Mobile Augmented Reality Integrating Fingertip Haptic Devices and Wrist-Worn Visual Displays

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***Abstract*— In the context of Mobile Augmented Reality (MAR), hand-based interaction with virtual environments is still an open challenge. Virtual objects projected on the smartphone screen are on a different layer than the camera-captured images, hence the user's hand cannot get in contact with virtual entities. In this work, we present an improvement to a previously published proof-of-concept that aims at overcoming current MAR limitations by mapping the hand in the virtual reference. To this end, we developed an *ad hoc* ring interface for finger tracking and haptic feedback, designed with wearability in mind. A wrist-worn display compacts the hardware on a single-arm, leaving the other completely free. The overall system is affordable thanks to the use of the smart-phone as core technology and provides "on-demand" augmented reality, tailored for daily activities scenarios. Eighteen users were enrolled to compare the wristband based system and the standard hand-held smartphone montage. Quantitative and qualitative results show that our system was positively received by the subjects, that completed the experimental task achieving similar performance in the two conditions but expressed their preference for the wrist-worn display.**

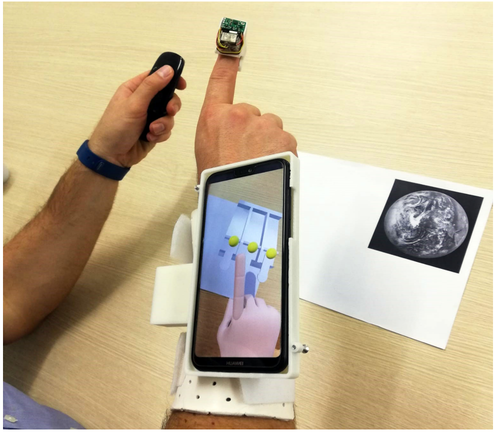

Fig. 1: The haptic device worn on the fingertip together with the wrist-worn display for MAR. In this picture the left hand is free and holds a remote controller.

I. Introduction

Augmented Reality (AR) enriches the real world with virtual objects, animations, and sounds. Even if AR systems have been developed for decades, only the most recent devices are bringing AR applications in our everyday life. Such fast growth suggests that Augmented Reality will become an essential technology in the future. For instance, the Industry 4.0 initiatives leverage on Augmented Reality to facilitate training of technicians, ease product assembly [1], and lower cognitive load and error rate during task execution [2].

Despite its potentiality, AR is still not fully adopted for daily use. Many AR apps lack the functionality to justify the burden of wearing a Head-Mounted Display (HMD) or hand-holding a smartphone for a prolonged time. A system capable of providing on-demand support may prove more versatile for daily activities, by removing the major sources of concern that operators face when wearing HMD, such as isolation and loss of situational awareness. Among others, we recently proposed a proof-of-concept system with these features in [3] as an alternative to other state-of-the-art solutions. Qian *et al.* presented a hand-held MAR system based on a smart-phone and an external portable processor to track the hand in real-time using a Leap Motion, obtaining good results in terms of user experience [4]. Although the user's hand is not constrained by wearing hardware, this solution cannot provide haptic feedback and always occupies one hand to hold the phone. Minseok *et al.* used a similar setup for developing a hand-held system based on touch and hand gestures [5]. The use of Leap Motion required a computer to detect gestures and forward them to the phone. Other strategies leveraged on using instrumented gloves to retrieve the hand pose from hand joint angles and provide vibrotactile feedback [6], or tracking the index finger using the smart-phone rear camera [7].

In our previous work [3] we presented a proof of concept solution to address this issue by moving the display from either the head mounted support or the other hand to a dedicated wrist holder (Fig. 1). This work extends previous preliminary results, compared to which we provide herein a new and improved prototype of the haptic device, a more extended theory, and a more comprehensive experimental validation.

The greatest advantage of this solution lays in its great affordability, as it employs a relatively cheap mobile phone as rendering device; it also overcomes the excessive immersion issue that characterize HMD while retaining the free use of the other hand. Following that proof of concept, in this paper we have deepened the study of the idea by working on the functionality and usability assessment. We conducted an experimental evaluation to compare our approach with the standard hand-held montage. In order for the comparison to be fair, we also developed a custom haptic renderer that is specifically designed to complement the wrist mounted system

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for Mobile Augmented Reality. In [3] the haptic rendering was achieved by means of a prototype featuring cumbersome wires that impeded the user free motion, and a dislocated battery slot uneasy and uncomfortable to wear. In this paper, the proposed device features an all-in-one design comprising battery, actuation, computation, inertial and magnetic sensors (IMU) and connectivity in a single, easy to wear and light-weight solution.

