^T$ in which $\omega_p$ represents the mobile platform angular velocity [57]. Furthermore, by differentiating Eq. 2.2, it is possible to define a relationship between cable length time derivatives $\dot{l}_i$ and $v_p$

$$\dot{l}_i = J_l v_p$$

(2.4)
Let now \( w_p = [f_p^T \ m_p^T]^T \in \mathbb{R}^6 \) be the wrench applied to the mobile platform (expressed with respect to \( S_0 \)), and \( Q = [Q_1 \ Q_2 \ Q_3]^T \) the vector of force (norms) applied to the cables by the actuators. Using the Principle of Virtual Works to the mobile platform, neglecting the friction in the motors and the cables, we obtain:

\[
w_p = J_l^T Q
\]  

(2.5)

We observe that a generic wrench \( w_p \) can be reproduced by the platform if it belongs to the \( \mathbb{R}^6 \) subspace whose basis is defined by the columns of \( J_l^T \). In this case the corresponding cable forces can be calculated as

\[
Q = (J_l^T)^\dagger w_p
\]  

(2.6)

where the \((\bullet)^\dagger\) is the pseudoinverse operator. The mobile platform includes three force sensors as shown in Fig. 2.1 Since their sensing areas are near to the platform vertices, we assumed that, approximately, the measured forces \( F_{m,i} \), \( i = 1,2,3 \) are applied in \( B_1 \), \( B_2 \) and \( B_3 \) respectively. Some experimental tests showed that the sensor measurement are quite well decoupled: actuating one motor once, we obtain a significant force signal on the corresponding sensor, while in the other two sensors the force variation is enough small to be neglected. We can then assume that the force sensors measure the component of each actuator force normal to the platform, and if we neglect the finger curvature radii we obtain the following approximated relationship

\[
F_{m,i} = Q_i \cos \theta_i
\]  

(2.7)

where \( k \) is the unit vector parallel to direction \( z \), and \( \theta_i \) is the angle between \( z \) axis and \( d_i \) vector. It is worth noting that the measure \( F_{m,i} \) depends both on the amplitude of the actuator force \( Q_i \) and on the mobile platform configuration.

### 2.1.3 Contact model

The platform displacement \( \xi = [p_x \ p_y \ p_z \ \alpha \ \beta \ \gamma]^T \) produces a deformation of the fingertip that leads to a contact stress distribution. In quasi static condition the stress distribution on the fingertip is balanced by the wrench applied by the platform \( w_p \) [58]. In this section we discuss the relationship between platform configuration \( \xi \) and wrench \( w_p \) applied by the platform to the fingertip. The fingertip is composed of two skin layers (epidermis and dermis), subcutaneous tissue, arterial bone, and nail. Different mathematical and numerical models of the fingertip have been proposed in the literature.
In [59], for example, a 2D continuum fingertip model is described, in which the finger is approximated by an homogeneous, isotropic and incompressible elastic material. In [58] a model that incorporates both inhomogeneity and geometry of the fingertip is proposed. The undeformed fingertip is modeled as an axial symmetric ellipsoidal elastic membrane filled with an incompressible fluid with an internal pressure. Also in this case the model is 2D and an external load is applied to the finger through a flat surface. The model predicts a pulp force/displacement relationship that can be represented as a non linear hardening spring, i.e. whose stiffness increases with the applied load. Most of the displacement is reached when the load reaches 1\(N\), which corresponds to a displacement of about 2\(mm\). In [60] a 2D Finite Element model of the fingertip is presented: the skin was modeled as an hyperelastic and viscoelastic membrane, the subcutaneous layer was considered a biphasic material.

The force/deformation behavior of the fingertips in the lateral, or shearing, direction, is studied in [61]. In this work the impedance characteristics of the fingertips in the tangential direction were experimentally measured. A simplified Kelvin model was adopted to describe the relationship between applied tangential force and finger deformation, and the impedance characteristics of the human fingertips were identified by means of experimental tests. The experiments showed that the fingertips have different stiffness properties in the shearing direction and more specifically that the thumb is more stiff than the other fingers. Furthermore, the shearing stiffness depends on the force direction: the finger is more stiff in the pointing direction than in the lateral one. Actually the stress/strain behavior of the fingertip under shearing forces is non linear: in [62] the authors experimentally quantified the anisotropic and hysteretic behavior of the fingertip deformation under the application of tangential forces. In this thesis we consider a simplified model for the fingertip: a linear relationship between the resultant wrench and the platform displacement. In other terms we assume that the platform

\[ F_m \xrightarrow{\text{eq. 2.7}} \dot{Q} \xrightarrow{J_p^T} w_p \xrightarrow{K^{-1}} \dot{\xi} \]

Figure 2.3: Block diagram of the procedure for the estimation of the platform position \(\dot{\xi}\) and wrench \(\dot{w}_p\).
configuration $\xi$ is proportional to the wrench $w_p$:

$$\xi = K^{-1}w_p$$  \hspace{1cm} (2.8)

where $K \in \mathbb{R}^{6 \times 6}$ is the fingertip stiffness matrix. For the sake of simplicity an isotropic elastic behaviour is assumed for all the components of the stiffness matrix:

$$K = kI$$

with $k = 0.5N/mm$ [63]. A more detailed model that is currently being investigated uses different values for the stiffness components

$$K = \text{diag}[k_t, k_t, k_n, k_b, k_b, k_s]$$

where $k_t$ is the skin stiffness in the tangential direction, or shear stiffness [61], $k_n$ is the finger stiffness in the normal direction [58], $k_b$ is the bending stiffness, that can be evaluated as a function of the normal stiffness $k_n$ and the contact patch dimensions, and finally $k_s$ is the torsional stiffness (spin), that can be evaluated as a function of the shear stiffness $k_t$ and the contact patch dimensions.

### 2.1.4 Control model

From the above described kinematic and static analysis, a procedure for the on-line estimation of contact forces and platform configuration has been developed. Assume that the platform displacement during the experiment is small compared to the platform

![Figure 2.4: Block diagram of the device force control. The reference force $Q_r$ is compared to the estimated one $\hat{Q}$: the error signal is the input for the DC motor PD controllers that generate the motor torque $\tau_m$. From the force $F_m$ measured by the sensors, indicated with the block $FS$ (Force Sensors), and the platform position $\hat{\xi}$ estimated in the preceding time step, the Force and Position Estimation block, detailed in Fig. 2.3, evaluates the wire forces $Q$.](image-url)
geometric dimensions, that the initial platform configuration $\xi(0)$ is known, and that the sampling time is small, so that the configuration variation between two consecutive integration steps is small, i.e., for a generic time step $j$, $\xi(j) \simeq \xi(j-1)$. The estimation algorithm is reported in the block diagram shown in Fig. 2.3 and summarized in the following steps:

for each time sample $j$:

- read from the sensors the normal component of the contact forces $F_{m,i}(j)$, $i = 1,\ldots,3$;
- approximate the actuator forces $\hat{Q}_i$ as described in Eq. 2.7;
- estimate platform wrench $\hat{w}_p(j)$ by means of Eq. 2.5;
- estimate platform configuration $\hat{\xi}(j)$ by means the compliant model defined in Eq. 2.8;
- solve the inverse kinematic problem of the platform and find the angles $\hat{\theta}_i(j)$.

From the control point of view, the device can be represented as a non linear, multi-input multi-output (MIMO) coupled system. In this preliminary work, two possible control strategies have been considered. The first control scheme, shown in Fig. 2.4, is a force controller where we want to regulate the cable forces $Q_r$: the reference force $Q_r$ is compared to the estimated one $\hat{Q}$ and the error drives the PD motor controllers. The cable strengths $Q$ are estimated from the force measurements $F_{m,i}$, according to the procedure described in the preceding section and summarized in Fig. 2.3.

![Figure 2.5: Block diagram of the platform position control system. From the reference position $\xi_r$, by means of the inverse kinematics procedure, represented by block IK, the reference wire lengths $l_r$ are estimated. Their values are compared to the estimated ones $\hat{q}$, evaluated applying the Inverse Kinematic procedure IK to the configuration $\hat{\xi}$ estimated in the FPE block, as a function of the measured forces $F_m$ and the position estimated in the preceding time step.](image-url)
2.1. The device model

The second control scheme is a position control as shown in Fig. 2.5, where the motors are regulated so that the mobile platform reaches a reference configuration $\xi_r$. The inverse kinematics of the parallel mechanism described in Eq. 2.1 allows us to evaluate the corresponding reference cable lengths $l_r$. The reference cable lengths are compared to the estimated one $\hat{l}$ and the error drives the PD controllers of the motors. The cable lengths are not measured, but estimated: from the contact force normal components $F_{m,i}$, measured on the platform, the estimation procedure described in and summarized in Fig. 2.3 allows us to estimate the cable strains $\hat{Q}_i$ and the platform configuration $\hat{\xi}_i$. The inverse kinematics allows us to estimate, from the configuration $\xi$, the lengths $\hat{q}_i$.

