Abstract

This thesis presents my contribution to the field of human guidance, collecting all the work I have done from December 2014 to December 2017 toward my Ph.D. degree.

In these years, I tried to contribute to address the challenge of guiding humans using haptic strategies, considering both the limbs posture and user’s position and orientation. We developed wearable human tracking systems, to estimate and reconstruct the pose of different body limbs, and studied algorithms to guide people by means of haptic interfaces, acting on walking speed and direction.

Chapter 1 presents results in the field of human tracking. As a starting point we introduce our tracking system: a glove for hand tracking [1]. The proposed device addresses the problem of reconstructing the human hand pose and, at the same time, provide haptic feedback in a wearable way. The glove can estimate the joints values of the hand as well as the hand rotation with respect to a global reference frame. It is designed to limit possible disturbances generated by the servomotors of the haptic interfaces. A modular solution is considered to connect an arbitrary number of cutaneous devices and to separately use the sensing and the actuation component. The experimental validation reveal an orientation estimation error comparable with the human ability of discriminating finger joint angle. As a further advancement, we will improve the glove by using customized and flexible sensing boards of smaller size. An embedded microcontroller will be included to make a wearable and stand-alone tracking system. Moreover wireless technologies will replace the serial communication.

The tracking glove enhancement is presented in Sect. 1.2 in which we introduce a new method to estimate the fingertip contact forces using the glove [2]. For a deformable object with known stiffness matrix, the force is obtained by multiplying the position of the fingertips in the contact frames and stiffness matrix of the object. In future works, we will validate the proposed technique with real objects and additional studies will be performed in order to make the proposed method more general.

Two further spin-off projects started from the developed tracking algorithm. The first, detailed in Sect. 1.3, consists in a wearable human machine interface [3]. A cap, instrumented with a nine axis MARG and three EMG sensors, is used to control a lightweight robot for people with mobility impairments. Outcomes show that individuals with severe motor impairments can comfortably operate assistive robotic manipulators using the proposed system interface. Moreover, patients confirmed its ease of use and performances comparable with the standard joystick controller. In future studies, force feedback techniques will be evaluated to improve control performance.

The second work is detailed in Sect. 1.4. Here we present a novel wearable input interface based on finger interaction [4]. Two conductive bands and a MARG sensor detect finger tap and orientation, respectively, so that Bluetooth connected device can be notified. We investigated the potential impact in the field of text input by implementing a mobile application. Although preliminary results seem promising, we need to involve a larger set of subjects to have much significant set of data to analyze. Moreover, the prototype presented is still far from a real commercial accessory, but we are currently working on a new design for each ring where its form factor will be reduced by half.

Contributions in wearable human tracking for guidance purpose are followed by developed policies to guide human towards a destination using haptics. We show the possibility of controlling walking speed and direction exploiting vibrotactile elastic bands. More in detail, in Sect. 2.2 we present a solution aim to address the problem of guiding multiple users along collision-free paths using the sense of touch. We consider a dynamic environment made by static obstacles and multiple moving users. Haptic feedback is used as an interesting way to provide directional information when audio and visual modalities are not available. Haptic stimuli are generated by an ad-hoc version of the Optimal Reciprocal Collision Avoidance algorithm for non-holonomic agents, which considers the reduced number of stimuli (i.e., instructions) that can be provided to the users and their motion uncertainty. The proposed navigation policy exploits the non-holonomic nature of human locomotion in goal directed paths, which leads to a very intuitive guidance mechanism. Experimental results reveal that all the blindfolded subjects could safely reach the goal area. In future work, we will consider more challenging scenarios including the presence of narrow passages, and scenarios in which the users have a limited interval of time to accomplish the task. In addition, we plan to evaluate the proposed approach with different feedback modalities (composed of a different number of stimuli), and with older adults and visually impaired.

The idea of guiding human walking inspired also the last part of this thesis. In Sect. 2.3 we report preliminary results regarding the problem of guiding humans acting on their step-cycle time i.e., controlling the linear velocity [5]. Haptics is used as an unobtrusive way to provide information when audio or visual channels are not available or overloaded, for instance in a real industrial scenario or in a human-robot interaction task. We consider two different locations for displaying vibrations and suggesting walking pace: wrists and ankles. A task requiring a significant manual and cognitive load was assigned to subjects. Experimental evaluation and user usage feedback show that ankle location is preferred. Such body position results with a smaller error in synchronizing the walking gait, with better performance in executing a real task, and was most ranked by the user for usability, wearability and comfort.
1. Wearable Tracking Technologies

In this chapter we present an innovative sensing system based on inertial and magnetic sensors for hand tracking. It can be combined with cutaneous devices for the rendering of the force feedback, thus producing a wearable sensing/actuation system. The proposed method does not suffer from occlusion problems, it is wearable and cost effective however, since the employed sensors use the magnetometer to compensate the drift, they are sensitive to variations in the magnetic field. This property makes it challenging to interface the sensing glove with wearable devices since their motors generate variations in the magnetic line field. Preliminary experiments showed the effectiveness of using inertial and magnetic sensors for hand tracking. Then, we report an extension of the proposed glove capable of estimating fingertip contact force in grasping deformable objects. The system estimates the configuration of the hand and the deformation of the object at each contact with the fingertips of the human hand. The force exerted by each fingertip is obtained by multiplying the stiffness matrix of the object and the vector of object local deformation in the contact point. We conclude the chapter reporting two more possible uses of the developed tracking system: the former is a wearable interface for controlling lightweight robotic arm, the other one is the development of a wearable input interface which allows interactions through fingers tapping.

1.1 Wearable interface for hand tracking

The human hand represents a complex fascinating system with highly sensitive sensory capabilities and Dexterous grasping and manipulation functionalities. As a consequence, estimating the hand pose and at the same time having the capability to provide haptic feedback in a wearable way may benefit limbs guidance in areas such as rehabilitation, human-robot interaction, gaming, and many more. Even if the existing solutions allow to accurately measure the hand configuration and provide effective force feedback to the user, they have limited wearability/portability. In this Section, we present the wearable sensing/actuation system GESTO (Glove for Enhanced Sensing and Touching) and its development steps. It is based on inertial and magnetic sensors for hand tracking, coupled with cutaneous devices for the force feedback rendering. Unlike vision-based tracking systems, the sensing glove does not suffer from occlusion problems and lighting conditions. We properly designed the cutaneous devices in order to reduce possible interferences with the magnetic sensors and we performed an experimental validation on ten healthy subjects. In order to measure the estimation accuracy of GESTO, we used a high precision optical tracker. A comparison between using the glove with and without the haptic devices shows that the presence of them does not induce a statistically significant increase in the estimation error. Experimental results revealed the effectiveness of the proposed approach. The accuracy of our system, 3.32 degrees mean estimation error in the worst case, is comparable with the human ability of discriminating finger joint angle.

1.1.1 Motivation

Capturing, analyzing, and interacting with the human body, and in particular with the human hands, is fundamental in several guidance scenario such as teleoperation [6], robotic surgery [7], and human-robot interaction [8]. In these contexts, wearability represents a key point since it improves the way humans interact with each others and the surrounding environment. Wearable devices have the advantages of being portable and well integrated into people habits, with the aim of providing valuable information to the users. The idea is that technology will increasingly become a more consistent part of our daily life as it will be part of our clothing and sometimes even part of our bodies [9].

We focused on MEMS technology to estimate the hand pose. This choice fitted the requirements of designing a wearable low cost sensing system capable of working in unstructured environments with varying lighting conditions. Moreover, since the goal is to provide also haptic feedback exploiting cutaneous devices, a glove instrumented with MARG sensors represents a good solution in terms of hardware integration, user customization, and tracking capability.

