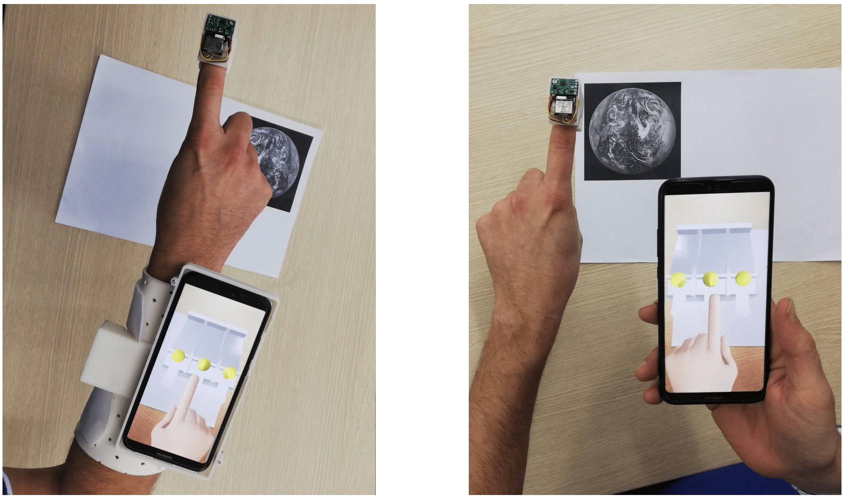


(a) (b)

Figure 4.11: Wrist Mounted condition (a) and Hand Held condition (b) tested during experiments.

we decided to dislocate the virtual hand projection. In fact, reconstructing the hand kinemantics with portable IR-cameras alone, *e.g.* Leap Motion (Ultraleap Ltd), would not yield the pose and location of the hand with respect to the target object. An external portable camera (also the smartphone camera) placed on top of the hand would cover most of the field of view. Moreover, the smartphone positioned on top of the hand could constrain its movements. An external grounded camera would achieve the best accuracy, at the cost of portability.

In our approach, the back of the virtual hand shares the same reference system of the smartphone camera, allowing to estimate the relative position and orientation between the hand and the fiducial marker. To avoid occlusions of the visual display, the virtual hand was scaled and positioned at the bottom of the smartphone display (see Fig. 4.11). The index finger motion is then transferred to the virtual hand. We integrate the orientation of the finger (estimated by the fingertip device IMU) and the smartphone to retrieve the relative motion. The same approach was adopted for the hand-held layout, except that the hand holding the camera and the one wearing the fingertip device were different.

Since the aim of this work is providing a proof of concept, and not to present a hand-tracking approach, we exploited an existent algorithm presented in [149].

We decided to use a simplified kinematic model of the hand, which requires a reduced number of sensors to estimate the finger pose. To reconstruct the hand posture, we combine two Inertial and Magnetic Units, postural synergies [163], and biomechanical constraints [160]. The IMU on the fingertip device embeds a triaxial accelerometer/gyroscope (ST LSM6DS33), a triaxial magnetometer (ST LIS3MDL), and an I^2C interface. For the smartphone, we used the embedded IMU. In this work we estimate the pose of a single finger, but the same approach can be used to easily track the entire hand as in [98]. The microcontroller is in charge of collecting inertial and magnetic data from each sensing board and send the measurements using a BLE connection to the smartphone. The developed Android app reconstructs the finger pose by computing the interphalangeus joint angles. The algorithm exploits only accelerometer and gyroscope measurements, thus the estimate is not affected by the magnetic field disturbances generated by the motor. In what follows, we briefly review the data fusion algorithm and the procedure used to estimate the orientation of a single IMU with respect to its initial position.

Quaternions are used to describe rotations. This redundant representation solves the problem of rotating from different reference frames without loss of precision due to the trigonometric functions. We denote by $q(t)$ the quaternion[3] representing the orientation of an object (haptic device or smarphone) at time t, by Δt the sampling time, and by $\omega(t)$ the angular rate of the body at time t. Thus, the resulting orientation at time $t + \Delta t$ can be computed as

$$q(t + \Delta t) = q(t) \otimes q(\omega(t)\Delta t), \tag{4.2}$$

where $\otimes$ denotes the Hamilton product.

Given a vector $\omega = [\omega_x \, \omega_y \, \omega_z]^\top$, we indicate with $q(\omega) = [0 \, \omega_x \, \omega_y \, \omega_z]^\top$ its *quaternion form.*

As a standard Kalman Filter, the implemented Multiplicative Extended Kalman Filter (MEKF) consists of two main steps: a prediction and a correction step. These are performed on the state vector containing the orientation error between the estimated attitude and the true one, and the gyroscope bias. In the prediction step, the quaternion is updated by (4.2) along with the state vector and the covariance matrix. During the correction step, the state vector and the covariance matrix are updated using the available inertial measurements and the quaternion estimate is corrected according to the new state vector (see [164] for further details). The key point during the correction step is the selection of the measurements to use. In fact, while accurate measurements effectively correct the estimated attitude, low quality ones can make the estimated attitude substantially wrong. The accelerometer readings are also unreliable when the measured

[3]We represent a quaternion as a 4 component vector $q = [q_w \, q_x \, q_y \, q_z]^\top$ where q_w is the scalar part.

acceleration (g) differs from the gravity. Here we assume the gravity acceleration to be normalized. Hence, when $||g|| \approx 1$, the measurements provided by the accelerometer are accurate. Such a condition is typically satisfied when the IMU is not moving. Regarding the gyroscope readings, they are usually very accurate. In this algorithm angular rates are used for updating the attitude quaternion, during the prediction step and are used for correcting the gyroscope bias. In fact, when the IMU is almost steady, the gyroscope accurately measures its own bias.