In both control schemes, each motor is controlled by a closed loop chain with a PD controller. The reference signal is transmitted via a USB-to-serial converter interface with a sampling time of 0.01s and stored in the Arduino register. An application where the device with the force control scheme can be used is described in [37] where a prototype of a joystick prototype implementing a sensory substitution technique is proposed. The joystick uses tactile cutaneous devices similar to those presented in this work, but with no force feedback control and consequently less accuracy. Position control is suit-

![Figure 2.6: The force control step response of the three motors (left). The dashed black line represents the reference force value and the green, blue and red solid lines represent the estimated wire strains $\hat{Q}_1$, $\hat{Q}_2$ and $\hat{Q}_3$ respectively. The rising time is about 0.1s and the steady state error is lower than 2%. The response to a variable reference force signal (right). The reference signal is a sinusoidal function between 0N and 0.3N. The dashed black line represents the signal reference and the green, blue and red lines represent estimated wire strains $\hat{Q}_1$, $\hat{Q}_2$ and $\hat{Q}_3$ respectively.](image-url)
able for applications in which the shape of the virtual contact surface is more important than the contact force. An example of this type of application is described in [64], in which the authors investigated the influence of tactile feedback in convex surface recognition tasks. Both the control schemes are based on a force and position estimation procedure depending on the finger compliance model and referred as FPE in the block diagrams in Fig. 2.4 and 2.5.

In this work we considered a linear model for the finger compliance, as those described in [61]. Work is in progress to investigate the sensitivity of the control performances on the finger compliance and to investigate the possibility of using different and more complex finger models.

To check the force control performance and accuracy, two experimental tests were performed. Fig. 2.6 shows the control system performance when a step signal is applied to the reference values of the cable strengths $Q_r$. The reference force value was the same for each cable: $Q_{r,i} = 0.3N$, for $i = 1, ..., 3$. In the figure, the reference value (dashed) and the estimated cable strengths $Q$ are shown. The test results show that the estimated forces reach the reference value with a rising time of about 0.1 s and an error in the stationary phase lower than 2%. The system bandwidth is about 3.5 Hz. Fig. 2.6 shows the behavior of the device when the force reference signal is sinusoidal:

$$Q_{r,i} = 0.15\sin(\pi t) + 0.15N \quad i = 1, ..., 3.$$ 

### 2.2 Experimental evaluation

#### 2.2.1 Experiment 1: curvature discrimination

In order to validate the device, an experimental test was performed. This works was inspired by the results on curvature discrimination presented in literature, in which it has been proved that tactile feedback is important for surface recognition and that it is more relevant than kinesthesia for convex surface recognition [64], [65]. We set up two experimental tests for surface discrimination using the proposed tactile device. The operator wears one tactile device at the index finger. A virtual circular arc is then generated and virtually moved under the finger wearing the device. The operator is asked to keep the finger still and then tell how the curvature of the sphere changed from one trial to the other. The user is only able to see the position of the finger moving along a line, the same one in each trial, in order to know where the finger is with respect to the virtual sphere. The line does not provide any information about the curvature. Moreover the operator is not able to see her/his finger, increasing the illusion of touching a virtual
2.2. Experimental evaluation

Figure 2.7: The convex curvature employed in the experiment. $d$ is fixed and $h$ changes thus changing the curvature of the virtual surface. In the experiments a virtual arc of a circle is generated under the finger wearing the device. In task A the surface is moving along $S_1 E_1$ and in task B the surface is moved along $S_2 E_2$.

The virtual sphere moves under the user’s fingertip from $S_i$ to $E_i$ (see Fig. 2.7b). The device’s actuators make the mobile platform tilt according to the curvature of the virtual surface thus giving the illusion of actually touching part of a sphere. In the first experiment (task A) the virtual sphere moves from $S_1$ to $E_1$ while in the second experiment (task B) the sphere moves from $S_2$ to $E_2$, as shown in Fig.2.7a. The virtual arc moved under the fingertip is defined by the length of its chord $d$ and the height of the circular segment $h$ (Fig.2.7b). Given $d$ and $h$, the radius of the circle $r_a$ and the length of the arc $l_a$ are

$$r_a = \left(\frac{d^2}{4} + h^2\right)^{\frac{1}{2}} \cdot \frac{1}{2h}$$
$$l_a = \arcsin\left(\frac{d}{2r_a}\right) \cdot 2r_a$$

2.2.2 Results of the experiment 1

Seven participants (6 males, 1 female, age range 20-25) took part in both the experiments, all of them were right-handed. Five of them had previous experience with haptic interfaces. None of the participants reported any deficiencies in the perception abilities. Each participant made twelve repetitions of the curvature discrimination task, with four randomized trials for each curvature height $h_i$:

- $h_{10} = 10\text{mm}$;
- $h_{20} = 20\text{mm}$;
• \( h_{30} = 30\text{mm} \).

The distance \( d \) was 30\text{cm} for all the trials. Fig. 2.8 shows the percentage of correct answers for each curvature and for each task. The collected data of each task passed the Shapiro-Wilk normality test. Then a parametric two-tailed paired t-test was performed, to evaluate the statistical significance of the differences between tasks (i.e. between the three curvatures). The obtained p-values reveal no statistically significant difference between the groups. It is worth reporting that no user confused the curvature with maximum height (\( h_{30} \)) with the one with smallest height (\( h_{10} \)) and vice versa. This experiment confirms that it is possible to discriminate different surface curvatures using the device here presented.

### 2.2.3 Experiment 2: exploring spherical curvature

Similarly to this presented experiment, a test as support of the previous results was performed. Inspired by the work in [66], the same different procedure of TSD (theory of signal detection) was implemented to evaluate the just noticeable difference (JND) for curvature [67, 68].

According to signal detection theory, signals are detected by humans against a noisy background. Two probability distributions describe the variations in the noise (N) and the signal-plus-noise (SN). Subjects set a criterion as a cut-off point for deciding if each observation belongs to N or to SN. On signal-plus-noise trials, positive responses are

![Figure 2.8: Percentage of correct answers for each curvature for each task. The results for both tasks for curvature \( h_{10}, h_{20}, h_{30} \) are shown, respectively, in green, white, and red.](image)
correct and are termed hits. On noise trials, positive responses are incorrect and are termed false alarms. The hit rate $p_h$, i.e. the probability of responding yes on SN trials, and the false-alarm rate $p_f$, i.e. the probability of responding yes on noise trials, fully describe the performance of the task. In TSD, sensitivity can be quantified by using the hit and false-alarm rates to determine the distance between the means of the SN and N distributions, relative to their standard deviations. A sensitivity index $d'$ is then defined as the difference between those means, divided by the standard deviation of the N distribution. The value of $d'$ can be calculated from the false alarm and hit rates, after converting them to z scores [66, 67].

Fourteen participants (12 males, 2 females, age range 20 – 31, finger size range 3.9 – 6.1 cm$^1$) took part to the experiment, all of whom were right-handed. Four of them had previous experience with haptic interfaces. None of the participants reported any deficiencies in their perception abilities and they were naïve as to the purpose of the study. The experimental setup was composed of one wearable device attached to the end-effector of an Omega 6 haptic device. Subjects were blindfolded, with a support for the elbow, and were instructed to wear the device on their right index finger.

According to the aforementioned TSD procedure, each trial involved exploring, in succession, a pair of virtual spheres. The exploration was carried out in a restricted workspace consisting of a cylinder with a diameter of 30 mm, as shown in Fig. 2.9. The task consisted in judging, on each trial, if the curvature of the two surfaces was different or the same. Each participant was informed about the procedure before the beginning of the experiment, and a 10-minutes familiarization period, both while using the wearable device alone and while using it attached to the Omega 6 end-effector, was given, in order to make the subjects acquaintance with the experimental setup. The hit rate $p_h$ corresponded to the percentage of correct responses given by a subject (“yes, the curvatures are different”) when the two surfaces had different curvatures, while the false alarm rate $p_f$ corresponded to the percentage of incorrect responses (“yes, the curvatures are different”) when the curvatures of the two surfaces were the same. Two different force feedback conditions have been taken into account. In condition H, both the wearable device and the Omega 6 provided haptic cues to the subject.

The mobile platform of the wearable device was providing cutaneous cues about the local geometry of the surface being touched, while the Omega device provided a kinesthetic force perpendicular to the given virtual surface. In condition K, only the Omega 6 fed back contact forces. The mobile platform of the cutaneous device was not in contact with the fingertip and its orientation was fixed. In all conditions, the

---

1The finger size was calculated as the circumference of the fingertip at the level of the base of the nail, i.e. where the cuticle is.
Omega prevented the user from exiting the restricted exploration area (see Fig. 2.9). Each subject carried out four series of trials, in which spheres with different curvature values, $\kappa_a$ and $\kappa_b$, were taken into account:

(i) $\kappa_{a,1} = 3.5m^{-1}$ and $\kappa_b = 6m^{-1}$ for Series 1,

(ii) $\kappa_{a,2} = 4m^{-1}$ and $\kappa_b = 6m^{-1}$ for Series 2,

(iii) $\kappa_{a,3} = 4.5m^{-1}$ and $\kappa_b = 6m^{-1}$ for Series 3.

(iv) $\kappa_{a,4} = 5m^{-1}$ and $\kappa_b = 6m^{-1}$ for Series 4.

Each series consisted of 100 repetitions of the curvature discrimination task, with 50 trials for each feedback condition H and K. The entire experiment lasted approximately 50 minutes. On each repetition of each series, two spheres with random curvature ($\kappa_a$ or $\kappa_b$) were rendered, i.e. the probability of exploring a pair of spheres with same (different) radius was 0.5. The order of presentation of the sequence of series and conditions was different for each subject, in order to minimize learning and fatigue effects.
2.2. Experimental evaluation

2.2.4 Results of the experiment 2

For each series, subjects’ responses were recorded, calculating the hit and false alarm rate. False alarm and hit rate were first converted to \( z \) scores of the normal distribution \([67, 68]\).