For what concerns the haptic feedback we consider haptic devices designed to be portable and wearable by using vibrations and motor-driven platforms. Vibrotactile stimuli are usually generated by DC motors with eccentric masses, which can be easily integrated in devices like suits, bracelets, shoes, gloves, etc. [10, 11, 12]. Although vibrotactile stimuli have been successfully used to guide the human motion [13, 14, 15], they can only provide multi-frequency patterns, with a limited force feedback rendering capability. Motor-driven platforms devices use
1.1. Wearable interface for hand tracking

Figure 1.1: GESTO (Glove for Enhanced Sensing and Touching) in a gaming scenario. It is made by 11 MARG boards (blue) for sensing, and 5 wearable haptic devices (red) for force rendering. It allows to estimate the joints values and rotation of the human hand with respect to a global reference frame. Also, it can provide cutaneous haptic feedback to the user while interacting with virtual/remote environments. A modular solution is adopted in order to easily connect a different number of cutaneous devices as well as allowing to separately use the sensing and the actuation components.

DC motors [16] or servomotors [17] to tilt a mobile platform and render 3-D forces on the finger pads. The idea behind these devices originates from the observation that stimuli received by the user, while interacting with an object, consist also of a cutaneous sensation perceived by mechanoreceptors in the skin. Previous researches demonstrated the potential of these interfaces in recognizing the local properties of objects, such as shape and edges [16]. Due to their reduced size, these devices can be integrated with an RGB-D tracker or with a Leap Motion controller in order to provide haptic feedback in virtual reality interaction [18, 19]. Wearable cutaneous devices which provide force feedback via motor-driven platforms to guide the subject using cutaneous stimuli. Even if vibrotactile motors represent a more wearable solution, cable-spring driven devices can generate a more realistic feeling of touch. To make the haptic interfaces more wearable, comfortable, and compatible with the proposed tracking glove, we design an improved custom version of the devices presented in [17] and [19].

Our contribution consists in presenting GESTO (Glove for Enhanced Sensing and Touching) based on MARG sensors for hand tracking and cutaneous devices for force feedback (Fig. 1.1). The sensing glove can estimate the joints values of the hand as well as its rotation with respect to a global reference frame. To the best of our knowledge, this represents one of the first attempts to combine a sensing glove based on inertial and magnetic sensors with haptic tactile devices. A possible disadvantage of combining magnetometer and motor-driven devices consists in having permanent magnet inside the devices that might affect the performance of the magnetic sensors. To overcome this limitation, we design the glove in order to take advantage of the biomechanical constraints of the human hand [20, 21]. Different from existing solutions, the proposed system is wearable, portable and it can be used in indoor/outdoor unstructured environments. This work started from previous results presented in [22] compared to which we provided a new and improved prototype of the sensing glove, a new haptic device, a more extended theory, and a more comprehensive experimental validation.

1.1.2 Design of the sensing glove

The cutaneous devices considered in this work are assumed to be rigidly attached to the distal phalanges of the fingers as the ones developed in [16]. Thus, we designed a sensing glove made by 11 MARG sensors (1 sensor for the palm and 2 sensors for each finger) and weexploited the biomechanical constraints. For the sake of simplicity and without loss of generality, we use a simplified 20-DoFs kinematic hand structure. We consider fingers with four DoFs: two in the metacarpophalangeal (MCP) joint, one in the proximal interphalangeal (PIP) and one in the distal interphalangeal (DIP). For the thumb we modeled two DoFs in the trapeziometacarpal (TM), one in the metacarpophalangeal (MC) joint, an one in the interphalangeal (IP) joint. For all the fingers, we placed the sensors on the intermediate and proximal phalanges and we exploited the relation between the upper finger joints, \( \theta_{DIP} \approx 0.88 \theta_{PIP} \) and \( \theta_{IP} \approx 0.77 \theta_{MCP} \). More details about the hand model and biomechanical constraints exploited in this thesis are in [1].

Each MARG board contains a triaxial accelerometer/gyroscope (InvenSense MPU6050) and a triaxial magne-
1.1 Wearable interface for hand tracking

Figure 1.2: GESTO (Glove for Enhanced Sensing and TOuching) is composed of 11 MARG sensors (blue): 1 sensor for the palm and 2 sensors for each of the remaining fingers. 5 wearable haptic devices (red) provide force feedback to the user.

tometer (Honeywell HMC5883L). Ten sensors boards are placed on the dorsal surface of the fingers and one on the back of the palm (Fig. 1.2). The last phalanx of each finger is left uncovered to not affect the user’s tactile perception. The sensing glove uses an Arduino Nano with an ATmega328 microcontroller. Arduino collects the raw data from the MARG boards, and sends them through an 115200 bps serial connection to an external computer in charge of all the mathematical computations.

The update rate of the system is 50 Hz. In particular, the accelerometer sample rate is 1 kHz, the gyroscope can provide an 8 kHz output data rate, whereas the magnetometer can achieve a maximum rate of 160 Hz in single measurement mode and 75 Hz in continuous measurement mode. The glove is designed by considering the 50th percentile of European men and women, age 20-50 [23]. This is a very common approach in objects design and ergonomics. The housing of the sensors is designed in order to fit the finger and narrow the possible movements of the electronic board as the hand/fingers move.

1.1.3 Design of the wearable haptic devices

Contextually with the tracking glove, we developed the cutaneous devices for cutaneous feedback. Cutaneous devices received an increasing interest in the last years, due to the possibility to provide haptic feedback in a wearable way, and thus contribute in bringing haptic technologies to everyday life applications. Minamizawa et al. [24] found that the deformation of the finger pads due to the interaction with an object can generate a reliable sensation even when perceptions on the wrist and arm are absent. This implies that a simple device for reproducing the virtual object can be realized by recreating the finger pad deformation. Based on these observations Pacchierotti et al. [7] presented a 3-DoFs wearable cutaneous haptic device able to provide cutaneous stimuli at the finger pad. The device was made of a body that contained three servomotors (placed on the fingernail) and a mobile platform that applied the required forces. To have a more compact, wearable, and suitable solution for the tracking systems, Scheggi et al. [19] developed a smaller 1-Dof device for the force feedback rendering. The device was composed of two platforms: one placed on the nail side of the finger and one in contact with the finger pad. Three cables and three springs connected the two parts, while one small servomotor controlled the length of the cables. The idea was to move the platform towards or away from the finger pad, to display a force at the user’s fingertip.

In this study, we improve the design presented in [19]. We changed shape and weight (reduced to 12.6 g) of the cutaneous device to optimize its use with the sensing glove. The size of the device is minimized and the motor (Hitec HS5035-HD Digital Ultra Nano) is moved from the back of the device to the front, positioning it horizontally in order to remove the magnetic disturbance affecting the MARG sensors (Fig. 1.3).

1.1.4 Conclusions

Estimating the human hand pose and, at the same time, having the capability to provide haptic feedback in a wearable way is a challenging task. In this chapter we presented a possible solution which relies on MARG sensors for the pose estimation, and cutaneous haptic devices for the force feedback. The proposed device can estimate the joints values of the hand as well as the hand rotation with respect to a global reference frame. It is designed to limit possible disturbances that may arise between the magnetometers of the MARG sensors and the servomotors of the haptic interfaces. A modular solution is considered to connect an arbitrary number of cutaneous devices as well as allowing to separately use the sensing and the actuation components. The experimental validation conducted on ten healthy subjects revealed that the 95% confidence interval for the orientation estimation error is
1.2 Wearable interface for fingertip force estimation

In the previous Section we addressed the problem of tracking the hand in a wearable way, the following step in the journey towards the human limbs guidance deals with the problem of force estimation. Here, we present a novel method to estimate the fingertip contact forces in grasping deformable objects with known shape and stiffness matrix. The proposed approach exploits the same hardware described in the previous chapter, i.e. a sensing glove instrumented with inertial and magnetic sensors (see Sect. 1.1).

Data obtained from the accelerometers and gyroscopes, placed on the distal phalanges, are used to determine the hand posture and the event when the fingers establish contacts with the object. In addition, the sensing glove is used to estimate the deformation of the object at each contact with the fingerpulps. The force exerted by each fingertip is computed multiplying the stiffness matrix of the object and the vector of object local deformation in the contact point. Extensive simulations were performed in order to evaluate the robustness of the proposed approach to noisy measurements, and uncertainties in human hand model. Experimental validations with a virtual object were performed. A high precision grounded haptic device was used to simulate the virtual object and accurately measure the forces exerted by the users during the interaction.