From the above discussion it is clear that measurements sufficiently accurate to be used in the correction step are, in general, not available when the body is moving. The developed algorithm is an adapted MEKF in which the correction step is performed only when accurate measurements are available, *i.e.*, during time intervals in which the IMU is steady. Conversely, when the object is moving, only the prediction step is computed.

The algorithm provides as output the quaternion q describing the orientation of each IMU with respect to its initial position.

Let $q_F(t)$ and $q_S(t)$ be the quaternions that express the orientation with respect to the initial position. We indicate with Σ_F and Σ_S the frames associated to the finger and to the smartphone, respectively. Follows that, at a certain time instant t, the orientation of the finger referred to the smarphone can be computed as

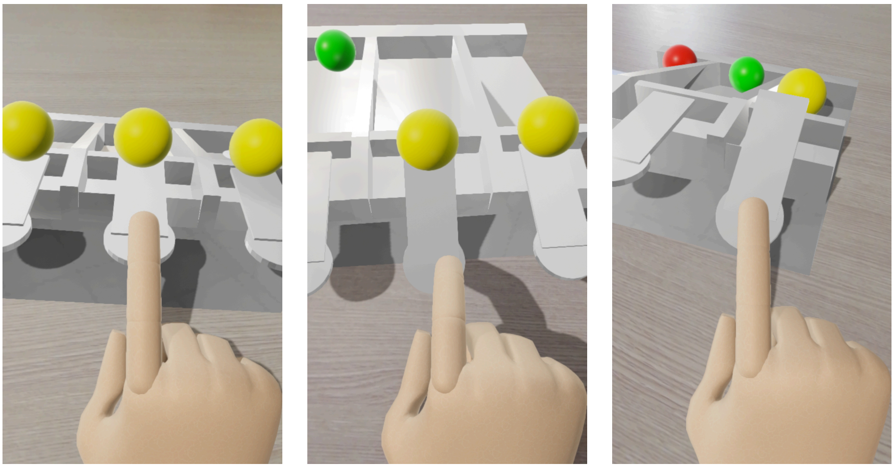
$$^{S}q_F(t) = q_F(t) \otimes q_S^*(t),$$

where $q_S^*(t)$ is the conjugate quaternion of $q_S(t)$. Then, the result is converted into *Euler Angles*. Finally, the software exploits biomechanical constraints [165] for reconstructing the finger pose by means of a single joint value.

We stress the adaptability of the estimation algorithm which can cope with measurements from different IMUs at different frequencies, provided that both sources are adequately calibrated and rescaled.

AR display

We transformed our smartphone into an AR interface using the RGB built-in camera and the 5" display. The Augmented Reality framework adopted in this work consists of a virtual hand and a virtual ramp with three levers and three spheres. Fig. 4.12 reports three screenshots of the proposed AR scenario. Because of the device unique positioning, the phone camera field of view does not include the real user's hand, which is instead replaced by a virtual avatar. The IMU tracking system aims at guaranteeing that the virtual hand mimics the movements of the real one. In the current version, the virtual hand is a totally undeformable mesh except for the index finger, that is replaced by three additional meshes representing the finger phalanges. The virtual hand is rendered



(a) (b) (c)

Figure 4.12: Representative trial: the user is tasked to test, determine, and order three spheres by their weight. At the beginning (a) all the spheres are yellow and placed on the top of a virtual ramp. The user perceives the objects weight by pressing onto the levers, then order the objects by increasing weigth. If the order is correct the spheres turn green (b), otherwise red.

in a fixed position, about 15 cm below the smartphone rear camera, so that it is visible in the shots. The virtual hand size is based on the average adult human male. A skin texture allows for a more immersive experience.

The AR application streams the rear camera images in the smartphone display and adds the virtual objects. For accomplishing that, the location and rotation of the virtual objects with respect to the phone camera are required. We adopt the ArCore [166] library which tackles the problem using an artificial intelligence based video processing technique. It aims at identifying a simplified virtual model of the real environment and provides routines to determine the estimated position and orientation of the camera. In addition, ArCore also estimates the position and orientation of a finite set of flat images on the real surfaces, which are referred to as markers in what follows. Our setup requires a single marker. Finally, ArCore contains rendering APIs that consider its internal light estimation and account for textures and materials, which all contribute to enhance the level of realism.