The sensitivity index \( d' \) was then calculated as the difference

\[
d' = z_h - z_f.
\]

According to the criterion commonly adopted \([66, 68]\), the discrimination threshold can be defined as the difference between the curvatures for which \( d' = 1 \). The threshold was computed for each subject for each condition H and K, assuming a linear proportionality between the values of \( d' \). The overall JND was then computed as the mean of the values obtained for all the subjects. The collected data of each condition passed the D’Agostino-Pearson omnibus K2 normality test. Then a parametric two-tailed paired \( t \)-test (\( a = 0.05 \)) was performed to evaluate the statistical significance of the differences between the two conditions.

The average JND values were significantly lower (\( p = 0.014 \)) for condition H than for K, with an average ± standard deviation of \( 2.22 \pm 0.29m^{-1} \) and \( 2.56 \pm 0.36m^{-1} \) for conditions H and K, respectively. Time needed to complete the given tasks was recorded as well, and no statistical difference was found between the average values for the two conditions. For the subjects enrolled in this experiment, we confirmed that, as discussed in \([66]\), the combination of cutaneous and kinesthetic force feedback led to better performance than employing kinesthetic force feedback only. These data confirmed that the display of surface orientation employing the wearable device here presented can help haptic perception of shape and, in general, it confirmed the importance of cutaneous cues in haptics. The discrimination threshold for curvature observed in this work is in agreement with previous results in the literature. Frisoli \( et \al. \) in \([66]\) found an average JND value of \( 2.62m^{-1} \) for kinesthetic feedback only and of \( 1.51m^{-1} \) when providing both cutaneous and kinesthetic cues. Our cutaneous device showed worse performance with respect to the one presented in \([66]\); however, we believe that this is a price worth paying to gain a great improvement in the wearability and portability of the system. In \([69]\), the authors found discrimination thresholds of \( 3.58m^{-1} \) and \( 2.6m^{-1} \) for direct and virtual discrimination of spheres, respectively, for a reference curvature of \( 25m^{-1} \) employing both kinesthetic and cutaneous force feedback. Goodwin \( et \al. \), in \([70]\), measured the ability of subjects to discriminate convex spherical surfaces from a flat plane using the fingerpad alone. A curvature of \( 4.58m^{-1} \) could be discriminated, at the 75% level (\( d' = 1.35 \)), from the standard curvature of zero. The authors of \([71]\), using real ob-
Table 2.2: Users’ experience evaluation. Participants rated these statements, presented in random order, using a 7-point Likert scale (1 = completely disagree, 7 = completely agree). Means and standard deviations are reported.

<table>
<thead>
<tr>
<th>Questions</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Q1) It has been easy to wear and use the cutaneous device;</td>
<td>6.1</td>
<td>0.7</td>
</tr>
<tr>
<td>(Q2) It has been easy to use the Omega 6 together with the cutaneous device;</td>
<td>5.0</td>
<td>0.7</td>
</tr>
<tr>
<td>(Q3) I was feeling uncomfortable while using the Omega 6 together with cutaneous device</td>
<td>2.3</td>
<td>0.7</td>
</tr>
<tr>
<td>(Q4) I was well-isolated from external noises;</td>
<td>6.3</td>
<td>0.5</td>
</tr>
<tr>
<td>(Q5) I was able to hear the sounds made by the actuators of the cutaneous device;</td>
<td>1.9</td>
<td>0.7</td>
</tr>
<tr>
<td>(Q6) It was easy to feel the presence of a curved surface;</td>
<td>6.7</td>
<td>0.5</td>
</tr>
<tr>
<td>(Q7) I had the feeling of performing better while receiving force feedback by the Omega 6 only;</td>
<td>3.4</td>
<td>0.8</td>
</tr>
<tr>
<td>(Q8) I had the feeling of performing better while receiving force feedback by the cutaneous device;</td>
<td>5.2</td>
<td>1.0</td>
</tr>
<tr>
<td>(Q9) The force given by the Omega 6 was enough to distinguish the curvature;</td>
<td>4.1</td>
<td>0.9</td>
</tr>
<tr>
<td>(Q10) At the end of the experiment I felt tired;</td>
<td>1.4</td>
<td>0.5</td>
</tr>
<tr>
<td>(Q11) It was easy to move my hand and fingers while wearing the cutaneous device;</td>
<td>6.6</td>
<td>0.5</td>
</tr>
<tr>
<td>(Q12) I felt hampered by the cutaneous device;</td>
<td>1.4</td>
<td>0.5</td>
</tr>
<tr>
<td>(Q13) I was feeling a force also on the back of the finger;</td>
<td>1.9</td>
<td>0.6</td>
</tr>
<tr>
<td>(Q14) The force provided by the cutaneous device on the fingertip felt strange;</td>
<td>1.9</td>
<td>0.7</td>
</tr>
<tr>
<td>(Q15) I felt the force provided by the cutaneous device only on the fingertip.</td>
<td>5.9</td>
<td>0.7</td>
</tr>
</tbody>
</table>

At the end of this experiment, we also asked the subjects to answer a questionnaire of 15 questions using bipolar Likert-type seven-point scales. It considered the comfort in using the proposed experimental setup (5 questions), the perceived performance (5 questions) and its level of wearability when detached from the Omega end-effector (5 questions). An answer of 7 meant a very high wearability of the system (or comfort or perceived performance), while an answer of 1 meant a very low wearability of the system (or comfort or perceived performance). The question and the evaluation of each question is reported in Table 2.2.

Since the forces should be exerted exclusively on the skin, wearability demands for cutaneous force feedback more than kinesthesia. However, kinesthetic stimuli could be partially recovered with wearable modules able to exert partial force feedback to arm joints. The relationship between cutaneous and kinesthetic perception in haptics is thus an important research issue. More in general, going to wearable haptic solutions, inherently leads to underactuated and undersensed devices, in which the cutaneous stimuli is predominant with respect to the kinesthetic one. However, similarly to other robotic research fields, we believe that underactuation and undersensing of haptic devices represent an opportunity, and not an issue, since they allow to simplify the actuation system, decrease the weight, lower the energy consumption, and improve the mechanical structure design, turning the haptic device into an intrinsically wearable structure. Another
advantage of wearable and small-size haptic devices is that they easily allow the simultaneous stimulation of several points on the human skin. We thus expect that the consequent richness of information will contribute to mitigate the lack of actuation and sensing, through methods based on cognitive models and multisensory integration.

The availability of wearable haptic devices will support the investigation of complementary approaches, which interact with different parts of the human body through the sense of touch. The complexity of the wearable system will be not apriori fixed; indeed the inherently modular nature of the wearable haptic solutions will allow us to customize the system according to the given applications. In comparison to similar existing cutaneous devices, this one has three actuated degrees of freedom and it is able to simulate a contact force with general direction at the fingertip. These tests also showed acceptable results in terms of response time and error, and low sensitivity with respect to finger stiffness values. Results showed that employing the wearable device together with a popular haptic interface (task H) improved the performance with respect of employing the haptic interface alone (task K). Average JND values were significantly lower for condition H than for condition K, with an average ± standard deviation of $2.22 \pm 0.29 m^{-1}$ and $2.56 \pm 0.36 m^{-1}$ for H and K.
Chapter 3

Two fingers cutaneous displays

Previous chapter described a wearable device for interaction with virtual and remote environments. In order to leave the user as free as possible to move the tracking of such devices should be done in a "wearable" way. This can be achieved through the use of unintrusive position sensors, such as the Kinect depth sensor, the TrakStar magnetic sensor, or the LeapMotion controller. However, some scenarios demand a sensing accuracy much higher than that guaranteed by the before mentioned device and, therefore, other solution need to be taken into account like the well known optical encoders. This chapter describes two novel cutaneous devices for interaction with virtual and remote environments. In order to track their position they have been embedded in the end-effector of popular grounded haptic interfaces.

3.1 Robotics in surgery

In recent years, the usage of robotic teleoperation systems in the operation room is increasing rapidly [72]. Among the large variety of applications dealing with teleoperation, in this section the attention is directed towards the experimental simulation of microinvasive neurosurgery. In the presented scenario a master-slave telemanipulation system must be designed to drive the insertion of a linear-stage rigid endoscope into the brain of the patient for neurosurgery interventions. The endoscope insertion will be assisted by a haptic interface, which will extend and complement the surgeon’s skills during the insertion process. The device will be responsible for the reproduction and the eventual amplification of the forces experienced by the end-effector linear stage via a force feedback interface onto the surgeon’s hand.

This teleoperation architecture will enable the servo-assisted insertion of the probe into soft tissues without the loss of an eventually augmented kinesthetic perception. Regarding transparency, the controller should be able to virtually reflect to the user the
same real impedance of the operational environment, in addition to guaranteeing safety and stability as well. Several approaches can be found in the literature, in which the transparency has been quantitatively defined in different ways. The transparency has been defined in terms of the ratio between the real and the rendered impedance. In [73], the fidelity metric is based on the ability of the system to render environmental compliance changes while taking into account some cognitive aspects of the operator perception. Although different point of views, all solutions are obviously subject to the same stability requirements, i.e. the system should not exhibit vibration or divergent behavior, under any operating conditions and for any environments. However, the stability is often achieved by adding damping elements in the control loop, eventually using nonlinear or switching techniques. For example, in [74] the reflected impedance is intentionally shaped by the bilateral controller in order to improve perception by the user and to achieve robust stability. In any case, any change of the rendered impedance results in a transparency degradation. In summary, transparency and stability may be conflicting design goals for a teleoperation controller, hence a suitable trade-off must achieved to guarantee realistic and stable operation in a wide range of environment impedance and in the presence of signal latency [75].