The functionality and usability of the new setup were tested involving 18 people, where the haptic feedback provided by the fingertip interface was essential for the task completion. Participants were asked to explore an augmented reality setting and solve a puzzle relying on visual and tactile information. Qualitative and quantitative indices were evaluated in two conditions to test the efficacy of the system condensed on a single arm, with respect to the standard hand-held montage. Results are presented as performance measurements retrieved during the experiments and users' personal evaluations from an *ad hoc* questionnaire.

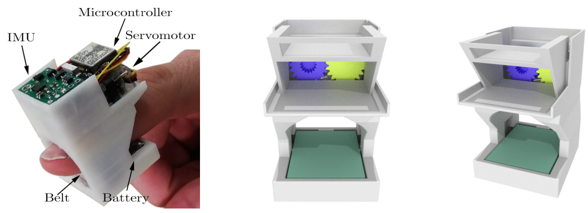
II. MAR Haptic Interface Design

In this manuscript, we present a novel, cheap, and wearable setup that combines a visual display for Augmented Reality and an acting part, capable of rendering forces as cutaneous feedback. The system was tested under two different layouts: the hand-held (HH) and the wrist-mounted (WM) version, respectively.

Our efforts were channeled in a twofold manner: *i)* designing the hardware necessary to collect the input data and display visual and tactile cues; *ii)* developing an Android software to collect measurements, process data, and calculate the appropriate feedback. The smartphone is the central processing unit, but also serves as visual input source. It is secured to the arm using a 3D-printed ABS support attached to a thermoplastic splint. The finger avatar reproduces the index finger pose estimated by an Inertial and Magnetic Unit (IMU), while the interaction forces are rendered through a tactile display on the fingertip (Fig. 2).

A. Visual Display

Similarly to [3], a commercially available smartphone was used as a display visual display. Three thermoplastic splints are used to fit different body sizes. Splint and support are secured through screws to have a firm grip. The support can house the smart-phone in two layouts, landscape and portrait, rotated 90° with respect to each other. The support has been designed to make sure that the camera field of view was not blocked by the user's hand or forearm, by introducing an offset between the position of the real and virtual hand. The splint is fastened to the arm using two Velcro strips. The smartphone app is displayed in panoramic layout, and was active for the entire duration of the trial. The support was used only in the wrist-mounted (WM) condition, while the smartphone was hand-held in the corresponding condition (HH).



(a) (b)

Fig. 2: The wearable haptic device is composed of a small servomotor and two gears that move a flexible belt towards and away from the finger pulp. A micro controller and a Bluetooth antenna are in charge of controlling and connecting the device, respectively. A $100\,\mathrm{mA\,h}$ Li-Po battery, placed in the bottom of the case powers the system. The total weight of thimble is $20.8\,\mathrm{g}$. A user wearing the device is depicted in (a), while the rendered 3-D model from two different points of view is reported in (b).

B. Haptic Display

The projection of the user's hand in the virtual environment allows to estimate the force interaction with virtual objects. As a consequence, the interaction force can be rendered using a tactile display.

Haptic rendering comes with a variety of interaction modalities, in particular we are interested in wearable actuators. A complete survey of wearable haptic interfaces is depicted in [8]. Among the different typologies of tactile stimulation, we selected skin indentation, which is the most intuitive for perceiving the sensation of making and breaking contact with objects.

Contextually with the AR system, starting from the results presented in [9], we designed a system capable of generating forces along a single axis, which is enough to perceive contact pressures. To reduce the device encumbrance, we employed a single servo-motor controlling a flexible belt. The torque generated by the motor determines the direction of rotation of a master gear that consequently moves a slave gear. Such coupling results in opposite spinning direction of the gears, that move the belt along the vertical axis (as depicted in Fig. 3). Subjects were asked to wear the interface on the index finger by placing the fingertip over the belt. The force exerted by the belt simulates the virtual contact forces by deformating the skin. The maximum belt translation in the vertical direction can be selected according to the external diameter of the gears, the length of the belt, and the rotation range range of the servo motor. We selected the maximum range available for the device, considering that also fingertips bigger than the average should fit without always being in contact with the flexible belt. We set the maximum range at $23\,\mathrm{mm}$. Considering that the servo-motor maximum rotating range is 120°, the optimal belt length and gears external diameter to minimize the mechanism size were respectively $65\,\mathrm{mm}$ and $11\,\mathrm{mm}$. The mechanism is integrated in a wearable interface worn at the fingertip, that

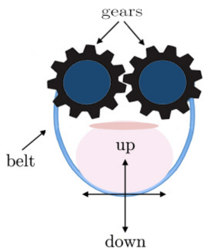


Fig. 3: The actuating solution adopted in the proposed haptic thimble. One of the two gears is directly connected to the servomotor shaft. When the motor rotates, the two gears rotate in opposite directions, and the belt is pulled up/down, providing a force normal to the finger.