1.2.1 Motivation

Contact forces determine the quality of a grasp in object manipulation for human and robotic hands. The knowledge of the fingertip contact forces in grasping and manipulating an object can be useful in a variety of research areas such as: human guidance [25], anatomical study [26], brain researches [27], rehabilitation [28], haptic rendering [29, 30], human action learning [31], and sensorimotor control [32].
In this Section we propose a new, and still preliminary, technique for fingertip contact force estimation in grasping deformable objects. The method uses MARG sensors to estimate the fingertip contact forces. The proposed system is wearable and allows unlimited workspace. We considered negligible rolling and skidding of the fingertips over the object, negligible finger pad deformation compared to the object deformation (hard finger model). We assumed that the stiffness matrix of the object does not change with its deformation. To estimate joint angles and fingers orientation, we used a simplified version of the sensing glove presented in the previous chapter. Then, by considering the kinematic model of the hand (see [1]), the pose of each fingertip is estimated with respect to the palm. The main idea is that accelerometer and gyroscope are sensitive to impact and we can use their information to detect the contact events. In fact, when a fingertip touches an object, it is subject to a change in the acceleration (and angular velocity), so we can detect the contact time analyzing the data of accelerometer and gyroscope. Once a contact event is detected, the position of the corresponding fingertip is considered as the contact frame origin on the object. The axes of the contact frame are defined as follows: two axes are tangent to the object surface and third one (normal axis) points inside the object. For a deformable object with known stiffness matrix, neglecting the change in stiffness matrix due to local deformation, the applied force of each fingertip during the contact is obtained by multiplying the stiffness matrix and the fingertip position vector w.r.t. the contact frame. Error sources in this method are: hand model errors (including the length of phalanges, and configuration of the hand), MARG measurement errors (including bias and noise), delay in contact event detection, and object stiffness matrix error. The palm configuration error, i.e., error in the placement of MCP and TM joints, and the phalanges length can cause error in both magnitude and direction of the forces. Thus, an accurate model of the hand improves the accuracy of the estimated forces. Errors in the orientation measurement of each MARG are the most important error sources of this approach. Therefore, an appropriate calibration of the MARG sensors is performed in order to have a better estimation of forces. The calibration procedure is detailed in [1]. Delays in contact event detection can also be a reason for error in the direction and amplitude of the estimated forces. It can be reduced by increasing the sampling rate of the sensors. Finally, errors in estimating the object stiffness matrix cause error in the estimation of the fingertip contact forces.

A simulation study was performed to evaluate the robustness of the proposed approach and to understand how the error sources affect the results of the proposed algorithm. Preliminary experiment with virtual objects were conducted to validate the proposed approach. An Omega.3 haptic device was used to provide the user with the contact forces with the object and accurately measure the forces exerted by the user during the interaction.

1.2.2 Hand pose estimation

In this Section we briefly describe the design of the MARG sensing glove, without detailing the algorithms used to estimate the hand pose since it has been already presented and more details are in [1]. The proposed glove is based on the design discussed in Sect. 1.1.2. In this preliminary study we instrumented only the thumb and the index finger. The prototype, depicted in Fig. 1.4, is made by seven MARG sensors: one on the palm, three on the thumb, and three on the index finger. The hand model is the same exploited in the previous work. The raw data of all the sensors are transmitted to an external PC through serial communication at 115200bps. All the pre-processing and calculations are performed by the external PC.

1.2.3 Contact force estimation

The idea behind our system is to use GESTO (see Sect. 1.1) to estimate the hand pose and simultaneously compute contact forces by detecting if and which finger enters in contact with the object. As a finger comes in contact with the object, the algorithm updates the contact frames, positions, and forces vectors. The hand model is the same used in the previous work.

1.2.4 Conclusion

In this Section, we presented a new method to estimate the fingertip contact forces using a customized version of GESTO. No force sensor was used. Contact event detection is performed by monitoring the data from the accelerometers and gyroscopes placed on the distal phalanges of the hand. The kinematic model of the hand is used to estimate the fingertips’ positions. For a deformable object with known stiffness matrix, the estimated force is obtained by multiplying the position of the fingertips in the contact frames and stiffness matrix of the object.
1.3 Wearable interface for controlling a robotic arm

Many common activities of daily living like open a door or fill a glass of water, which most of us take for granted, could be an insuperable problem for people who have limited mobility or physical impairments. For years the unique alternative to overcome this limitation was asking for human help. Nowadays thanks to recent studies and technology developments, having assistive devices to compensate the loss of mobility is becoming a real opportunity. Off-the-shelf assistive robotic manipulators have the capability to improve the life of people with motor impairments. Robotic lightweight arms represent one of the most spread solutions, in particular some of them are designed specifically to be mounted on wheelchairs to assist users in performing manipulation tasks. On the other hand, usually their control interface relies on joystick and buttons, making the use very challenging for people with limited motor abilities. In this Section, we present a novel wearable control interface for users with limb mobility impairments. We make use of muscles residual motion capabilities, captured through a Body-Machine Interface (BMI) based on a combination of head tilt estimation and electromyography signals. We exploited for this purpose a single module of GESTO system to estimate the head orientation. The proposed BMI is completely wearable, wireless and does not require frequent long calibrations. Preliminary experiments showed the effectiveness of the proposed system for subjects with motor impairments, allowing them to easily control a robotic arm for activities of daily living.

1.3.1 Motivation

According to the European Health and Social Integration Survey in 2012 over 49 million people need assistance in their daily lives [33]. Assistive technologies like powered wheelchairs, walkers, canes, and prosthetic devices have greatly enhanced the quality of life for individuals with disabilities. Nevertheless, people with limited limbs usage have difficulty in performing Activities of Daily Living (ADLs) such as picking up a bottle, opening doors, filling a glass of water, etc. Interest and effort in this field have led to design Wheelchair-Mounted Robotic Manipulators (WMRMs) to increase autonomy in manipulating objects in ADL for people with upper extremity reduced mobility, like persons with spinal cord injuries [34, 35]. Several robotic arms designed as WMRM are commercially available. The Manus manipulator, produced by Exact Dynamics, is a 6-DoFs system [36]. Kinova developed JACO and MICO lightweight robots ready to be carried on a wheelchair to help people with limb impairments [37]. A common drawback for this robot typologies is having more DoF than the dimensionality of their control interface, thus resulting a hard usability for impaired users.

In this Section, we present a novel Body Machine Interface to control an assistive robotic arm. The proposed BMI extracts signals from body motions exploiting residual movements available even in people with severe impairments. Our system employs a MARG sensor for estimating the patient’s head orientation and EMG electrodes for detecting muscle contractions. The patient can thus drive the assistive robot tilting the head and contracting the frontalis muscles. This choice fitted the requirements of designing a low cost interface capable of working in unstructured environments with varying light conditions, being portable and independent from grounded tracking hardware. Moreover, since the goal is to create a wearable system, an instrumented cap represents a good deal between user customization, portability, and tracking capabilities. Pilot experimental results show the effectiveness of the proposed approach, allowing the patient to grasp a bottle and fill a glass of water in about a minute and half.
1.4 Wearable interface for finger tapping

This Section presents a further wearable tracking interface developed as a branch of the GESTO project (see Sect. 1.1). Hand in Air Tapping (HAT) is an innovative controller which allows interactions through fingers tapping. It consists in a Bluetooth Low Energy rings system enabling wireless communication with any compatible device. Each ring is hardware-wise independent from the others. This allows full modularity, i.e., the number of employed devices can be chosen to meet each application requirements. The proposed system was evaluated in two user studies, both on text input: (i) users learning curve in terms of writing speed; (ii) rate of text entry comparison between the proposed interface and that of numpad style keyboards. We associated each keystroke to a set of letters/symbols and compared two approaches: one based on T9 technique and the other on multi-tap input method. Results show comparable performance between HAT and numpad style keyboards. HAT keeps the

1.3.2 The wearable interface

A patient oriented control interface should be easy to use and effective. Based on this principle we built a system in which the user is both in control and assisted by the robot during the manipulation tasks. The interface presented in this work aims at replacing dedicated inputs to fully control a robotic arm. Typically joystick and buttons are used to control assistive robots, but they are not suitable for patients with severe disabilities or upper limbs impairments. To overcome this functional limitation we replaced buttons with frontalis muscle contraction, and the joystick with the head inclination.