3.2 2-DoF cutaneous device for teleoperated needle insertion

3.2.1 Device design and performance

In order to perform a basic needle insertion simulation a 2-DoF cutaneous device for teleoperated needle insertion is presented in [76]. Two motors are used to flex two mobile platforms, applying a normal force to the user’s thumb and index finger pads. The cutaneous device substitutes the typical kinesthetic and cutaneous feedback, usually provided by grounded haptic interfaces, with the cutaneous component only. The main advantage of this approach is that it does not suffer from typical stability issues and it can be considered intrinsically safe when used in a teleoperation system.

The proposed technique can be casted in a sensory substitution framework but there are relevant differences which are worth underlining. Its main advantage, with respect to classic sensory substitution techniques which employ visual and/or auditory feedback, is that the substitution occurs at the cutaneous level and the feedback is applied directly on the finger pads, i.e. exactly where the force feedback is expected by the operator. A teleoperated needle insertion application is considered, in order to evaluate the effec-
3.2. 2-DoF cutaneous device for teleoperated needle insertion

Figure 3.1: On the left side of the picture the cutaneous device mounted on the Omega 3 end-effector. The motors flex the platforms, applying a force to the thumb or to the index finger (cyan arrows). Each force is balanced by a force supported by the structure of the device on the back of the each finger (red arrows). On the right side, CAD rendering of the handle prototype. Part A is fixed to the haptic device end-effector while parts B and F permit to use the torque of the motors (C) to flex the two platforms (D). Two sensors (E) are in charge of registering the actual force applied by the device while platforms (G) support the fingers.

The device consists of a static part (named A in Fig. 3.1), rigidly connected to the haptic interface end-effector, and two platforms (D). Two servo motors (C), connected to the pulleys (F), make the platforms (C) flex backward and forward, applying a normal force to the thumb and to the index (cyan arrows in Fig. 3.1). The parts of the device which are behind the finger pads and in contact with the back of the fingers (G) are in charge of balancing the force applied by the device at the fingertips (red arrows in Fig. 3.1).

Two piezoresistive force sensors are fixed to the surface of the platforms, in contact with the finger pads. The aim is to measure the actual force applied at the fingertip, in order to implement a closed loop force control strategy. The sensors employed in the prototype have a diameter of 5 mm and a thickness of 0.3 mm, making them very transparent to the user and easily embeddable in the device. The actuators used for the device prototype are two HS-55 MicroLite Servo motors [77]. To properly use the cutaneous device, the operator has to insert the thumb and the index finger in the device, as shown in Fig. 3.1. The device is controlled by an Atmega 328 microcontroller, installed on an Arduino UNO board, which commands the motors via PWM and reads the force sensors analog signals. The force applied by the two mobile platforms to the
user’s fingertips is regulated by a PD controller. In order to check the device accuracy in applying a desired force to the fingertips, two different tests were performed. Fig. 3.2 shows the step response of the system. The estimated forces reach the reference value with a settling time of about 0.25s and an error in the stationary phase lower than 2%. Fig. 3.2 analyses the behaviour of the device when following a sinusoidal force reference signal with a period of 2s and an amplitude of 2N. Note that when the force generated is positive the force is applied to the index finger and when the force value is negative the force is applied to the thumb (see Fig. 3.1).

The normal force applied by the device to the user’s finger pads (cyan arrows in Fig. 3.1) is balanced by the force supported by the structure of the device on the back of the finger (red arrows). The support force is distributed on a larger contact surface so that the local pressure is much lower and the contact is perceived only on the finger pad and not on the back side of the finger. This idea was inspired by the gravity grabber presented by K. Minamizawa et al. in [13], where a wearable haptic display was employed to simulate weight sensations of virtual objects.

### 3.2.2 Experimental evaluation

The scenario considered is a teleoperated needle insertion along one direction. Two different experiments have been performed. In the first one a needle insertion in soft tissue has been simulated while in the second experiment a robot, equipped with a needle, and
a real object have been used. In both cases the master side consists of the proposed device fixed to the Omega 3 end-effector (Force Dimension, CH) as shown in Fig. 3.1. The motion of the Omega 3 is constrained along the $z$-axis by means of three rigid clamps fixed to the parallel structure of the haptic device. The human operator puts his/her fingers in the device as shown in Fig. 3.1. The sensory substitution approach consists of substituting the force feedback, usually provided by the haptic device, as follows: if the force is directed towards the negative direction of the $z$-axis, a pressure is applied to the index finger pad and, alternatively, if the force is directed towards the opposite direction, a pressure is applied to the thumb pad (see Fig. 3.1). The position of the haptic device end-effector (i.e., the position of the cutaneous device proposed) is linked with the position of the needle. The operator holds the tool as in Fig. 3.1 and steers the needle by moving the end-effector along the $z$-axis of the haptic device.

The force feedback employed during the trials was either haptic feedback (i.e., cutaneous and kinesthetic feedback) provided by the Omega 3 haptic device (task H) or cutaneous feedback only provided by the proposed cutaneous device (task C). In tasks H the motors of the cutaneous device are turned off while in tasks C the motors of the haptic device are the ones to be turned off. In both cases the Omega 3 haptic device is used to track the position of the operator’s hand. This first experiment aimed at showing that there is no relevant degradation of performance in haptic interaction tasks when a normal force is fed back to the user’s finger pads using the proposed cutaneous device in substitution of the force feedback generated by a grounded haptic interface.

The task consisted in inserting the needle into a soft tissue and stopping the motion of the hand as soon as a virtual stiff constraint was perceived. The stiff constraint played the role of a virtual fixture, i.e. a software function used in assistive robotic systems to regulate the motion of surgical implements. The motion of the surgical tool, the needle in our case, is still controlled by the surgeon, but the system constantly monitors its motion and takes some actions if the surgical tool fails to follow a predetermined procedure. Developing this experiment we consider an example of a forbidden-region virtual fixture. It is in charge of preventing the needle from entering a specific region of the workspace. This is a common scenario for biopsies, deep brain stimulation and functional neurosurgery [78]

A virtual environment simulating a needle insertion in soft tissue has been employed. The model used to simulate the phases of tissue needle insertion is described in [37]. Our aim is not the design of an accurate tissue simulator, as, for example, in [79], but the validation of the proposed cutaneous force feedback device. If the operator steers the needle towards the unsafe area delimited by the stiff constraint, a force is fed back
Figure 3.3: On the left side of the figure the experimental setup. The haptic device, with the proposed device mounted on, controls the motion of the manipulator. The force measured at the needle tip by a sensor is fed back to the operator either by the motors of the Omega 3 or by the motors of the cutaneous device. On the right side, the experiment in a simulated environment. Mean penetration depth $\bar{p}$ into the stiff constraint, expressed in mm, during tests with the haptic (task H) and cutaneous feedback (task C).

to the operator in order to avoid the penetration of the needle in the forbidden area:

$$F_{vf} = -K_{vf}(z_n - \bar{z}_{vf}),$$

where $K_{vf} = 2N/mm$, $z_n$ represents the position of the haptic device end-effector and $\bar{z}_{vf}$ the position of the stiff constraint. The operator was able to see a lateral virtual image of the needle out of the tissue, while the position of the stiff constraint and the part of the needle inside the tissue were not visible. The haptic device measures the position of the operator’s hand, sends it to the controller and then the virtual environment computes the force feedback and tissue dynamics. The controller then sends these forces back to the user through either the haptic interface or the cutaneous device. Seven participants (5 males, 2 female, age range 20-26) took part to the experiment, all of whom were right-handed. Four of them had previous experience with haptic interfaces. None of the participants reported any deficiencies in the perception abilities. Each participant made six repetitions of the needle insertion task, with three randomized trials for each feedback modality: haptic feedback (task H) and cutaneous feedback (task C). Fig. 3.4 shows the needle position and the force measured at the needle tip versus time, for a representative run, while using haptic feedback (task H) or cutaneous feedback (task C). Fig. 3.3 shows the mean penetration depth $\bar{p}$ into the stiff constraint.
Figure 3.4: Experiment in a simulated environment. In the left column the needle position versus time, expressed in mm, is shown in red. The blue line represents the position of the tissue surface while the dashed black line represents the position of the virtual fixture surface. In the right column the force measured at the needle tip versus time, expressed in N, is shown in red. The dotted black line represents the instant the needle enters the soft tissue and the dashed black line represents the instant the needle collides with the virtual fixture surface.

The collected data of each task passed the Shapiro-Wilk normality test. Then a parametric two-tailed paired t-test was performed in order to evaluate the statistical significance of the differences between tasks (i.e., between the two feedback modalities). The p-values found reveal a statistically significant difference between the groups.

The results of this experiment indicate that haptic feedback (task H) produced better performances with respect to cutaneous feedback only (task C). However all the subjects were able to perceive the presence of the stiff constraint while using the cutaneous device and stop the motion of the hand right after having penetrated into the forbidden area. We believe that this is a price worth paying, in terms of performance, in...
order to get a great improvement in the stability of the teleoperation loop.