For what concerns our setup, ArCore provides us with online estimations of camera position, which we use to determine collisions and movements. Thus, we render the objects exactly over the marker and then determine the position of the fingertip, properly rotated on each phalanx by the IMU estimation. Upon contact between the fingertip and a lever edge, detected using the Euclidean distance and a reasonable threshold, the lever rotates and the user perceives the sphere weight via the haptic device.

4.2.3 Experimental validation

We evaluated the functionality and usability of our system by comparing it with the traditional hand-held montage. In an experimental procedure, we investigated performance and participants' preferences during a task requiring exploration and manipulation in a virtual environment. Subjects were tasked to perform a weight evaluation on three virtual spheres, rendered on virtual ramps. The haptic display was necessary to complete the task: the three objects were visually identical, so perceiving the weight was the only way to distinguish them. To avoid input asymmetries in the two conditions, we extended the use of the fingertip interface to the hand held condition. In the wrist-mounted (WM) condition, subjects were provided with the smartphone attached to the forearm support and the fingertip device worn on the right hand; in the hand-held (HH) condition they were given the smartphone to keep with the right hand and the fingertip device worn on the left hand.

Eighteen participants (13 males, 5 females, age range 23 - 45, mean 31) took part in the experimental evaluation campaign. Informed consent was obtained from all individuals included in the study. During a training stage, lasting 5 minutes per condition, the users familiarized with the hardware and the task to avoid bias due to training effect. After the training, subjects performed two experiments consisting of 10 trials each using the HH and the WM modality, respectively. The order was pseudo-randomly selected to avoid results polarization. At the beginning of each trial, the user was sitting in front of a desk with a fiducial marker positioned in portrait orientation. The time count began when the application started. After the marker was in the camera field of view, the virtual objects were displayed on the screen. The users were allowed to adjust the orientation of the marker during the trial. The task consisted in placing the virtual finger on the three levers to sense the weight of the three spheres (Fig. 4.12). A sphere was released on the ramp by pushing and tilting the levers above 30°. A force proportional to the ball mass was displayed on the fingertip when in contact with the levers. We decided to give a flat information (not proportional with the tilt) to have an immediate and easy to perceive response. To complete the trial, the user had to sense all three spheres before releasing them in increasing weight order. If the user happened to release a sphere before sensing all of them, the trial was restarted. Once a sphere reached the bottom of the ramp, it changed its color to green if the releasing order was right, or red in the other case. The time count was stopped after all three spheres reached the bottom. Elapsed time and number of error were recorded for each participant. At the end of the two trials the users were asked to fill two questionnaires, one per condition. The questionnaire was composed by 15 statements rated on a seven-point Likert scale and grouped in three blocks of 5, each covering a different aspect of the participants' experience. The first 5 statements investigates *"Mental Workload"* perceived during the task [167]. The *"Manipulability"* block analyses the participants physical efforts and comfort during the task, given the smartphone montage. The last block is referred to as *"Embodiment"*, and is aimed to evaluate participants' impressions about the realism provided by the haptic feedback, and the feeling of owning the virtual hand. The questionnaire statements are reported in Table 4.4.

4.2.4 Results

All participants always selected the proper order in releasing the virtual objects from the lightest to the heaviest. Although this aspect cannot be discussed through statistical analysis, it was necessary to have the user respecting a task schedule. Task completion times were analysed to quantitatively evaluate the participants' performance.

Visual inspection of data revealed skewness of data distributions, as later assessed by Shapiro-Wilk test for WM ($W = 0.890$, $p = 5.353e - 07$) and HH condition ($W = 0.954$, $p = 0.0016$). Raw data are graphically reported in Fig. 4.13. A logarithmic transformation was applied to the data and then a Shapiro-Wilk normality test was conducted, both for WM ($W = 0.975$, $p = 0.056$) and HH condition ($W = 0.982$, $p = 0.1973$). Results of Leneve's test reported not significative difference in variance homogeneity ($F(1, 358) = 2.109$, $p = 0.148$) for WM and HH task time distributions after transformation. A paired sample t-test on the normalized data shows a significant probability of performing the AR task faster in WM condition than in HH condition ($t(179) = -5.070$, $p < 0.005$), although the effect size after log transformation is very small. In fact, the task completion time ranges were in the interval 20 s to 60 s and 3 s to 4.5 s before and after normalization, respectively. Logarithmic transformed data reported a difference of the means equal to 0.148, corresponding to 10% of the total range.

Regarding the questionnaire, Shapiro-Wilk test confirmed the normality of scores distributions, for each block and condition. Levene's test revealed no significant difference in variance homogeneity between the two conditions. The average scores for the HH condition for what concerns Embodiment, Mental Workload and Manipulability, are 3.35 ± 0.79, 3.55 ± 0.74 and 3.65 ± 0.72, respectively. The average scores for the WM condition are 4.45 ± 0.73 (Embodiment), 3.93 ± 0.89 (Mental Workload) and 4.31 ± 0.88 (Manipulability), respectively. Results are