A cap (see Fig. 1.5), instrumented with a single MARG board and three electrodes (one channel bipolar EMG), is employed and used both as inputs for the tilt estimation and for the control mode selection. With the proposed system the user can switch between different robot control modes contracting the frontalis muscle, and move the gripper tilting the head. The algorithm for tilt estimation is detailed in [1] whereas in [3] the EMG signal detection is explained. An ATMega328 microcontroller, included in the cap, is in charge of collecting the values from the MARG board and from the EMG electrodes and send them through two Xbee® modules to the wheelchair controller. The acquisition rate of the inertial and magnetic values is 100 Hz. A Kinova MICO2 robotic arm is actuated using an Intel® NUC PC under C environment. The PC can be powered using the wheelchair battery and it is configured for a low power consumption. Thanks to these features the MICO2 arm could be mounted to the seat frame of a motorized wheelchair together with the controller. The architecture of the proposed wearable interface is illustrated in Fig. 1.6.

1.3.3 Conclusion

Results of the users evaluation and time comparison confirm the feasibility and greater usability of the proposed system. The developed interfaces combines in a wearable way a MEMS tilt estimation and an EMG signal detection to control a 6 DoF lightweight arm. A cap, instrumented with a nine axis MARG (a single module of the glove presented in Sect. 1.1) and three EMG sensors, was used both to move and control the opening/closing of the end-effector. Results of the user study showed that individuals with severe motor impairments can operate assistive robotic manipulators using the proposed system interface. Moreover patients confirmed its ease of use and performances comparable with a joystick based controller.
1.4 Wearable interface for finger tapping

hands free, not affecting hand movements and human interactions with the surroundings. Moreover, as a general input technology, it might have several potential applications in the field of computer-human interfaces.

1.4.1 Motivation

Keyboards and typing technologies have come a long way over the past couple centuries. The first typing devices were designed and patented in the 1700s while the first manufactured came about in the 1870s. By definition, a typewriter is a small machine, either electric or manual, with type keys that mark characters one at a time on a piece of paper. Typewriters have totally changed their shape over the years, they have been updated in terms of technology, efficiency, design and eventually the age of computers transformed them in keyboards, but, essentially, people still have something with letters in front of them. Although this idea, as simple as functional, has remained the same for many years, it has limitations in terms of size, weight, and portability. The recent wide dissemination of wearable interfaces may change the old habits, addressing these issues. World’s major companies are highly sponsoring devices like the Apple Watch, the Google Moto 360, and the Asus ZenWatch. We propose a new system based on rings with easy typing in mind: the Hand In Air Tapping (HAT). When the thumb touches a ring a data packet is sent via Bluetooth to a master device. The idea is pictorially represented in Fig. 1.7. We believe that devices that collect information solely relying on accelerometers, no matter the quality of the filtering process, nor the quality of the artificial recognition algorithms, suffer from user’s undesired actions, especially when the hand is involved. Our main aim is to provide an unobstructive system reliable at any moment, regardless if you are sitting at your desk, or walking in the street. In the era of portable technologies we cannot constrain the use of a device to a very specific scenario only. Moreover, the number of misunderstood actions must be minimized, possibly even fully eliminated, so as to avoid turning the system from an useful tool into an annoying device.

1.4.2 HAT - Hand In Air Tapping system

We proceed now describing the whole system. Both the hardware component and software implementation are described in the next pages.

1.4.2.1 Hardware

A 3D printed ring-shaped housing, made of ABS material, guarantees high wearability and embeds the electronic core of each device. The input interface is firmly attached on the proximal phalanx of the finger by means of an adjustable velcro strap. On it two conductive copper bands are sewn allowing 3 distinct types of contact detection: upper band, lower band and both bands simultaneously. This latter modality is achieved software-wise by means of a timer set to 30 ms. HAT is managed by a RFduino, a fingertip sized, Arduino compatible, wireless microcontroller (RFduino, USA). The device embeds also a MARG unit, the same used in the previous Chapters (see 1.1, 1.2, and 1.3). The algorithm detailed in [1] estimates the orientation of each device, and thus enables wrist movements to control the keystroke input in combination with the touch actions. Therefore the number of available input activations for each ring is doubled, and allows to cover the whole set of required inputs using few devices. Each ring is powered by a tiny (19x15x7.5 mm) 3.7 V 100 mAh LiPo battery, that guarantees a long
lifetime. The stand-alone hardware structure makes the system completely modular: according to the task to be accomplished a different number of rings (i.e., input devices) can be used.

1.4.2.2 Software

In this work we focus on testing the proposed rings performance in a text input case study exemplified on an Android mobile phone. To enforce modularity, each ring is individually programmed to exhibit a predefined behavior, i.e., notify 4 types of events: i) upper band touch detection, ii) lower band touch detection, iii) contemporary touch on both bands, and iv) orientation variation. Implementing an event-triggered paradigm, each ring exploits the onboard Bluetooth Low Energy (BLE) to notify the occurred event to the phone, acting as BLE master. The binding between an event from a specific ring and a functionality is performed in the phone app and it is partially customizable to meet user’s needs.

1.4.3 Conclusions

In this chapter we presented a novel wearable input interface based on finger interaction. Two conductive bands and a MARG sensor detect finger tap and orientation, respectively, so that a Bluetooth connected device can be notified. We investigated the potential impact in the field of text input by implementing a smartphone companion application with two available modalities: multi-tap and custom T9. The resulting extreme modularity was tested in two comparative user studies against a widespread numpad mobile phone. Overall the reported experimental results shows an interesting learning slope and a curve fitting study predicts a potential typing speed of at least 60 CPM. Bearing in mind the wearable nature of the proposed device, it may not be ideal for writing your novel, but a longer practice can significantly improve the way we currently interact with our smartwatches.

As mentioned in the experimental evaluation, all the participants who took part in the experiments were not native English speakers. Although this might affect the absolute performance in terms of the metrics adopted in this work, the results presented should not be biased because of this; most of the conclusions and results shown come from comparisons with other data collected by the same subjects.

While the numpad keyboard is a non-wearable device, HAT is a scalable and minimally hindering device. That makes HAT suitable to compensate the missing typing ability for those wearable devices, such as smartwatches, that are designed for a particular use in which wearability is a necessity. Basing on our experiments, the performance loss, compared to widespread devices implementing the same functionality, is acceptable and HAT is a viable way to enable a new era of smart wearable devices. We believe that for a number of applications, including fitness activities, device wearability is a requirement and that HAT can potentially compensate for missing input degree of freedom limitation that affects currently available smartwatches.

One relevant characteristic of HAT is the presence of tactile feedback while typing. The absence of that kind of feedback limits the ease of use of current smartphones for visually impaired, thus the use of HAT could potentially improve their experience. Basing on our past collaborations with the Italian Union of Blind (UIC1) future works will include a dedicated study on the most adequate features for visually impaired possibly involving hardware enhancements like vibrotactile feedback.

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1 Unione Italiana dei Ciechi e degli Ipovedenti [https://www.uiciechi.it/organizzazione/regioni/Toscana.asp](https://www.uiciechi.it/organizzazione/regioni/Toscana.asp)
2. Haptic Guidance Algorithms and Policies

This Chapter presents our contribution for what concerns "Guiding humans suggesting directions and velocities", concept introduced at the beginning of this dissertation. We start this Chapter outlining the capability of haptic cues in guiding humans. Motivation, preliminary experimental results, and discussion prepare the background for the explanation of the developed approaches. Then, we present an innovative policy to navigate subjects in a dynamic environment. It consists in a synergistic combination of stimuli generated by vibro-haptic interface and obstacle avoidance algorithms. Finally, we conclude the Chapter moving our attention in controlling the human walking speed, reporting preliminary and confidential results on the potentiality of haptic interfaces in pace suggesting.