It is worth emphasizing that larger penetration depth into the virtual fixture corresponds to higher forces fed back by the virtual environment (applied by either the haptic device or the cutaneous actuator), according to the stiff element chosen for the virtual surface. During the experiment, the motors of the cutaneous display never reached its saturation limits. The main advantage of cutaneous feedback is that it makes the haptic loop intrinsically stable, no matter what happens in the external environment. To support this argument a new experiment was carried out, in which the same protocol of the

Figure 3.5: In the left column the experiment in a real world scenario. Needle and haptic interface positions, expressed in \textit{mm}, are respectively shown in blue and red. The dotted black line represents the position of the object being penetrated while the dashed black line represents the position of the virtual fixture. In the right column the force measured at the needle tip and force generated by the virtual fixture model, expressed in \textit{N}, are shown, respectively, in blue and red. The dotted black line represents the instant the needle penetrate the object and the dashed black line represents the instant the needle collides with the virtual fixture surface.
A needle insertion task with the same feedback modalities was proposed in a real scenario. The experimental setup is reported in Fig. 3.3 and consisted of the 6-DoFs manipulator KUKA KR3 teleoperated by an Omega 3 haptic interface. A needle and a force sensor, able to measure the force at the base of the needle, were fixed to the robot end-effector. The motion of the manipulator was controlled using the haptic device. The haptic interface controller runs at a rate of 1kHz which is higher than the TCP/IP KUKA maximum frequency of 83Hz, resulting in a haptic interface-to-robot command delay. It is worth noting that the instability problem of the haptic loop in the presence of time delays can be solved with advanced controls, as the wave variable transformation [22, 80] or passivity controls [81]. Nonetheless, with the aim of emphasizing the intrinsic stability of cutaneous feedback, this method was not used in the experiment. Our sensory substitution approach makes the haptic loop intrinsically stable. The instability behaviour of the haptic device, induced in this experiment with a communication delay, is a case of study for generic stability issues in teleoperation.

We asked a single subject to insert the needle in an object made of expanded polystyrene (EPS) and then stop the motion of the hand when the stiff constraint was perceived. Fig. 3.5 shows the position of the needle fixed to the remote robot’s end-effector and the operator’s hand position versus time, while Fig. 3.5 shows the force measured at the needle base and the force generated by the virtual fixture model versus time. This result shows that haptic feedback (task H) can bring the haptic loop near to instability, as significant oscillations of the probe position occurred, whereas cutaneous feedback (task C) allows a stable contact with the virtual fixture surface. The same behaviour is expected in every case of serious failure of the haptic device’s actuators, which can cause an abrupt change in the behaviour of the remote robot.

Concluding the experiments have shown that cutaneous feedback at the fingertips may be effectively used in the proposed scenario to substitute complete haptic feedback (i.e. cutaneous and kinesthetic feedback). The main advantage of using the fingertip cutaneous display instead of the complete haptic feedback is that the stability of the haptic loop is intrinsically guaranteed. This can be very convenient for critical applications, such as robot-assisted surgery. The main drawback of this novel approach is that, in spite of a practically indistinguishable perception of touching a virtual wall, the realism of the interaction certainly improves with kinesthetic feedback. Moreover, it is worth underlining that, to exploit this idea in medical applications like robotic surgery, we need to prove that applying cutaneous feedback to the fingertips of the operator will not distract him/her from the surgical task. To improve the performance and the accuracy of the control of the device, we are considering to introduce a position sensor in addition to
the two force sensors. Furthermore, work is in progress to validate the device with more subjects and more tests. We also want to compare other sensory substitution techniques existing in literature with the proposed cutaneous device performance.

3.3 3-DoF cutaneous device for virtual interaction

In this section, we present an experiment of two-finger grasping. The task considered is the peg-in-hole and the simulated force feedback is cutaneous or kinesthetic. The kinesthetic feedback is provided by a commercial haptic device while the cutaneous one is provided by a new haptic display proposed in this work, which allows us to render a wide range of contact forces at the fingertip. The device consists of a mobile surface, which interacts with the fingertip, actuated by three wires directly connected to the motors placed on the grounded structure of the display. The device developed is a three DoF cutaneous display used to interact with objects in a virtual environment. It is able to apply contact forces to the fingertip by applying forces to the vertices of a rigid platform by means of three wires. Three servo-motors are in charge of moving the platform and applying the requested force to the user’s fingertips, ensuring precision, strength, and lightness. The system provides cutaneous stimuli only and most of the kinesthetic feedback is missing.

The proposed device is similar to the wearable haptic device presented in [82] but there are relevant differences which are worth underlining. The cutaneous display here presented can be easily integrated with other systems which provide kinesthetic stimuli: it uses three servo motors and can render higher forces at the fingertip. The idea of providing realistic cutaneous sensations while using haptic interfaces has been also discussed in [18]. However, the thimble there presented was only able to provide the cutaneous sensation of making and breaking contact with virtual surfaces. An important contribution of this work is to show how this cutaneous device can be used to simulate a pinch grasp and perform a peg-in-hole task. This section summarizes the design of the proposed display and presents the main relationships which describe its kinematics and dynamics. Results showed that cutaneous feedback exhibits improved performances when compared to visual feedback only.

3.3.1 Device structure and specifications

Fig. 3.6 shows the main idea of the proposed three DoFs cutaneous device while a prototype is shown in Fig. 3.6. It consists of a static part (parts A, C-E in Fig. 3.6),
3.3. 3-DoF cutaneous device for virtual interaction

Figure 3.6: In the left side of the figure, the three DoFs cutaneous display prototype: the three servo-motors move the platform according to the virtual surface being touched. The device is fixed to the end-effector of the Omega 3 haptic device. On the right side a sketch of the three DoFs cutaneous device. Three servo-motors control the lengths of three wires in order to tilt the mobile platform according to the virtual surface being touched.

and a mobile part (part G), able to apply the requested stimuli to the fingertip’s volar surface. Referring to Fig. 3.6, the user should place the fingertip between part G and part E. Three springs, placed between the mobile platform and the static part, keep the platform horizontally aligned with the rest of the device. Three servo-motors (B) control the length of the three wires (H) connecting the mobile platform vertices to the static platform (E), making the platform able to apply the requested force at the user’s fingertip. The actuators used for the device prototype are three HS-55 MicroLite Servo motors [77]. The motors are fixed to part C and D of the device structure. Part A is devoted to connect the cutaneous display to an external support. In this work the device will be fixed to the end-effector of an Omega 3 haptic device in order to provide kinesthetic feedback, if necessary, and/or track the position of the finger. The mechanical supports for the actuators and the mobile platform are made using a special type of acrylonitrile butadiene styrene, called ABSPlus™ (Stratasys Inc., USA). The device uses a velcro strap, fixed to part D, to be fasten tightly to the fingers and make it easier to wear (see Fig. 3.6). The total weight of the whole device, including actuators, springs, wires, and the mechanical support is about 45g.

The force applied by the device to the user’s finger pad is balanced by a force supported by the structure of the device on the back of the finger (part E). This structure has a larger contact surface than the mobile platform (part G) so that the local pressure is much lower and the contact is mainly perceived on the finger pad and not on the back side of the finger. This idea was inspired by the gravity grabber presented in [13, 34] and previously summarized, where a wearable haptic display was employed to simulate weight sensations of virtual objects. Both devices are able to render cutaneous stimuli
and most of the kinesthetic feedback is missed. The kinematic structure of the proposed device is similar to the wearable display described in [82]. The main differences is that this is not designed to be portable. The power of the actuators is larger and three passive springs have been included in the design. Similar to the device proposed in [82], the cutaneous platform can be modeled as a three DoFs parallel mechanism, where the static part is fixed and the mobile platform is in contact with the finger pulp. The mobile platform is moved acting on three wires connecting its vertices to the actuators. Three springs, which contain the wires, make it possible to fix the platform in a reference configuration. The model of the wearable device presented in Chapter 2 device differs from the one described in [82] because:

- in this case the wires do not follow the finger shape but take a straight line from the static to the mobile platform,

- in the evaluation of actuator forces the compliance of the three springs is taken into account.

Let \( w_p = [f_p^T \ m_p^T]^T \in \mathbb{R}^6 \) be the wrench applied to the mobile platform (expressed with respect to \( S_0 \)), and \( Q = [Q_1 \ Q_2 \ Q_3]^T \) the vector of force (norms) applied to the wires, being their directions defined by the unit vectors \( s_1, s_2, \) and \( s_3 \) respectively. We can express he external wrench as a function of the force applied to the wires

\[
w_p = J_p^T Q. \tag{3.1}
\]
3.3. 3-DoF cutaneous device for virtual interaction

where \( J_p \in \mathbb{R}^{3 \times 6} \) is the Jacobian matrix and can be evaluated from the analysis of the differential kinematics of the platform. The wire forces \( Q_i \) are given by the sum of two components

\[
Q_i = Q_{a,i} + Q_{p,i}
\]

where \( Q_{a,i} \) is the force applied by the \( i \)-th actuator, proportional to the motor torque, i.e. \( Q_{a,i} = T_i/r_i \), \( T_i \) is the \( i \)-th motor torque and \( r_i \) is the \( i \)-th motor pulley radius. \( Q_{p,i} \) is the contribution generated by the spring deformation

\[
Q_{p,i} = k_i (\|d_i\| - \|d_{i,0}\|)
\]

where \( k_i \) is the spring stiffness, \( \|d_i\| \) is the actual wire length, \( \|d_{i,0}\| \) is the nominal spring length. The described device is underactuated, since it has only three actuators to control the six-dimensional displacement of the mobile platform, so it is not possible to find a one-to-one relationship between the wire lengths and the platform displacement and orientation in the three-dimensional space. If the platform touches the fingertip, the platform displacement \( \xi = [p_x \ p_y \ p_z \ \alpha \ \beta \ \gamma]^T \) produces a deformation of the fingertip that leads to a contact stress distribution. In quasi static condition the stress distribution on the fingertip is balanced by the wrench applied by the platform \( w_p \) [58]. Different mathematical and numerical models of the fingertip have been proposed in the literature. In [59], for example, a 2D continuum fingertip model is described, in which the finger is approximated by an homogeneous, isotropic and incompressible elastic material. Serina et al., in [58], developed a model that incorporates both inhomogeneity and geometry of the fingertip. In [83] an experimental method for obtaining the 2-dimensional skin tension/extension-ratio characteristics of living human skin is described. In [84] the authors conducted an experiment in order to characterize the response of the in vivo fingertip pulp under repeated and compressive loadings, aiming to better understand the force modulation by the pulp. The force/deformation behavior of the fingertips in the lateral, or shearing, direction, is studied in [61]. Actually, the stress/strain behavior of the fingertip under shearing forces is non linear, in fact in [62] the authors experimentally quantified the anisotropic and hysteretic behaviour of the fingertip deformation under the application of tangential forces. In this tested device we considered a linear relationship between the resultant wrench and the platform displacement. In other terms we assume that the platform configuration \( \xi \) is proportional to the wrench \( w_p \)

\[
\xi = K^{-1}w_p \tag{3.2}
\]

where \( K \in \mathbb{R}^{6 \times 6} \) is the fingertip stiffness matrix. In this preliminary study an isotropic elastic behaviour is assumed for all the components of the stiffness matrix: \( K = kI \),
Two fingers cutaneous displays