	Questionnaire Statements
Q1	*I think that interacting with this application requires a lot of mental efforts.*
Q2	*I think that the task was easy to learn.*
Q3	*I felt stressed and irritated during the task.*
Q4	*I think that performing the task successfully was easy.*
Q5	*I had to work hard to accomplish my level of performance.*
Q6	*I felt that using the application was comfortable for my arms and hands.*
Q7	*I found the device difficult to hold while operating the application.*
Q8	*I found it easy to input information through the application.*
Q9	*I felt that my arm or hand became tired after using the application.*
Q10	*I think the operation of this application is simple and uncomplicated.*
Q11	*I think that the hand delocalization was confusing for operating the application.*
Q12	*I felt like I was manipulating objects with my own hand.*
Q13	*I think that the tactile information was difficult to couple with the finger motion.*
Q14	*I think that the tactile feedback was realistic.*
Q15	*There was no correspondence between what I was seeing and what I was perceiving.*

Table 4.4: The table reports the questionnaire statements divided in three blocks, corresponding to Mental Workload, Manipulability and Embodiment, respectively. Each sentence was rated on a 7-point Likert scale.

depicted in Fig. 4.14.

Paired sample t-test showed that subjects' preference for the wrist-mounted display was significant for what concerns Embodiment ($t(17) = 4.86$, $p < 0.005$), while the condition did not have significant effect on the perceived Mental Workload ($t(17) = 1.65$, $p = 0.12$). In average, the Manipulability items were rated higher for the WM condition ($t(17) = 2.07$, $p = 0.053$).

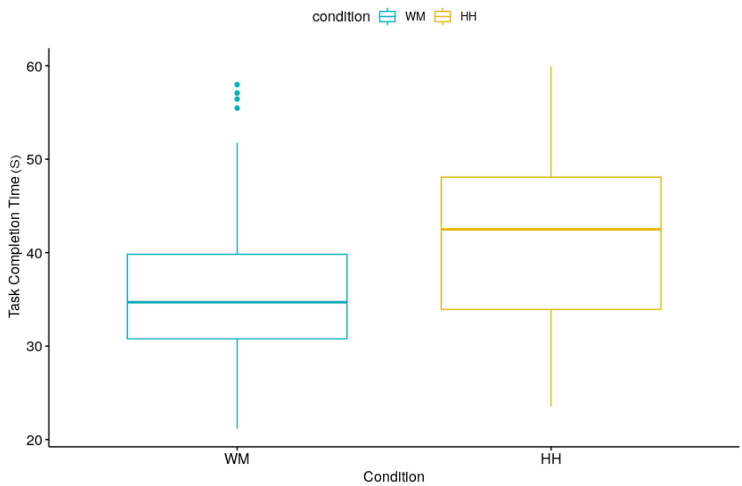


Figure 4.13: Completion time boxplot representation for wrist-mounted and hand-held condition, respectively.

4.2.5 Discussion

The fact that no participant have mistaken the spheres weight order means that they executed correctly the task, thus time values are reliable. Moreover, it means that everyone was capable of successfully distinguishing the three levels of haptic feedback provided (force values were in the range 0-3 N).

Moving to the analysis of time values, we supposed that the WM condition would have performed worse than the HH condition, mostly due to the widespread habit of hand-holding the phone. Conversely, we noticed that during the training phase participants got used to the wrist-mounted modality and exploited different strategies to easily control the system. In particular, most of them decided to use the free hand to accommodate the marker position in order to simplify the contact with the virtual levers.

Participants reported that the hand delocalization was confusing at the beginning, but practice relieved the stress of controlling a misplaced end-effector. Instead, almost everyone preferred the WM montage because it allowed to control the position of the display with the same arm perceiving the haptic feedback and controlling the finger movements. This is in line with [168], as the haptic feedback fosters the embodiment of a virtual hand moving in accordance to the real one. Questionnaire results support the more realistic feeling of ownership of the virtual hand in the WM condition. All participants reported that the hap-

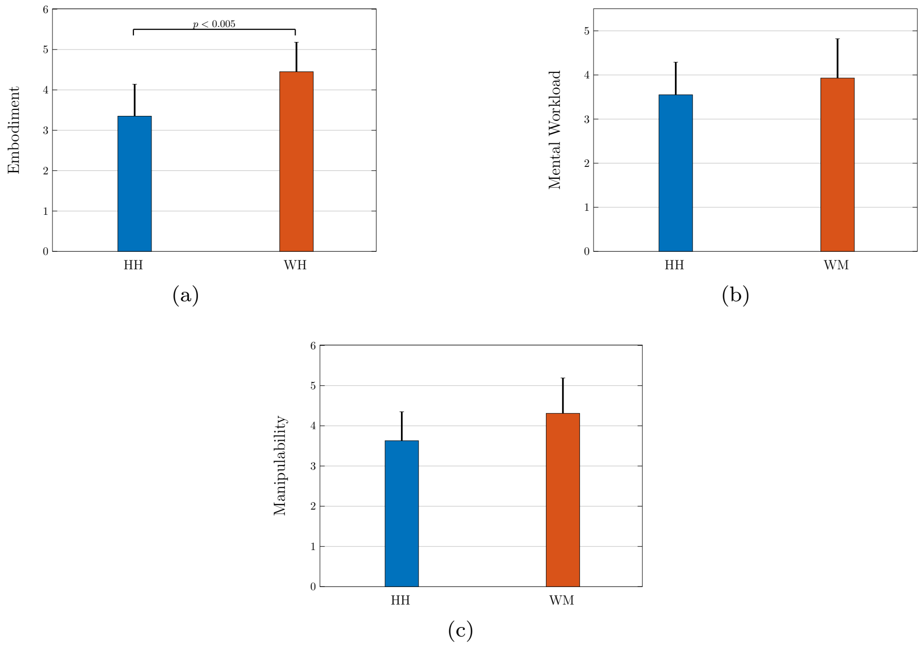


Figure 4.14: The boxplots report the average ratings for the two experimental conditions, divided by questionnaire subsection: a) Embodiment, b) Mental Workload and c) Manipulability.