2.1 Human navigation using haptic cues

In real world scenarios, visual and auditory channels may be overloaded with a huge quantity of information, resulting in some cases, unusable. A following consequence is the rapid error increasing and the overall user performance reduction if cues are provided through these channels. A possible solution is to deliver necessary information exploiting an underutilized sense, i.e., the sense of touch. As the sound, a tactile stimulus is made up of a signal with varying frequency and amplitude, but different from the auditory feedback, tactile sensation directly engages our motor learning system with extraordinary sensitivity and speed [38, 10]. Moreover, tactile communication can be used in situations where visual or auditory stimuli are distracting, impractical, unavailable or unsafe. For instance, let us assume that single or multiple humans want to reach a final location in a large environment. Demonstrative scenarios are for instance, assisting older adults or visually-impaired persons, and helping people in a dangerous situation with poor visibility and no way of hearing clearly due to environmental noise.

While kinesthetic feedback is common in haptic systems, we tested vibrotactile interfaces, since tactile devices are generally more portable, less encumbering and have a wider range of action than the kinesthetic ones [39]. Different from existing strategies, our idea has the following pros: (i) the user has the hands free, thus other physical tasks may be accomplishable; (ii) it is easy to extend the physical interaction to multiple users; (iii) since we are using wearable devices, the proposed approach can be extended to other body parts, for example it can be combined/extended to guide the arms of the user along feasible trajectories in cooperative manipulation/transportation tasks. Similar approaches are [40] and [41]. In the former authors present an haptic belt used for waypoint navigation. The system relied not only on vibrotactile stimuli but also on GPS information. In [41] instead, humans are guided to a goal point with a system based on a tactile belt interface.

Before starting to develop a new algorithm we tested the possibility of guide human using haptic interfaces. Elastic bands were tested considering both their capability in displaying cues and investigating the after-effect problem. The idea of the preparatory experiments was to evaluate whether the vibro interface were able to suggest direction.

2.1.1 Description of the haptic interface

Tactile vibratory sensitivity is influenced by the spatial location on the body, the distance between the stimulators, the frequency of stimulation and the age of the user. Studies have demonstrated that vibration is better sensed on hairy skin due to its thickness and nerve depth, and that vibrotactile stimuli are best detected in bony areas [42]. In particular, wrists and spine are generally preferred for detecting vibrations, with arms and ankles next in line [43]. Due to the aforementioned considerations and since our aim is to design an intuitive and non-obtrusive device which could be easily worn, we concentrated on the development of vibrotactile bracelets. Starting from the results presented by Scheggi et al. in [44], we decided to use the bilateral configuration, that required two bracelets, one for each arm. Please refer to [44] for further details about study procedures and results. In order to improve the intuitiveness of the haptic feedback, we investigated a solution in which two haptic bracelets, equipped with vibrating motors, are used (see Fig. 2.1).
2.2 Suggesting directions in dynamic environments

Human guidance in situations where the users cannot rely on their main sensory modalities, such as assistive or search-and-rescue scenarios, is a challenging task. In this Section, we address the problem of guiding users along collision-free paths in dynamic environments, assuming that they cannot rely on their main sensory modalities (vision, audio). In order to safely guide the subjects, we adapted the Optimal Reciprocal Collision Avoidance to our specific problem. The proposed algorithm takes into account the stimuli which can be displayed to the users and the motion uncertainty of the users when reacting to them. The proposed algorithm was evaluated in three different scenarios. A total of 18 blindfolded human subjects were asked to follow haptic cues in order to reach a target area while avoiding real static obstacles and moving users. Three metrics: time to reach the goal, length of the trajectories, and minimal distance from the obstacles were considered to compare results obtained using this approach and experiments performed without visual impairments. Experimental results reveal that blindfolded subjects are successfully able to avoid collisions and safely reach the targets in all the performed trials. Although in this work we display directional cues via haptic stimuli, we believe that the proposed approach can be general and tuned to work with different haptic interfaces and/or feedback modalities.

2.2.1 Motivation

Let us consider the problem of guiding a subject toward a goal location in a dynamic environment while avoiding obstacle collisions (Fig. 2.2). Possible scenarios are assistive and search-and-rescue scenarios. In such cases, environmental noise, dust, or fog from debris severely reduce the human operator sensing. Other examples of applicability of human guidance are human-robot cooperative tasks, where the robot can guide the user along collision-free paths without violating the mechanical constraints of the robot itself.

As we mentioned, haptic feedback has been found an effective, yet non-intrusive way for providing directional cues to users. It represents an interesting way to provide information when audio and visual modalities are not available. In fact, audio and/or visual displays may be ineffective in circumstances where vision is temporarily impaired. In search-and-rescue scenarios, background noise can make auditory feedback difficult to hear or understand. The proposed method relies on the Optimal Reciprocal Collision Avoidance (ORCA) algorithm for non-holonomic agents proposed in [46], that we adapt to our specific problem. ORCA has been demonstrated to provide smooth, collision-free motions which are as close as possible to the desired motions of the agents. The proposed algorithm is based on the assumption that the human locomotion can be approximated by the motion of a unicycle system, i.e., non-holonomic constraints similar to those of mobile robots seem to be at work when a human is walking [47]. In designing the proposed obstacle-avoidance algorithm, we address the following chal-
2.2. Suggesting directions in dynamic environments

Figure 2.2: With this algorithm, we address the problem of guiding human subjects in situations where the users cannot rely on their main sensory modalities. The subjects have to reach the respective goal areas while avoiding collisions with static obstacles and moving users. The proposed obstacle avoidance policy generates online suitable stimuli (in our specific case, haptic stimuli), which guide the users along collision-free trajectories (dotted).

challenges. First, it is worth pointing out that while it is simple to steer a robot, it is not trivial to impose a desired velocity to a human. In fact, by providing directional cues via haptic feedback, only a discrete set of different stimuli (i.e., instructions) can be displayed to the users. Such set of stimuli is far smaller than the set of all the possible velocities that a user can perform. Moreover, the larger is the set of stimuli provided to the users, the harder could be for a subject to recognize a particular stimulus and to react accordingly. Second, when a user perceives a guiding stimulus, she/he will never react in the same exact way. Differently from related studies, the proposed algorithm takes into account the limited number of stimuli that can be displayed to the users, and the motion uncertainty of the users when reacting to a particular stimulus. We evaluate the proposed obstacle avoidance algorithm in combination with haptic stimuli. The haptic policy has been demonstrated to be intuitive and effective in guiding users in the previous Section, and in works considering mixed human-robot scenarios [13, 14, 44], older adults in assistive tasks [48], and visually impaired [11]. Without loss of generality, in what follows we assume that the human is free to select her/his desired walking speed. Control signals are sent to the users in order to steer their locomotion. The proposed method is evaluated in three different scenarios consisting of: (i) two users; (ii) two users and a static obstacle; and (iii) three users. A total of 18 users participate in the evaluation.

In all scenarios, the users have to move toward their respective goal areas, while avoiding reciprocal collisions and collisions with the environment. Three metrics such as time to reach the goal, length of the trajectories, and minimal distance from the agents have been considered to compare the results obtained using this approach with experiments performed with sighted people.

The proposed research demonstrates the navigation of multiple users in dynamic scenarios, assuming that: (i) the users cannot rely on their main sensory modalities; (ii) a limited discrete set of directional cues can be displayed to the users. Different from related research, the users do not rely on additional tools (like the white cane). Moreover, the proposed approach tries to avoid as much as possible oscillations in the users’ motions. Although in this work we display directional cues via vibrotactile stimuli, the proposed approach can be general and tuned to work with different haptic interfaces and/or feedback modalities (audio, visual).

2.2.2 Obstacle avoidance for human navigation

The algorithm is based on the extension of the Optimal Reciprocal Collision Avoidance (ORCA) algorithm for non-holonomic robots (NH-ORCA) presented in [46], that we adapt to our specific problem.

ORCA is a velocity-based collision avoidance approach for multiple holonomic agents, [49]. The algorithm provides a sufficient condition for each agent to be collision-free for at least a fixed amount of time \( \tau \) into the future. Each agent takes into account the observed velocity and pose of the other agents in order to avoid collisions with them. Then, the optimal velocity is selected by using linear programming. The main advantage of ORCA with respect to other obstacle avoidance algorithms is that it provide smooth, collision-free motions, avoiding as much as possible oscillations in the agents’ paths.