Figure 3.8: Experimental setup and virtual environment. The user had to wear two cutaneous devices, one on the index and one on the thumb finger, and then grasp the virtual cube and complete the peg-in-hole task as fast as possible.

\[ k = 2N/mm \] [63]. From the control point of view, the device can be represented as a non-linear, multi-input multi-output (MIMO) coupled system. Different control strategies can be considered; we can control for instance the force applied by the platform to the fingertip or the position and orientation of the mobile platform. In particular, in the device position control, the motors are regulated so that the mobile platform reaches a reference configuration. The inverse kinematics of the parallel mechanism allows us to evaluate the corresponding reference cable lengths. These values are compared to the actual ones and then the error drives the PD controllers of the motors.

3.3.2 Experimental evaluation

The presented cutaneous device can tilt the mobile platform according to the reaction force of the virtual object being touched, enhancing the users illusion of telepresence. This experiment aimed at evaluating user dexterity while using the device in a virtual environment. Two cutaneous devices were each fixed to the end-effector of two Omega 3 haptic interfaces, as shown in Fig. 3.6. Users were able to interact with virtual objects in a virtual environment built using CHAI 3D [85], an open-source set of C++ libraries for computer haptics and interactive real-time simulation. The experimental setup is shown in Fig. 3.8. Nine participants, six males, three females, age range 19-35, took part to the experiment, all of whom were right-handed. Five of them had previous experience with haptic interfaces. None of the participants reported any deficiencies in their perception abilities. The subjects were asked to wear two cutaneous devices, one on the thumb and one on the index finger (see Fig. 3.8) and complete a peg-in-hole task in a virtual environment [86, 87]. The virtual environment was composed of a cube and two holes (named hole1 and hole2, as shown in Fig. 3.8). The two holes were 3.5cm deep (x-
3.3. 3-DoF cutaneous device for virtual interaction

direction), 3.5 cm wide (y-direction), and 0.5 cm high (z-direction). The peg was a cube with an edge length of 3 cm. Therefore the hole had a tolerance of 0.5 cm in the x and y directions. The task consisted of grasping the cube from the ground, inserting it into the right hole (hole2), then in the left hole (hole1) and then again in hole2 and hole1; therefore the correct sequence was hole2, hole1, hole2, hole1. The task started when the user grasped the object and finished when the user inserted, for the second time, the peg in hole1. At least half of the length of the peg had to be inserted in the hole in order to move to the next hole and the peg had to be inserted from the top to the bottom. When the object was correctly inserted into a hole, the color of the peg changed1. Each participant made twelve repetitions of the peg-in-hole task, with three randomized trials for each force feedback modality proposed:

- both kinesthetic and cutaneous feedback provided by the Omega 3 haptic devices and the proposed cutaneous devices (task K + C),
- kinesthetic feedback only provided by the Omega 3 haptic devices (task K),
- cutaneous feedback only provided by the cutaneous devices (task C),
- no force feedback (task N).

Visual feedback, as shown in Fig. 3.8, was always provided to the users. To evaluate the performance of the different force feedback modalities, the time needed to complete the task was recorded, together with the forces generated by the contact between the two proxies, controlled by the user, and the cube. A spring $k_o = 600 N/m$ is used to model the contact force between the proxies and the object. Data resulting from different trials of the same task, performed by the same subject, were averaged before comparison with other users’ data. Fig. 3.9 shows the average time elapsed between the instant the user grasps the object and the instant it completes the peg-in-hole task. The collected data of each task passed the D’Agostino-Pearson omnibus K2 normality test. Comparison of the means among the feedback modalities was tested using one-way ANOVA (no repeated measures). The means differed significantly among the feedback modalities. Post-hoc analyses (Bonferroni’s multiple comparison test) revealed statistically significant difference between all the groups, showing that the time needed to accomplish the task depends on the feedback modality employed in the experiment. The subjects, while receiving both kinesthetic and cutaneous feedback (task $K + C$), completed the task in less time when compared to that obtained while receiving kinesthetic feedback.

1A short video of the experiment can be found at http://goo.gl/O3Ax8
only (task $K$). Using cutaneous feedback only (task $C$) yields significantly better results than employing no force feedback at all (task $N$). This means that employing cutaneous feedback improves subjects’ performances in terms of time needed to complete the task proposed. Using kinesthetic feedback (both in task $K+C$ and $K$) produced better performance than cutaneous feedback only or no force feedback at all. Fig. 3.9 shows the average forces generated by the contact between the two proxies, controlled by the user, and the cube along the $y$-direction, i.e. the one perpendicular to the object surface. Note that a higher force fed back to the user means a larger penetration into the virtual object and a higher energy expenditure during the grasp. Measuring the average of intensities of the two contact forces is a widely-used approach to evaluate energy expenditure during the grasp [88]. The collected data of each task passed the D’Agostino-Pearson omnibus K2 normality test and a one-way ANOVA test was performed to evaluate the statistical significance of the differences between tasks. The post-hoc analyses (Bonferroni’s multiple comparison test) revealed no statistical significance between the two tasks employing kinesthetic feedback (task $K+C$ and $K$) while it revealed a difference between the task employing no force feedback (task $N$) and the one using cutaneous feedback only (task $C$). It is worth noting that cutaneous feedback caused a smaller force to be fed-back to the operator and to a smaller penetration into the virtual object in comparison to the no-force modality.

Concluding, the peg-in-hole experiment has been carried out on nine users who have completed the peg-in-hole task employing four different force feedback modalities: no force feedback at all, kinesthetic feedback, cutaneous feedback, and both kinesthetic and
cutaneous feedback. Results showed that employing cutaneous and kinesthetic feedback led to a higher quality of the grasp (i.e., a smaller energy expenditure) and it improved the performances in terms of time needed to complete the given task with respect to the kinesthetic only feedback. Future developments will include the analysis of other types of control schemes and the employment of three force sensors placed at the vertices of the mobile platform. The sensors will provide a measurement of the force the platform is applying to the user’s fingertip and will allow the system to modulate correctly the force applied by the cutaneous device.
Chapter 4

Wearability for guidance

In this chapter we will explore a vibrotactile feedback paradigm which allows the human to intuitively interact in human-robot applications. In particular we focus on a haptic bracelet which helps the human to move along trajectories that are feasible for the leader-follower formation tasks. The bracelet consists of three vibrating motors circling the forearm and represents a non invasive way to provide essential guidance information to the human.

4.1 The vibrotactile device

In this chapter we focus on a vibrotactile bracelet which aims at improving the human-robot interaction in leader-follower formations where a human is followed by a group of nonholonomic mobile robots (see Fig. 4.1). The goal of the robot followers is to maintain a certain desired distance and orientation with respect to the human leader. Our purpose is to warn the human during his/her motion in order to let him/her move along trajectories that are feasible for the leader-follower formation tasks. Compared to [54], this device has a reduced number of motors to allow a basic guidance for the proposed experiment. Recent studies have demonstrated that a bracelet shape with three vibrating motors circling the forearm ensures a sufficient distance between the vibro-motors while at the same time covers a minimum forearm area [89]. Following this layout, we designed a wearable actuated device in which three vibro-motors, L (left), C (center) and R (right) are independently controlled via an external PC using the bluetooth 802.11 communication protocol as shown in Fig. 4.1. The communication is realized with a RN41 bluetooth module connected to an Arduino Nano board. The bracelet is equipped with three LilyPad Vibe Boards with 10mm Shaftless Vibration Motors. An Atmega-328 microcontroller installed on the Arduino Nano board is used to independently control the vibration amplitude of each motor. The microcontroller
4. Wearability for guidance

Figure 4.1: A human leader is followed by a team of mobile robots equipped with RGB-D cameras. A vibrotactile bracelet allows the followers to inform the leader about the formation consistency. The human-robot interaction is achieved via a vibrotactile bracelet equipped with three vibrating motors A: L (left), C (center) and R (right) attached to an elastic strap B. The three motors are disposed equidistantly in order to improve the vibrotactile perception. A 9V battery and an Arduino board are disposed on the back of the forearm inside a plastic case C.

controls the external actuators using 3 PWM outputs, each one fixed at 5V, 800Hz. The haptic bracelet is powered by a 9V, 200mAh battery. The minimum duty-cycle required to start the motor rotation is 20% and the amplitude of the vibration and its frequency increase proportionally to the duty-cycle. The maximum vibration frequency of each motor is 200Hz while the maximum amplitude of vibration is 0.8G.

4.2 Mobile robot guidance through vibrotactile feedback

In order to clearly describe the algorithm used, we briefly recall the leader-follower formation control strategy proposed in [90], that we adapted to our mixed human-robot setup.