tic feedback is valuable, not only for the purpose of this task, but in general to increase the immersiveness of the AR experience.

The bulkiness of the forearm support marginally affected the participants' judgment of the wrist-worn display, although they found easier to input commands through it. Authors and users agree on the fact that flexible lightweight displays will represent the tipping point for the proposed idea.

4.2.6 Conclusions

This section presented a solution for interacting with Augmented Reality in a portable and immersive way. The proposed system embeds a mobile phone as a visual display coupled with IMU for the index finger tracking and a haptic thimble for force rendering. The proposed system overcomes common issues related to the standard wearable AR devices. Differently from existing solutions, users are able to interact with virtual objects and perceive haptic feedback. Participants successfully perfomed the experimental trials and gave positive feedback on the developed system, encouraging further improvements.

In the next future, we will extend this evaluation to other modalities of cutaneous stimuli to enrich the haptic rendering. We will investigate the role of the displaced hand avatar in an embodiment study, especially to assess whether the haptic feedback facilitates the virtual hand ownership. Finally, we would like to extend the sensing and actuation to other fingers, starting with the thumb for simulating pinch grasps.

Chapter 5

Discussions

This chapter provides *a posteriori* discussions on the concept of guidance investigated during my PhD period, highlighting how the methods developed can be linked together to extract generic concepts for the design of a guidance methodology.

In the presented works, the problem of human guidance has been addressed using two different approaches, one coming from the world of robots and the other defined on a human scale. In fact, it is possible to assist a person in the execution of a task either by communicating step-by-step instructions, or by enriching his knowledge of the task, allowing a more informed and therefore better execution. The two approaches have been defined respectively Motion Guidance and Sensory Augmentation. In the various applications proposed within the thesis work, the two methodologies were applied to different scenarios, according to the needs of the participants during the tasks.

As regards the guidance of locomotion, a blend of the two methodologies has been adopted. In Sect. 2.1, the motion of the lower limbs was instructed by providing participants with alternate vibrations on the ankles, according to the Motion Guidance paradigm. The participants were asked to voluntarily match their walking cadence to that suggested by the haptics. On the other hand, one could also interpret the periodic stimulation as an external reference for the person to match during walking. This concept becomes more concrete when applied to the bidirectional transmission of the walking cadence described in Subsect. 2.2.4. Indeed, the vibrations allow the user to perceive the pace of the partner, and to alter the own cadence accordingly: the user can decide either to synchronize to the perceived rhythm, or to propose a different pace to reach a walking tempo that is comfortable for both the users. In this case, the methodology adopted for guidance falls within the category of Sensory Augmentation, since the haptics enable the perception of the companion's steps. Instead, a Motion Guidance approach is used in the rendezvous scenario (see Sect. 2.3), where the vibration patterns deliver very precise indications about walking tempo and direction to the next checkpoint. The users have to stick to the commands in order to fulfill the task on time.

From the researches on guidance of human locomotion it is already clear how the two approaches are based on two different pillars: the Motion Guidance assumes that the person strictly follows the commands (though the commands are actually suggestions), while in the Sensory Augmentation the choice of movements is in the person's hand, and the priority aspect of the guide is the choice of the optimal parameters to display (*e.g.* the objective).

The work on human-human cooperation (see Sect. 3.1) instead provides an insight on the comparison between the two guidance methodologies: given an example task that involves two people, is it possible to complete it using both approaches? And which of these has the best performance? The formation was successfully guided during the task using the three proposed haptic policies (two of them inspired by the Motion Guidance approach, the other by the Sensory Augmentation approach). The Sensory Augmentation strategy obtained better overall performance on the investigated metrics, *i.e.* temporal efficiency, smoothness of the trajectory and perceived comfort and usability. The guidance policies were designed as different combinations of the following factors: i) availability of the target, ii) freedom of movement, iii) walking model and iv) number of haptic pattern provided (complexity of the stimulation). The availability of the target had the greatest impact on the measured performance, especially time efficiency and smoothness, supporting the concept of Sensory Augmentation. In fact, regardless of the type of guidance imposed, participants did better when the direction to the target was available, so they could adjust their movements accordingly. It must be mentioned that the outcome of this work was biased by the simplicity of the selected task. Different results would have been obtained, for instance, with a larger formation and stricter conditions (*e.g.* presence of obstacles and narrow spaces), which would have required more meticulous guidance.