NH-ORCA is the generalized version of ORCA for any non-holonomic agents. The underlying idea is that any non-holonomic agent \( i \) can track a holonomic speed vector \( v_i \) with a certain tracking error \( \epsilon_i \), i.e., a non-holonomic robot can drive along an arc and then along a straight line which is close to a holonomic vector in that direction (Fig. 2.3). In accordance with [46] we can compute the holonomic speed vector \( v_i \) that approximates the non-holonomic velocity with the minimum error \( \epsilon_i \) as follows,

\[
v_i = v_{i,h}[\cos(\theta_{i,h}), \sin(\theta_{i,h})]^T.
\]
If $\omega_i \neq 0$, then Eq. (2.1) can be computed assuming,

$$
\theta_{i,h} = \omega_i t \quad v_{i,h} = v_i \frac{2(1 - \cos(\omega_i t))}{\omega_i t \sin(\omega_i t)},
$$

where $\omega_i$ is the non-holonomic angular velocity, and $t \neq 0$ is the time to achieve the correct orientation $\theta_{i,h}$. If $\omega_i = 0$, $v_i$ can be computed from (2.1) assuming $v_{i,h} = v_i$ and $\theta_{i,h} = 0$. Given a non-holonomic velocity $(v_i, \omega_i)$ with $\omega_i \neq 0$, the maximum error $\epsilon_i$ in tracking the related holonomic velocity $v_i$ is given as (cf. [46]),

$$
\epsilon_i^2(v_i, \omega_i, v_{i,h}, \theta_{i,h}) = \epsilon_i^2 v_{i,h} t^2 - \frac{2 v_{i,h} t \sin(\theta_{i,h})}{\omega_i} v_i + \frac{2(1 - \cos(\theta_{i,h}))}{\omega_i^2} v_i^2.
$$

Velocity-based collision avoidance approaches use the pose of the agents and their actual velocity to generate collision-free velocities [46, 49, 50]. Guiding users via haptic, audio, or visual stimuli, implies that we are not imposing a desired velocity to the subjects (different from a robot). Instead, we are providing stimuli which should be translated into suitable velocities. This arises two challenges. First, a mapping between the directional stimuli and the velocity of the human should be defined. Second, motion uncertainty of the users when reacting to a given stimulus should be taken into account (cf. Sect. 2.2.1).

For the mapping between the directional stimuli and the velocities of the human, we used the results presented in [14] The online obstacle avoidance algorithm consists in the following steps. Let $\delta t$ be the constant sampling time of the system and let $N_S$ be the number of stimuli displayed to the users. At each iteration, the proposed collision avoidance policy performs a continuous cycle of sensing and acting for each user (Fig. 2.4). First, the system estimates the pose and actual velocity of all the users. For each user $i$, the algorithm calculates the holonomic velocities $v_i$ and related tracking errors $\epsilon_i$ from the actual non-holonomic velocities $(v_i, \omega_i)$ (Fig. 2.4(a)). By using the holonomic velocities $v_i$ and the tracking errors $\epsilon_i$, constraints are added to the linear program in the ORCA formulation (Fig. 2.4(b)). Each constraint is represented as a half plane in the holonomic velocity space. Let $p_i = \mathcal{N}(\mu_p, \Sigma_p)$ be a bivariate normal distribution of the measured position $p_i$ of the user $i$, having mean $\mu_p$ and standard deviation $\Sigma_p = \text{diag}(\sigma_{p_1}, \sigma_{p_2})$. For example, positions might be estimated using a Extended Kalman Filter which provides an estimate of the variance, and hence the standard deviation, of the measured quantities. These values are taken into account by the obstacle avoidance algorithm by expanding the edges of the velocity obstacle (Fig. 2.4(c)). In order to select the guiding stimulus $k = 1, ..., N_S$, first we calculate the holonomic velocities $\Sigma_{S_k}$ related to the non-holonomic velocities and uncertainty of stimulus $k$ (Fig. 2.4(c)). Finally, the algorithm selects the stimulus whose $\Sigma_{S_k}$ maximizes the intersection with the obstacle-free region in the ORCA formulation. It is worth pointing out that the collision-free velocities are computed in order to be as close as possible to the preferred ones. In our particular case, the preferred velocities are the ones that minimize the walking time of the users towards their goal areas. The proposed algorithm differs from [46], since NH-ORCA starts by considering a holonomic behavior for the agent. Then, a set of holonomic allowed velocities is computed. Finally, the algorithm calculates the optimal holonomic velocity, which is mapped to the corresponding non-holonomic control inputs for the agent. Moreover, the proposed algorithm takes into account the fact that only a discrete set of stimuli (i.e., control inputs) can be displayed to a user and the presence of motion uncertainty when the users react to such stimuli.

![Holonomic trajectory](image)

Figure 2.3: The underlying idea of NH-ORCA is that any non-holonomic agent $i$ can track a holonomic speed vector with a certain tracking error $\epsilon_i$. Such error $\epsilon_i$ is used to compute the collision-free velocity based on the actual pose and velocity of the user.
2.2.2 Human guidance via haptic feedback

In this section, we briefly describe the haptic guidance policy used to validate the obstacle avoidance algorithm described in Sect. 2.2.2. The proposed policy is based on the assumption that the human locomotion can be approximated by the motion of a unicycle system (cfr. Sect. 2.2.2). Moreover, we assume that the human is free to select her/his desired walking speed. Thus, haptic stimuli are sent to the user in order to steer the heading.

Let us consider the problem of guiding a user along a path, given walking pace. This problem consists in steering the human by acting on her/his angular velocity $\omega$. In order to provide stimuli which are easily recognizable by the user, the device could elicit only three basic behaviors on the human (turn left, turn right, and go straight). Thus, only three stimuli would be sufficient in principle. As a consequence, we display vibrotactile stimuli via two haptic armbands placed on the forearms: vibration of the left armband alerts the participant to turn left ($L$), while vibration of the right armband alerts the participant to turn right ($R$). If the armbands do not vibrate, it means that the user can go straight ($C$).

For simplicity, in the algorithm we consider possible collisions among users. However, the proposed approach can be easily extended to avoid collisions with static objects such as walls, etc. In this case, the ORCA half-plane for user $i$ is computed at the point $v_i + u$ instead of at point $v_i + 1/2u$.

2.2.4 Conclusions

We detailed a solution for addressing the problem of guiding multiple users along collision-free paths in situations with poor/no visibility and reduced hearing capabilities. We considered a dynamic environment made by static obstacles and multiple moving users. Haptic feedback was used as an interesting way to provide directional information when audio and visual modalities are not available. Haptic stimuli are generated by a modified version of the Optimal Reciprocal Collision Avoidance algorithm for non-holonomic agents, which considers the reduced number of stimuli (i.e., instructions) that can be provided to the users and their motion uncertainty. The proposed navigation policy exploits the non-holonomic nature of human locomotion in goal directed paths, which leads to a very intuitive guidance mechanism. The proposed method is evaluated in three scenarios. Three metrics were used for evaluating the functionality of our approach: time to reach the goal, length of the trajectories, and minimal distance from agents. In all trials and for all the modalities, no collision with other agents (either another user or the obstacle) happened. While for the visual conditions this was expected, regarding the haptic guidance condition the obtained results show that our approach works, i.e., our system is able to successfully guide two or three users along collision-free paths, towards a goal area. All the blindfolded subjects could safely reach the goal area.

2.3 Suggesting walking pace under manual and cognitive load

This Section presents a comparison between two different approaches for controlling human cadence. Elastic haptic bands are used to suggest walking-pace during an exercise aimed at reproducing real industrial or human-
with stimuli involving other senses. This prevents channel s from saturating and lowers the overall mental efforts

2.3. Suggesting walking pace under manual and cognitive loa d

The users are represented with red and green colored circles. The starting point and the goal are two circles of radius 0.35 m centered in two opposite vertices of a square room with side of 2 m. (Left) Snapshots of a performed trial. Haptic stimuli are provided to the user via two vibrotactile wristbands.