For the sake of simplicity, we prefer to omit most of the mathematical calculation which led to the definition of the leader-follower formation control law, focusing instead on the trajectory constraints which contribute to the generation of the vibrotactile stimuli. Let us consider a nonholonomic robot $R = (x, y, \theta)^T$ with initial condition $\tilde{R} \in \mathbb{R}^3$ and control $(v, \omega)^T$. Denote by $P(t) = (x(t), y(t))^T$ the position of $R$ at time $t$, $\theta(t)$ its heading, $\tau(\theta(t))$ the normalized velocity vector and $v(\theta(t))$ the normalized vector orthogonal to $\tau(\theta(t))$. If we assume $v(t) > 0$, then the (scalar) curvature of the path followed by the robot at time $t$ is $\kappa(t) = $ $\omega(t)/v(t)$. We suppose that every robot $R$
which takes part in the team satisfies the trajectory constraint \((V_p, K_p^-, K_p^+) \in \mathbb{R}^3, \forall t \geq 0\)

\[
0 < v(t) \leq V_p K_p^- \leq \kappa(t) \leq K_p^+ \tag{4.1}
\]

This constraint is assumed to be the mechanical limitation common to all the robots. When the leader is a mobile robot, it is relatively simple to force the robot to satisfy such constraints. On the contrary, in presence of a human leader, it is necessary to establish a simple communication channel between the human and the robot such that the leader is warned when he/she is violating a possible constraint.

Let \(f_M, f_m\) be the maximum and minimum vibration frequency of each motor and \(f_i(t)\) the vibration frequency of motor \(i \in \{L, C, R\}\) at time \(t\). As discussed previously, the leader constraints can be divided in velocity and curvature constraints. The curvature constraints involve the activation of the lateral motors, while the velocity constraints will be displayed through the central motor of the bracelet. Our vibrotactile feedback briefly consists in activating the vibro-motors as soon as the leader approaches the formation constraints within a given threshold, and increasing the vibration frequency proportionally to the constraint violation. Let \(\delta^+(t), \delta^-(t)\) be the amount of violation of the given constraints at time \(t\), when \(\omega_0(t)\) is positive and negative. In order to control the vibrating frequency of the motors we consider the

\[
f_i(t) = \mathcal{F}(\delta^+(t), \alpha_c)
\]

where \(\mathcal{F}\) is the function which computes the value of the frequency depending on the violation and the curvature threshold \(\alpha_c\) as documented in [46]. In particular, the frequency increases together with the violation and the lateral motors are activated if the angle is violated turning left or right respectively. And when the human speed exceeds the limit of the robot, all the motor vibrate simultaneously. Formally, the index \(i\) is \(L\) or \(R\) if the motor used is the left one or the right one respectively. In other words, the vibrating frequency grows if the error of the human grows and we arbitrarily decide to use a pulse wave for the central motor in order to be correctly perceived by the user.

### 4.3 Experimental evaluation

The proposed device has been tested on 15 healthy male subjects (aged 23 to 33, all right-handed). Although tactile stimulations under 100Hz improve the spatial resolution of the vibrations’ perception [91], we preferred to use a vibration frequency between 80Hz and 200Hz, which turned out to be more comfortable for the subjects. We performed two different experiments. In the first one a single signal or a combination
of signals at different vibrational frequencies was sent to the haptic bracelet, this experiment allowed us to understand if the human is capable of recognizing which motor is vibrating. In the second experiment two consecutive signals with different frequencies were sent to the same motors. This experiment showed the minimum frequency variation the user can perceive. Each subject was initially trained with a training set of 20 trials. For both the experiments, the evaluation set was composed of two sets of 30 trials each. We avoided cases in which all motors were turned on and cases in which the left and right motors were contemporary activated, since they cannot be encountered in real applications.

In the first experiment, the users could correctly perceive and distinguish 83% of the vibrotactile stimuli. In particular, a single signal was always correctly perceived. The average time elapsed to perceive the vibration was 1.13s with standard deviation of 0.43s. An in-depth analysis revealed that in the presence of two signals, the subjects could always correctly perceive at least one of the two involved stimuli, usually the most intense. This means that in real world experiments, the leader should always be able to perceive the vibrotactile feedback relative to the constraint that is violated the most.

In the second experiment, the users could correctly perceive 85.61% of the frequency variation of at least 30Hz. This means that the user can perceive, within a good percentage, if the constraint violation is increasing or decreasing. The bracelet showed the ability to exert vibrotactile signals which can be correctly perceived by the human user. In this regard it can be effectively used in the leader-follower formation control proposed in [90]. Ongoing research aims at testing such devices in the proposed scenario as well as extending its applicability to other case studies.
Imagine a world in which wearable haptic systems allow you to perceive, share, interact and cooperate with someone that is miles away from you in a much more integrated way. Think of the variety of new opportunities this interaction will bring to our fingertips in cooperation, health, social interaction, remote assistance and in much more intriguing scenarios we can now only envisage. In this chapter a concept which is currently in progress state called RemoTouch is presented. In this idea wearable haptics meets the communications substituting a robot avatar with an human avatar who can interact from a distance. Here, we will introduce the system device and some preliminary tests in order to present the remote touch technology.

5.1 Toward wearable devices for communication: RemoTouch

The system consists of an avatar equipped with an instrumented glove and a user wearing tactile displays allowing him/her to feel the remote tactile interaction. The main features of RemoTouch are that it is a wearable system and that a human avatar is used to collect remote tactile interaction data. New paradigms of tactile communication can be designed around the RemoTouch system.

Two simple experiences are reported to show the potential of the proposed remote touch architecture. The idea of RemoTouch is to substitute the robot avatar with an human avatar: the user (on the left) perceives the force feedback recorded by the human avatar (on the right). The human avatar wears a glove equipped with force sensors, one per finger as in Fig. 5.2. The measured contact force at the remote interaction is fed back to the user through simple and wearable tactile displays, one per finger, as in Fig. 5.2.
The tactile display is similar to those developed in [34] and has been adapted to the idea of remote touch. The tactile display consists of two motors and a belt able to deform the fingertip according to the contact force measured by the remote instrumented glove. RemoTouch is a project which involves telepresence and communication between two users without using a robotic avatar. So the goal is to be able to transfer the contact signal in the same way the voice and the video image are sent to the remote user. Note that the force feedback is tactile only and the kinesthetic feedback is missed. Recently, results have been presented to study to what extent the kinesthetic feedback can be substituted with tactile feedback only [14]. Practical experiments have shown that this lack of feedback in force is well compensated by the presence of other modalities like video and audio feedback, which are extensively used in our experiments.

A very important feature of RemoTouch is that the involved technology is simple, wearable, low energy consumption and not expensive. Of course this is a direct consequence of having chosen a human avatar instead of a remote robot which is not a secondary point but the main point of our project. The device in charge of recording tactile perception is not a robot, as in teleoperation, but a human avatar. The human avatar wears a glove equipped with a force sensor. The piezoresistive force sensor by FlexiForce (model A201) has been chosen to equip each finger of the human avatar as in Fig. 5.2. This force sensor is easily wearable due to its flexible structure and has been integrated with a glove to measure the deformation of the human avatar’s fingertip during the contact interaction. A standard protocol based on USB has been used for communication with the computational unit and to provide the power supply.

Regarding the user, the force feedback recorded by the human avatar is presented
to the user using a simple and wearable tactile display as shown in Fig. 5.2. It consists of two motors and a belt able to deform the fingertip according to the contact force measured by the remote instrumented glove. When the motors spin in the opposite directions, the belt applies a perpendicular force on the user’s fingertip. Note that this tactile display can also render tangential forces, but this capability is not used in RemoTouch since the force sensors on the human hand measure only normal forces. The tangential forces will be implemented on the next version of the system. For this reason two motors, instead of one, are used to generate the normal force. The motors are current controlled and the torque command is sent by an embedded C++ library.

The actuators are a couple of DC motors of $5V$ and $500mA$ maximum current. The maximum torque is about $5.80N\cdot cm$, so the maximum force applied by the belt on the pad is about $3N$. As far as calibration is concerned, the same force sensor used for the remote instrumented glove has been also used to calibrate the tactile display. The force sensor was fixed between the belt and the fingerpad, as if the same user was using both the instrumented glove and the tactile display at the same time.

The relationship between the current to the two motors of the tactile display and the resulting normal force applied at the fingerpad and measured by the FlexiForce sensor is approximately linear. The relationship used to map the normal forces to motor currents
Figure 5.3: An experience of remote touch in a context where the mother remotely touches the child and transmits the tactile interaction to the father who is able to perceive the remote touch experience.

\[ c = 0.72 \frac{A}{N} f + 0.15A \]

where \( f \), in \( N \), is the normal force measured at the remote interaction point with the force sensor fixed to the glove of the remote avatar and \( c \) is the current, in \( A \), to be sent to the motors of the tactile display to render the remote measured normal force at the contact. The remote user, who wears the tactile display, enhances his perception using head-mounted video-glasses displaying what the head-mounted camera on the human avatar is capturing. The video signal is acquired by the human avatar camera and transmitted to the user’s head-mounted display. Particular attention has been paid to get coherence between the point of view of the head-mounted camera and the display.

The visual feedback is a relevant part of the remote touch experience. The experience perceived by the user is justified by a perceptive illusion similar to the one described for the rubber hand in [92]. The main idea is to let the operator perceive the remote objects through the human avatar. Using only the tactile modality, there is not enough information about the remote context. Experiments on brain cognition show that the human brain needs some knowledge about the remote environment [93]. In particular the human avatar needs to share what he’s seeing with the remote user using the same point of view of the 3D scene.