The system developed within the No-FaceTouch project represents another example of Sensory Augmentation (see Sect. 4.1). The smartwatch takes care of the face-touch detection in place of the human, and warns him when the event occurs or is about to occur, enabling better awareness without occupying mental resources. From this point of view, the user is empowered with a reliable and effortless detection of face-touches as a form of augmentation.

The Mobile Augmented Reality system proposed in Sect. 4.2 allows a multimodal exploration of the virtual environment, and therefore an improved sensory acuity. So, the guidance is intended as enabling the user to perceive a greater amount of task-relevant information to facilitate the task completion.

The proposed works highlight how the two methodologies show different capabilities and are based on two distinct concepts. The Motion Guidance approach is task-centered, in the sense that the optimal strategy to complete the task is computed and provided to the user as a sequence of instructions. The task planner acts as a leader in a master-slave configuration, where the human follows the guidance indications. Instead, the Sensory Augmentation methodology is user-centered, in the sense that the delivery of additional information enables the human to efficiently complete the task according to a self-selected strategy. The primary requirement in the design of Sensory Augmentation policies is determining which information are most relevant to the user, *e.g.* parameters that are otherwise inaccessible or incomplete, and conveying such data intuitively.

On the basis of the previous considerations, Motion Guidance is a viable approach for leading one or more persons, and it is especially useful in scenarios that expect precise movements and/or have strict requirements, *e.g.* sticking to a time schedule, and that present a straightforward way to complete the task. The user is relieved from the effort of planning his motions, since he is completely guided by the system. As a consequence, the application of Motion Guidance can be easily extended to a formation, where every member is guided independently. Also it proves very useful for training applications, especially if users are naive to the task. A major flaw of the instruction-based approach though is that it does not leverage the experience of the users.

Sensory Augmentation, on the other hand, leaves the user in command of the own actions and enhances the perceptive abilities, with the aim to promote a more effective and mindful planning. The Sensory Augmentation can also monitor parameters that are not strictly necessary for the primary task under execution, but are relevant for secondary tasks (*e.g.* face-touch detection during daily activities). In fact, the Sensory Augmentation concept is not restricted to guidance scenarios, as it extends the human perceptive capabilities to many different parameters and events.

For what concerns the delivery of guidance stimuli, haptic technology has proved to be an effective means. Relying on touch doesn't interfere with other input channels. Instead, using sight or hearing to communicate information would result in a partial occlusion of the afferent perceptions. Conversely, tactile receptors have the largest distribution between the sensory organs, and are mostly unused. Thus, communicating through touch opens the possibility to stimulate different body areas to increase the input data flow. The use of simple stimuli, such as vibrations or skin indentation, allowed humans to receive information without overloading the interpretative process. Furthermore, the devices necessary for simple stimulations allow to maintain a reduced form-factor, that does not obstruct the users' motions.

Chapter 6

Conclusive Summary

This thesis reports the researches on human guidance via haptic stimuli conducted during the course of my Ph.D. The main results and hypotheses described in this manuscript are summarized as follows.

Chapter 1 describes the background knowledge related to human locomotion, to the brain mechanism that enable the entrainment to external stimuli, and to touch perception. Then, the literature on wearable haptic device for cutaneous stimulation is presented.

Chapter 2 presents the research work on the use of tactile stimuli to regulate walking cadence in humans. Previous works investigated the possibility of instructing walking cadence using tactile stimuli. We shifted our attention on the placement of haptic interfaces and its effect on task performance, *i.e.* synchronization rate with haptic stimuli, and comfort and intuitiveness perceived by participants [93]. The haptic interfaces placements tested in this work were selected according to experimental setups proposed in literature. We hypothesized that delivering the haptic feedback close to the foot, that senses the impact with the ground during the heel-strike, could be beneficial for the synchronization aspect. In preliminary experiments, the task performance retrieved were statistically different between the two conditions, but the effect size was small. In other words, the experimental results indicate modest benefits of the ankle positioning with respect to wrist positioning. In order to stress the differences between the two placement conditions, we introduced a secondary task involving manual and mental workload, that reduced the attentional resources available for the walking task. Subjects were also asked to answer a questionnaire at the end of the experimental procedure to collect personal evaluations on the comfort and usability of the two placements. Although the experimental protocols used in the two experiments were different, thus the results could not be compared directly, data showed that the ankle positioning was again slightly favourable. The subjects' evaluation instead reported a clear preference for the ankle positioning. Participants stated that receiving the vibration at the ankle helped with the synchronization because they could predict the tempo of vibrations and align the heel-strike with it.