(b) Experimental validation for scenario S2. Two blindfolded and audio-occluded users have to move towards their goal areas, while avoiding a static obstacle. (Left) The trajectories performed by the user are shown in red and green, whereas the obstacle is depicted with a blue circle. The users are represented with red and green colored circles. The starting point and the goal are two circles of radius 0.35 m centered in two opposite vertices of a square room with side of 2 m. (Right) Snapshots of a performed trial.

(c) Experimental validation for scenario S3. Three blindfolded and audio-occluded users are guided to reach the opposite corner of square room with side of 2 m. (Left) The trajectories performed by the user are shown in red, green, and blue. The users are represented with colored circles. The starting point and the goal are two circles of radius 0.35 m. (Right-handed sequence) Snapshots of a performed trial. Haptic stimuli are provided to the user via two vibrotactile wristbands.

robot cooperation task. The proposed system consists of two wearable interfaces for providing timing information to the users, and a pressure sensor to estimate the step time, thus resulting in a combination of walking-state monitoring and vibro-tactile stimuli to regulate the walking pace. Vibrational stimuli with a constant presentation interval are alternately and repeatedly given to the right and left side of the human body, in accordance with the desired walking speed. We tested two different interface placements: wrists and ankles. The guidance system has been evaluated under mental and manual workload using three additional tasks: answering to questions using a smartphone, playing a memory game on a tablet, and balancing a small sphere in the center of a flat surface. Experimental results revealed that subjects prefer the ankle position for what concerns wearability, comfort and easiness in task execution. Examples of the proposed approach in daily use are training and coaching in sports, rehabilitation, and human-robot cooperation and interaction.

2.3.1 Motivation

Nowadays there is growing interest in technologies and methods to assist people during daily activities; despite many attempts, research in navigation aids is still in its infancy. Most of them rely on vision or hearing as primary communication channels, which could be overloaded in many multi-tasking scenarios. We investigated the opportunity of controlling pedestrian cadence at non-attentional level. Related works demonstrated that walkers are able to synchronize to auditory and visual cues [51], but this approach demands more attention and may conflict with daily tasks due to the limited resources availability [52]. The interaction with electronics and mechanical devices may arise interference due to the dependency on visual and auditory channels, contributing to overload, thus reduce, sensory perceptions [53, 54]. A clear way to reduce cognitive load consist in replacing the audiovisual cues with stimuli involving other senses. This prevents channels from saturating and lowers the overall mental efforts [55].

We prove that given a desired walking pace, users can adjust their gait cadence to match it with little error and minimal effort by means of vibro-tactile cues. The coordination of a team of humans for sport training and the cooperation between humans and robots, represent two examples among the numerous guidance scenarios. As we introduced previously, haptic communication offers an effective, yet non-intrusive, way for providing cues to the users when visual modality is temporarily impaired or the audio modality is overloaded by background noise. The
underlying idea is that audio or visual systems do not represent the right solutions to guide the walking velocity of a subject while hands are involved in a task, such as assembling parts in an industrial environment or writing on a touch display. By freeing cognitive and attentional resources, the users can carry out their tasks with improved safety and quality.

With this work, we present results concerning the idea of using haptic interfaces to suggest walking pace when users are asked to accomplish additional tasks. We tried to replicate the traits of a real scenario, such as human-robot cooperation and industrial tasks. In particular we concentrate on applications where the operator use her/his hands to perform manipulation tasks while walking towards a target.

Two different solutions to provide the periodic vibro-tactile guidance have been tested and compared with the approach proposed in [56, to extend it under cognitive and manual load.

### 2.3.2 Human pace suggestion via haptic feedback

In this Section we analyse the gait synchronization strategy developed to control the user gait cadence \( i.e., \) the linear velocity. The principles of our guidance approach are based on the step cycle schema proposed by Philippson in [57]. A step consists of a limb movement performed from heel strike to next heel strike of the same foot. The step cycle and length are defined as temporal duration and spatial distance of a single step. Our method exploits a feature of the human sensory-motor system, called sensory-motor entrainment, to suggest a specific walking cadence \([58, 59]\). It is known that the frequency of a cyclic movement, such as walking and running, can be affected by rhythmic sensory inputs and can smoothly converge on the rhythm of the input \([60]\). For example, when people walk while listening to music, their step cycle gradually conforms to the rhythm of the music. Recent works proved that haptic stimuli can be used to deliver the walking cadence without interfering with other sensory channels, which might be useful for the user safety or task execution. In our method, haptic stimuli, \( i.e., \) vibrations, are periodically provided to different left/right body parts to assess which is the most suitable haptic input location. The user mean gait cadence is measured using a pressure sensor placed under the right foot, and is compared with the suggested cadence.

In this final part of the thesis, we want to investigate whether it is more performing to place the haptic interface on the wrists or the ankles to guide the human linear velocity through the suggestion of a specific step cycle. Synchronization capability and comfort are the metrics used to evaluate the two policies. To identify which is the best location for the haptic stimulation in a work environment, we asked participants to perform additional tasks, which purpose was to increase the manual and mental workload to verify differences in performances related to the haptic bands locations.

### 2.3.3 System overview

The proposed system aims at suggesting human cadence by controlling their step cycle time. It is composed of two parts: the former is in charge of providing haptic cues to the user, whereas the latter, used only for experimental testing and validation, detects contacts between the foot and the ground, thus to compute the user cadence. In what follows we describe the two components of the system.

**Haptic bands**  The desired cadence is suggested to the users through rhythmic vibrations provided by remotely controlled elastic haptic bands. The haptic band is a customized version of the bracelet presented in Sect. 2.1.1.
compared to which we updated the design to best suite both ankles and wrists. The hardware and electronic components are the same of the previous version. Whenever a trigger is sent to a haptic device, the motors vibrate providing a vibro-tactile stimulus to the wearer. In order not to overload the user’s tactile channel and reduce the recognition time, we do not modulate the frequency of the signal, but we use a simple on/off mechanism, similar to the one used in [14]. We activate alternatively the two devices in accordance with the desired step duration. An additional stimulus to stop the user by activating both the haptic devices is implemented. When an interface is activated, its motors vibrate for 0.1 s at a frequency of 250 Hz. Subjects wear one haptic bracelet on each ankle or wrist in order to maximize the stimuli separation, keeping the discrimination process as intuitive as possible.

Pressure Sensor  The second component has been developed to capture the walking pattern, with the aim to extract the step timing. Its function is the heel strike detection and consists in a flexible force sensor (SFR 400) and a XBee radio module. The force sensing resistor measures the force applied through the deformation of the active surface, which produces a resistance variation. We use this component as unobtrusive and comfortable switch to detect the contact of the shoe with the ground. The XBee module is used to convert an analog signal into a digital signal and send it wirelessly to another module, connected to the laptop. The pressure value is converted into a 10 bit digital signal. The step extraction procedure exploits a single-threshold value, defined as the double of the standard deviation of the data, measured during an initialization phase. The sensor measures the pressure under the heel at 100 Hz. Thus, we are able to measure the step cycle and monitor the walking state from the obtained pressure data. The step-detection procedure consists of three phases. In the first step, raw pressure data are acquired by the system and normalized, then it is transformed into a two-levels signal using a custom threshold. The square wave indicates whether the foot is in contact or not with the ground, assuming value 1 or 0, respectively. As a final step, the algorithm extracts positive edges matching the contact of the heel with the floor, identifying the step as the interval between two consecutive edges. Let the number of steps per minute be the stride-frequency and the space between two subsequent steps the stride-length. Walking velocity can be thus computed as the product of stride-frequency and stride-length. Even if the walking speed seems to be controlled by two parameters, Laurent et al. in [61] demonstrated that the gait can be controlled acting on only one of the two parameters.

2.3.4 Experimental validation

The experiments were performed to assess the feasibility and functionality of the developed approach. We validated the proposed walking-pace suggestion technique using two different body locations for the haptic interfaces, wrist and ankle.