The RemoTouch vision system consists of a camera, fixed on the head of the human avatar, and a head-mounted display worn by the user during the experience. Although the 3D display is an immersive experience for vision system, RemoTouch doesn’t use a 3D vision system. This lack is due to the high cost of the 3D vision devices and the con-
Figure 5.4: The second experience of remote touch where a remote piano player transmits the tactile interaction to another player who is able to perceive the remote touch experience.

sequent increase in hardware complexity and portability reduction. The camera position and the multimedia glasses are crucial; they need to be adapted to each user since, as discussed in [93], the visual information from the first person perspective plays an important role in establishing the location of the perceived body relative to environmental landmarks and in defining the origin of the body-centered reference frame.

### 5.2 Experimental evaluation

Two experiences of remote touch are presented. One of the aims of the RemoTouch project is to improve the quality of communication. Touch is important to communicate feelings and emotions. The aim of the experiences was to test the tactile communication and a possible application where touch could be useful. For these two reasons a family context and a music training activity were selected.

#### 5.2.1 Experiment 1: the father and the remote family

The first experience shows RemoTouch performing the task of touching a baby. Think of a family where the mother with her child are at home and the father is far away. The mother, in this case, wears the instrumented glove to record and transmit the interaction forces while touching her child. The mother also uses a head-mounted camera to feed back visual data to the remote husband. The father plays the role of the user and, through the tactile display and the head-mounted display, perceives the tactile and visual
experience recorded by his wife while touching their child (Fig. 5.3).

Preliminary tests show that the realism of this remote experience largely improve with the tactile feedback. The context chosen for the remote experience is very important: having a tactile interaction with their own child involves intense emotions thus increasing the sense of presence even if important components like the kinesthethic feedback are missed in the communication.

### 5.2.2 Experiment 2: play a remote piano

The second experience deals with playing and listening to music. This is another very involving experience in everyday life. In the experiment, the human avatar plays the piano and records the tactile experience, with the instrumented glove, to be played back to the remote user wearing the tactile displays (Fig. 5.4). For audio feedback, a microphone is used to capture the audio signal and in-ear headphones have been used for playback.

To perform these experiences a TCP/IP LAN connection has been used. TCP protocol is optimized for accurate delivery rather than timely delivery, and therefore, TCP sometimes incurs in delays while waiting for out-of-order messages or retransmissions of lost messages. Several techniques were used to synchronize the video flow and the tactile feedback recorded by the instrumented glove. The current implementation of RemoTouch uses synchronising signals, but we plan to add the support, in the next iteration, for the Real-time Transport Protocol (RTP) running over the User Datagram Protocol (UDP), which is the now-a-days used protocol for real-time applications such as Voice Over IP. The video of the two experiences can be found at [http://remotouch.dii.unisi.it](http://remotouch.dii.unisi.it).
Conclusion and future works

This thesis has presented several devices for cutaneous haptic feedback. Using cutaneous feedback for different applications needs a simplified wearable mechanical system which allows us to reduce costs and complexity with respect to grounded haptics. We explored four different scenarios: a wearable device designed for virtual interaction, cutaneous devices embedded on grounded haptic interfaces, wearable vibrotactile devices for guidance and a novel wearable context for communication called Remo-Touch.

Regarding wearability, in comparison to similar existing cutaneous devices, we designed a 3-DOF device that can simulate the contact with an oriented surface at the fingertip. The device can be represented as a 3-DoF parallel mechanism in which a mobile surface is actuated controlling the lengths of the three wires. The mobile platform is connected to the finger and applies a force whose direction and amplitude depend on cable strengths and on the platform’s position and orientation. A simplified linear model has been assumed to model the finger’s six dimensional compliance, necessary to analyse the device performance in terms of feasible forces and to develop the device control system. Two control schemes were presented: in the first one (force control) the wire strains were controlled, while in the second one (position control) the platform configuration (position and orientation) was controlled. Tests on the force control performance showed that the dynamic response of the system is stable and quite accurate. These tests also showed acceptable results in terms of response time and error, and low sensitivity with respect to finger stiffness values. In order to validate the device and verify its accuracy and effectiveness, we planned an experiment aimed at evaluating the JND in curvature discrimination. Results showed that employing the wearable device together with a haptic interface (task H) improved the performance with respect of employing the haptic interface alone.

This kind of highly-wearable device can be useful in many applications, ranging from rehabilitation to entertainment purposes, from robotic surgery to e-commerce, and will contribute to bringing haptic technologies to everyday life applications. The presented device provides tactile stimuli only, while the kinesthetic feedback is missing.
Possible solutions to compensate for this lack of information, while preserving the portability of the device, are currently being investigated. New experiments aiming at evaluating users’ experience while interacting with real objects and augmented scenarios will be performed in the future. Moreover, we are planning to equip the device actuators with position encoders in order to be able to provide more accurate and efficient control algorithms. Finally, we are taking into account the variability of fingertip mechanical properties, in particular stiffness and damping, among different users and the effect of such variability on device performance.

Regarding the surgical scenario, a novel device able to provide cutaneous feedback has been presented in this thesis. The actuation used for the cutaneous display requires less power and is less bulky than the one required to generate haptic feedback; the mechanical structure is thus simpler and the costs are limited. Experiments have shown that cutaneous feedback at the fingertips may be effectively used in the proposed scenario to substitute complete haptic feedback (i.e., cutaneous and kinesthetic feedback). The main advantage of using the fingertip cutaneous display instead of the complete haptic feedback is that the stability of the haptic loop is intrinsically guaranteed. This can be very convenient for critical applications, such as robot-assisted surgery. The main drawback of this novel approach is that, in spite of a strong perception of touching a virtual wall, the realism of the interaction certainly improves with kinesthetic feedback. Moreover, it is worth underlining that, to exploit this idea in medical applications like robotic surgery, we need to investigate that applying cutaneous feedback to the fingertips will not distract the operator from the surgical task. To improve the performance and the accuracy of the device control, we are considering to introduce a position sensor in addition to the two force sensors. Furthermore, work is in progress to validate the device with more subjects and more tests. We also want to compare the proposed cutaneous device with other existing sensory substitution techniques.

We created in order to improve the tactile feedback information of grounded haptic device, a 3-DoF cutaneous device, that can be mounted on an Omega 3 haptic interface. Regarding this device, an experiment of pinch grasping with cutaneous feedback only has been presented along with a new device used to exert cutaneous forces at the two finger pads. A peg-in-hole experiment has been carried out. Nine users had to complete the peg-in-hole task employing four different force feedback modalities: no force feedback at all, kinesthetic feedback, cutaneous feedback, and both kinesthetic and cutaneous feedback. Results showed that employing cutaneous and kinesthetic feedback led to a higher grasp quality (i.e., a smaller energy expenditure) and improved the performance in terms of time needed to complete the given task with respect to the kinesthetic only feedback. Future developments will include the analysis of other types of control
schemes and the employment of three force sensors at the vertices of the mobile platform. The sensors will provide a measurement of the force that the platform is applying to the user’s fingertip and will allow the device to modulate correctly the force applied. New experiments of interaction with virtual objects in virtual environments and in augmented reality scenarios will be performed in the future. Finally, work is in progress to validate the device with more subjects.

A guidance application for mobile robotics using vibrotactile feedback was reported. The human-robot interaction in leader-follower formation task was realized by means of a vibrotactile bracelet. The bracelet was able to apply vibrotactile signals which can be correctly perceived by the human user. In this regard it can be effectively used in the leader-follower formation control. Ongoing research aims at testing such devices in different scenarios as well as extend in its applicability to other case studies. This kind of application can be considered as research support in human-robot interaction scenario in which the cutaneous devices can have an important role.

In Chapter 5 we presented RemoTouch, a system to perform remote touch experiences. Transmitting tactile information can be used to enhance communication between humans. In particular we can communicate different emotions which cannot be easily transmitted through commonly used communication modalities like audio and video. When RemoTouch is used as a tactile communication system, the data-flow consists of recording tactile interaction forces with the instrumented glove to be transmitted to the tactile display along with video and audio signals. Another very interesting scenario for RemoTouch is to use this system not as a real-time communication system but as a system to record the many visual-tactile experiences to be played back. These experiences can be shared with other people as usually happens for images or music in social networks. A further interesting aspect is to build a database of tactile experiences recorded through RemoTouch. The challenge here is to store tactile data to get information retrieval using simple search engines. We are planning to develop a tactile database where users can submit their recorded experiences using tagging techniques as for audio and video files, e.g. the ID3 tag system for mp3 files. Two examples have been presented dealing with particularly emotional contexts. An important feature of RemoTouch is that the involved technology is low cost and with low energy consumption. Of course this is a consequence of choosing a human avatar which is not a secondary point, but the main point of our project. This work is still at the beginning and we believe that many other applications can be found for it. Consider rehabilitation where RemoTouch can be used to easily control the force distribution among fingers in grasping tasks. Substituting the robotic avatar with the human avatar means lower costs, a simplification of the system and a simpler approach for the user. On the other hand, since the kinesthetic
feedback is missed, a vision system is used for any position feedback of the human avatar. The weak point of the proposed remote touch architecture is that the performance, especially in terms of realism, of the overall system has been sacrificed for the portability and wearability of the devices. We believe that new interaction paradigms based on tactile communication can be developed around RemoTouch for applications in both telepresence and teleoperation. Regarding teleoperation, we furthermore observed that RemoTouch deals only with the remote perception, while the action needed to control the remote avatar is an open and very interesting issue; this will be the object of future investigations.
Bibliography