The results on the placement of haptic interfaces were exploited in a successive work on the remote synchronization of walking cadence between two users, described in Sect. 2.2. The scenario envisioned is the Remote Social Walk, inspired by the 'social walking' trend that brings people together to perform physical activity and leverages the social aspect to motivate people into healthy behaviors [138]. In the case of Remote Social Walking, participants are not physically close to each other, but are connected by tactile stimuli provided at the ankles that display the partner's gait cadence. Although the system has been designed to support more than two users, we started by testing its effectiveness with couples of participants. The experimental campaign was split in five experimental sessions that tested the participants' capabilities in aligning their walking rhythm to constant and variable tempo. Experimental results showed that participants successfully aligned their steps to the haptic tempo for constant and variable rhythms generated by a software. Then we tested the alignment of the participants' walking cadence to the walking cadence of a human partner, that acted as leader in a leader-follower configuration. The scientific question in this case was understanding if human could align their steps to walking frequencies that featured small variations, that could not be predicted through the Neural Entrainment mechanism. Experimental results showed that followers aligned to the leaders' walking rhythm for the majority of the trial time (if the haptic stimulation was enabled). Moreover, the small tempo fluctuations due to human variability did not interfere with the step frequency predictions, in accordance with the results presented in [19]. The conclusive experiments validated the use of the wearable haptic system for the bi-directional communication of walking cadence. Participants managed to align their step frequency to the partners' ones, and in the majority of the cases the couple settled on a rhythm that was intermediate between the comfortable cadence of the two participants. The gait alignment process was slower than in the case of the leader-follower scenario, probably due to the initial oscillatory transient before converging to a common cadence. Participants appreciated the remote social walking application and expressed their interest in using it in real-life. Future works on this aspect will tackle the communication between a larger group of walkers, to understand which is the preferrable strategy to convey to each group member the cadence of the others. Possible hypotheses are displaying the average cadence of the group, the average cadence of the group excluding the considered participant, or the walking rhythm of a group member that is closer to the average cadence. Moreover, we want to test whether filtering the participants walking cadence (*e.g.* using a moving average on a limited number of steps) helps the achievement of a common cadence or compromises it due to the delay introduced.

Chapter 2 ends with the description of a live-demonstration presented at the Asia Haptics 2018 conference on guidance of direction and cadence of human locomotion (see Sect. 2.3). The envisioned scenario is the rendezvous between two users in an unknown and unstructured location, guided by haptic cues [89]. The path navigation was designed using 'checkpoints', that are specific locations where the route forks, to update the task parameters and provide the users with the direction to the next checkpoint using haptic patterns. The system takes into account the stride length and stride duration at comfortable cadence of each user, measured before the experiment, to estimate the arrival time to the final goal and thus calculate the optimal cadence to complete the task in time. When a user arrives to a checkpoint, the actual stride length is estimated and used to update the stride duration provided to the users. During the demo session, two participants at time took part to the trial. An initial training phase of 5 minutes was necessary for the users to get acquainted with the haptic stimuli and the alignment of steps to the external rhythm. Almost all the couples managed to reach the final goal on time (assuming 5 seconds tolerance in over 100m path length), and felt satisfied with the experience. Although the scientific question was not addressed with experimental results, the demo session demonstrated that this approach can be extended to real-life scenarios with due arrangements. For instance, providing a reliable tracking system (*e.g.* GPS) would allow to monitor the task for the whole duration and update the parameters instantaneously. The checkpoint approach instead might be useful for unstructured environments.

The guidance problem is then contextualized in a collaborative object-loading task, as described in Chapter 3. During the experiments, two users were guided along an unknown path by haptic patterns. The participants wore eye-masks and were asked not to talk. So their motion was guided only by the instructions received from the haptic interface, *i.e.* a belt equipped with four vibro-motors, and they were able to exchange forces with the other member of the formation through the carried object [169]. Three guidance policies have been tested, that leveraged guidance under holonomic and nonholonomic motion constraints and a sensory augmentation approach, respectively. In each experimental condition the participants were provided with haptic patterns according to the selected policy, and moved the object along the suggested path without breaking the formation. The discussion on the experimental results allowed to form *a posteriori* hypotheses on the factors featured by the guidance policies that had the most relevant effect on the task execution metrics. These hypotheses pave the way toward the definition of guidelines for haptic policies design in human guidance tasks. Participants exhibited smoother walking trajectories and lower task completion time when the goal objective, *i.e.* the direction to the target, was constantly indicated by the haptic patterns. Conversely, the haptic policy featuring two instruction patterns had lower overall task performances, probably due to the temporary obstruction of the goal direction caused by the rotational haptic pattern. The motion constraints and the walking model adopted (holonomic and nonholonomic) defined by experimental protocol had a minor impact on the task performance, but affected the comfort perceived by the participants during the experiments. Providing the fundamental information to the users through haptics might be seen as a way to augment the sensory perception of humans using an underused channel, *i.e.* touch. In our hypothesis, the sensory augmentation plays a paramount role for the effectiveness of the haptic policies, and should be a key factor in the design of human guidance paradigms. Moreover, users also benefit by not having their motions constrained (by experimental protocol) as they can apply the most straighforward strategy to accomplish the task once they know the goal. On the other hand, receiving strict instructions and sticking to them may be necessary whenever the motion of the formation has to be precise, *e.g.* when transporting a fragile object in a narrow environment. In this light, the adoption of the grasping theory for keeping the formation and steering its motion proved useful and should be improved for a finer control of the formation as a whole. On the other hand, we should consider that receiving more accurate instructions would result in providing more complicated haptic patterns, this way increasing the cognitive load perceived by the users.