Preliminary test  We started the experimental validation of our system by exploiting the results presented in [56]. We performed preliminary tests using haptic interfaces either as bracelets or anklets. Eight healthy subjects walked for 220 meters following the path depicted in Fig. 2.7. Three step duration values (0.8 s, 1.0 s, and 1.2 s) were tested for each configuration. We selected these values to test the system since we observed in preparatory experiments that [0.8 – 1.2] s is a suitable range considering the standard human comfortable cadence. The aim of this test was to verify the attitude of our system in suggesting walking speed and compute a rough estimation of users’ response. Users, step duration and body location were pseudo-randomly selected. We discarded the first 4 s of data, where the participant is transitioning from stationary to walking state. During task execution, participants wore headphones reproducing white noise to acoustically insulate them from the environment and avoid cues generated from the motors vibrations. The metric is the error in adapting to the proposed rhythm. We defined the error as the average of the difference between subject’s and desired stride duration per each step, normalized and expressed in percentage (with respect to the suggested cadence):

$$error = \frac{1}{N} \sum_{k=1}^{N} \left| \frac{u(k) - d(k)}{d(k)} \right| \times 100\%.$$  

(2.2)

Where $N$ is the number of steps walked during the test, $u_k$ and $d_k$ are the duration of the $k-$th step and the desired time, respectively. Experimental results revealed an average error among all trials of 3.46 ± 1.78 % and 2.93 ± 1.56 %, in the case of interfaces worn as bracelets and anklets, respectively. Since we were interested in selecting the optimal location, we performed statistical analysis tests to assess if the difference in error was significant or not. The standard deviation of the error, calculated for each subject, is considered the user synchronization capability, in fact, higher is standard deviation the more is the differences among the steps.
2.3. Suggesting walking pace under manual and cognitive load

Cognitive load The main objective of this work is to compare the performance of the haptic guidance method for users performing tasks requiring cognitive load. Two conditions were considered: vibrations provided on wrists and ankles. The results of the preliminary experiments suggested ankle as desired location, and laid the bases for what follows.

Once the capability of suggesting walking pace using vibrations was established, and a candidate location was determined in absence of secondary tasks, we studied the potential of the proposed system in association with manual and cognitive tasks. To increase the subject cognitive load during the synchronized walk, three tasks have been designed in a preparatory phase: i) answering to questions asked by another operator via smartphone app, ii) a memory game on the tablet, and iii) a balancing ball-plate game. These tasks involved the use of both hands, to simulate a real work situation, and required a discrete effort to successfully accomplish the trial. Eight healthy subjects (all males, age range 23-35) took part only to this prior test. The texting approach was implemented first. The questions concerned logic, numerical calculations and general knowledge, randomly drawn from a standard set [62]. Subjects were asked to answer appropriately, while keeping the focus on the gait synchronization. The second tested task was a memory game, that resulted excessively demanding, it was extremely difficult to keep the synchronization while achieving a good score, regardless of the body location and cadence. The game consisted in keeping track of a sequence of buttons which turned on sequentially, and replicating the same sequence in a limited time. Each round the sequence became more complex, by increasing the memory load by one. The third exercise was a customized version of a ball-plate game. The aim of the task was to maintain a ball inside a plate avoiding contacts with the edges. This resulted as the best option for our purpose. Firstly, it can be considered very close to a real task. Maintaining a ball in the center of a plate involves hands, eyes, and it is not excessively immersive. Moreover, differently from the first game, we can score and rate how the user is performing the tasks. The plate is equipped with a touch sensor on the border, thus the number of hits (i.e. errors in execution) gives a rate on the accomplishment. We decided to test the guidance policy while executing this task.

The evaluation of the system with a cognitive load was performed on 16 healthy subjects (10 males, age range 23-35): one of them had experience with the proposed vibro-tactile device, the remaining users had less or no experience with our haptic interfaces. None of the participants reported any deficiencies in perception abilities or physical impairments. To enrich the discussion after the trials and to better understand the results we estimated the user’s physiological cadence before starting the experiment. We asked users to walk for the entire pathway without haptic suggestions. In the first 20 meters we checked and calibrated the pressure sensor, whereas in the remaining we evaluate the most comfortable walking cadence while the user acquainted with the pathway. Then, subjects were asked to synchronize the gait cadence to the vibrations provided by the haptic devices. Two values of cadence were tested: $\pm 10\%$ with respect to the comfortable one (previously estimated). We adopted user-dependent cadences to preserve uniformity in testing an heterogeneous set of volunteer with variegated ages, heights, and walking habits. Each participant performed 5 trials: the comfortable gait cycle was estimated during the first trial, then the 4 remaining trials were haptic-guided. Subjects and desired walking pace were sorted in a pseudo-random order. Our setup was not designed to measure the step length, so we refer to the mean cadence, which is the inverse of the mean step duration. During task execution, participants wore headphones reproducing white noise to acoustically insulate them from the environment and avoid cues generated...
2.3. Suggesting walking pace under manual and cognitive load

Table 2.1: Questionnaire factors and relative marks.

<table>
<thead>
<tr>
<th>Questionnaire factors</th>
<th>Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comfort</td>
<td>6.33 (0.88)</td>
</tr>
<tr>
<td>Ease of use</td>
<td>3.82 (0.90)</td>
</tr>
<tr>
<td>Wearability</td>
<td>5.67 (1.10)</td>
</tr>
</tbody>
</table>

Marks range from “1 = strongly prefer Wrist” to “7 = strongly prefer Ankle”. Mean and standard deviation (Mean (SD)) are reported.

from the motors vibrations. As the primary hypothesis was to provide a purely tactile stimulus, the white noise was designed to cover the motor vibration noise. Each subject was followed by a ghost operator equipped with a laptop for data acquisition, walking at distance of about 5 meters behind. This distance was selected not to disturb the task execution, while keeping the communication active between the wireless devices. Furthermore, vibrations parameters were manually set by the operator via an ad-hoc software. The operator was also in charge of starting the pressure data recording, using the same software. The pressure sensor was placed in the same position of the previous experimental setup. The pressure sensor placement has proven critical for the success of the measurement: the optimal place was the posterior part of the sole, where there was no contact with the foot during the swing phase. We selected this location after numerous prior tests.

2.3.4.1 Discussion

In addition to the statistical results, we take into account also the users’ point of view. The aim of this work is to compare different haptic guidance strategies for real applications. Thus, not only numbers but also personal experiences represent a key value. At the end of the trials, a survey based on the Usability and User Experience (USE) [63] in the form of a bipolar Likert-type was proposed to the subjects. The USE questionnaire evaluates three dimensions of usability: comfort, ease of use, and wearability. Each feature is evaluated using a number of items: subjects must select a mark on a seven-point scale (1 = strongly prefer Wrist, 7 = strongly prefer Ankle). Results are shown in Table 2.1.

From Table 2.1, we can assert that the subjects rated positively the overall features of the system. For what concerns the easy of use, since the working principle is the same for both anklets and bracelets, results outline the equivalence of the two approaches. Without any doubt, we can affirm that the subjects strictly prefer the anklets from the comfort point of view. Users motivated this choice since the vibration in the arm was considered at the same time both a pace suggestion and a disturbance to the task. They were using their hands to balance a ball; a vibrations represented an interference in the task execution. For what concerns the last factor, the wearability feature, results of the questionnaire revealed that user prefer the anklet with respect to the bracelet. This answer can be attributed to the subjects often wearing bracelets, watches and other accessories on their forearm. Despite the haptic device being lightweight (89.3 g), subjects preferred wearing it on their legs because it felt less constraining and tiring. A further suggestion users gave us after the experimental session was the possibility to hide more easily the haptic interface under their clothes in the case of ankle.

2.3.5 Conclusions

In this Section, we reported preliminary results regarding the problem of guiding humans by modifying their step-cycle time i.e., the linear velocity. Haptic stimulation is used as an interesting way to provide velocity information when audio or visual channels are not available or overloaded. We considered two different location for displaying vibrations and suggesting walking pace, the wrist and the ankle. A task requiring a not negligible cognitive load was assigned to users. Experimental evaluation and subjects usage feedback showed a preference for the ankle location. Such body position resulted in a smaller error regarding rhythm synchronization and better performances in executing a real task; it also was preferred by the users for usability, wearability and comfort.
Bibliography