Chapter 4 introduced two research projects that exploited the haptic stimulation to increase the task/situational awareness. Firstly, Sect. 4.1 presented the use of haptic cues and inertial and magnetic measurements in a solution to support public safety during the Covid-19 pandemics [170]. The No Face-Touch project addressed the issue of self-inoculating viruses (*i.e.* touching infected surfaces and then contacting mucosal areas with the infected hand) by detecting face-touches and alerting the user. If the face-touch attempt is stopped before it happens, the user is protected from possible inoculations. On the other side, if the detection occours after the contact, the alert reminds the user not to touch her/his face, building this way a corrective habit. The behavioral advantages of this approach were not tested and should be addressed in a future work to assess long-lasting effects of the face-touch detection and alerting.

Section 4.2 instead proposes a system that integrates Mobile Augmented Reality (AR for smartphones) with finger tracking and tactile feedback to provide a realistic AR experience [171, 172]. The solution has been designed to promote MAR adoption in industrial or daily use scenarios, *i.e.* a smartphone holder attached to the wrist (as a big smartwatch) keeps both hands free from the encumbrance of hand-holding the smartphone. The forearm placement of the smartphone also simplifies the hand tracking, as the displacement between the real hand and the smartphone is fixed, and the system can reconstruct the real position of the hand in the virtual environment by knowing the relative position and orientation of the camera from a reference in the environment (in this case, a fiducial marker that indicates the position of the virtual object to interact with). The tracking and haptic feedback functionalities are provided by a compact fingertip interface. Although the current form factor is far from unnoticeable, it was used as a proof of concept that can be optimized in the near future. To conclude, the 'final version' of the system was intended to feature a foldable display around the wrist (as a bracelet) instead of the smartphone attached to the support, that would reduce the bulkiness of the system and promote its usability in real life scenarios.

Appendix

Interfacing and using Nike+iPod Kit

In this subsection we briefly detail the interfacing procedure for using the Nike+iPod sensor for customized application. The kit (approx. 29$ (USD)) contains two modules: a tiny sensor to be placed in the shoe and a receiver to be used with iPod. When the user walks or runs, the piezo-electric sensor estimates and wirelessly transmits information about the user's gait to the receiver. Following the result presented in [173], we modified an iPod female connector by soldering wires from the serial pins on the iPod connector to our adapter, adjusted the voltage accordingly, and powered with 3.3V. We then plugged a Nike+iPod receiver into our female connector replacing the Ipod with a PC running an *ad-hoc* developed software. This caused the receiver to start sending packets over the serial connection to our computer, allowing us to monitor the measured cadence. Acosta *et al.* in [174] and Kane *et al.* in [175] validated the accuracy of the *Nike+ Wireless Sport Kit* to estimate pace (min/km), and distance (km) during treadmill walking and running. Results showed that the *Nike+* device overestimated the speed of level walking at $3.3\,km/h$ about 20%, underestimated the speed of level walking at $6.6\,km/h$ by 12%, but correctly estimated the speed of level walking at $4.9\,km/h$, and level running at all speeds ($p < 0.05$). Similar results were found for distance estimation. Starting from the preliminary results presented in [173] we developed a device for receiving and decoding messages from the *Nike+* sensor. We designed and built an *ad-hoc* PCB for connecting the receiver with an Arduino based micro-controller. We can split the developed code in two main parts. The former acquires information from the sensor and sends the computed cadence to a remote server using internet, the latter receives the information about the partner rhythm and activates the motors correspondingly. Two serial communications were created in order to communicate at the same time with the sensor and the smartphone. The communication between the pedometer and our system starts sending a header packet of 8 byte. This packet puts the sensor in active mode and the stream of data is enabled. We observed that the sensor streams a packet of 34 bytes every seconds. We collected and analyzed several packets from multiple sensors, noticing some common bytes. A representative packet is the following: `FF 55 1E 09 0D 0D 01 24 F2 1D 30 A3 A1 97 E3 86 C1 F3 39 DC C6 12 5C CE FB 3C 83 0D EE 4C 1F FB F8 38`. We discovered that `FF 55` is the packet header, and the payload starts with `1E 09 0D 0D 01` for all the sensors and all packets. The packet continues with 27 bytes. The first 26 bytes carries all the information estimated by the pedometer, such us walking steps, running steps, sensor ID, lifetime walking and running miles, etc. The last byte is used as a check-sum to validate or discard received packets. We tested all the possible combination of packet bytes and checksum type and we found that the last byte is a *8bit 2s Complement* checksum. The 26 bytes payload are decoded using a library based on the work done by Grinberg [176]. All the sensors use the same radio frequency, and a packet per second is sent regardless the presence of a request or ack from the receivers, thus to use multiple Nike+ we process packet only if the descrambled serial number matches the one associated to the user. Once per second Arduino receives the total amount of walked (or run) steps. We exploit this incremental measures to compute the cadence *i.e.*, the number of steps per minute. A moving average with time window of 5 seconds is used to have good compromise between response time and smoothness. As soon as a change in the cadence occurs, the smart-phone (or smart-watch) is notified.

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