is also used to estimate the index finger orientation with respect to the back of the hand (Fig. 3). The fingertip device is controlled by a microcontroller based on an ARM Cortex-M0, that is in charge of communicating with the smartphone via BLE, reading the IMU, and controlling the servo-motor. The Android app, presented in Sect. III, estimates the contact force and sends a corresponding value mapped in the useful range (defined during the calibration phase). The control of the haptic display is based on the assumption of linear relationship between the force generated and fingertip deformation. Hence. the force exerted by the center of the belt can be expressed as:

$$F_f = \left(\frac{\tau}{r} - k_f \Delta l \right),$$

where F_f is the force exerted on the fingertip, τ is the motor torque (max $0.8\,\mathrm{kg\,cm^{-1}}$ for the servomotor used), $r = 5.5 \times 10^{-3}\,\mathrm{m}$ is the pulley radius, Δl is the finger pulp indentation. The stiffness of the fingertip refers to a simplified model. In accordance with [10], we assume the relationship between the belt displacement and the generated normal force to be linear. We consider a stiffness k_f =$0.5\,\mathrm{N\,m^{-1}}$ as elastic behavior of the finger pulp. So that, we can compute the desired displacement for generating a requested force:

$$\Delta l = K_f^{-1} F_f,$$

where Δl is the displacement of the belt with respect to its initial position, i.e., when the belt is in contact with the finger pad without producing any skin deformation. Thus, the evaluation of the motor angle results straightforward. Because of the design of the device, the maximum force that can be provided to the human's finger pad is about 5.0 N. Interested reader is referred to [11] and [10] for further details on the force feedback generation.

The useful servo range in each experiment was decided depending on the subject fingertip size. During the manual calibration, the operator selected the point corresponding to maximum force exerted by the motor and the minimum contact point. This values were then inserted in the app settings interface, which communicated the useful range to the microcontroller. Every time the app detects contact, it sends a value to the microcontroller which performs the mapping in the useful servo range. We did not take into consideration an automatic calibration procedure to avoid inserting a pressure sensor, thus extra cables which would reduce the system wearability.

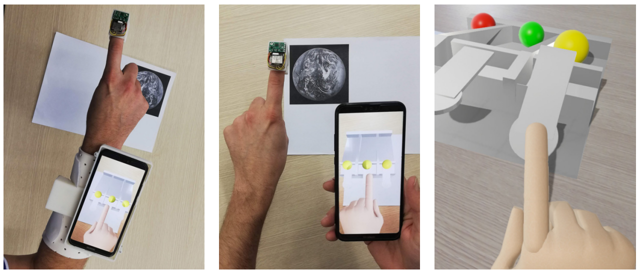
C. Hand Tracking

A necessary step to achieve and measure the interaction with virtual objects is to project a representation of the hand in the virtual environment reference system. In order to measure the distance between the hand representation and the fiducial marker without additional external hardware, we decided to dislocate the virtual hand projection. Portable IR-cameras, i.e. Leap Motion (Ultraleap Ltd), can reconstruct the hand kinematics, but cannot locate the hand with respect to the target object. An external portable camera (e.g. 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 would constrain its movements. An external grounded camera would achieve the best accuracy, at the cost of portability.

In our approach, the palm 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). 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 are 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 [12]. 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 [13], and biomechanical constraints [14]. 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, the same approach can be used to easily track the entire hand as in [11]. The microcontroller is in charge of collecting inertial and magnetic data from each sensing board and send them 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.

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



(a) (b) (c)

Fig. 4: Wrist Mounted condition (a) and Hand Held condition (b) tested during experiments. Frame of the Android app during the weight evaluation task (c).

Let $q_F(t)$ and $q_S(t)$ be the quaternions that express the orientation with respect to the initial position of the finger and 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 [15] for reconstructing the finger pose by means of a single joint value.

III. AR display

Similarly to [3], we used an off-the-shelf Android smartphone and built an *ad-hoc* forearm support. The 3D printed ABS support is attached to a thermoplastic splint to firmly hold the phone at a fixed distance from the wrist (for the hand tracking) avoiding constrains of the hand motion and camera occlusions.

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, in Fig. 4c a screenshot of the proposed AR scenario is reported. Because of the device unique positioning, the phone camera field of view does not include the real user hand, which is in fact replaced with 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 in a fixed position just below the camera, *i.e.* the smartphone rear camera, so that it is visible in the shots. A skin texture allows for a more immersive experience.

The virtual hand size is based on the average adult human male. It is placed about $15\,\mathrm{cm}$ below the camera and appears fixed on the phone display. The augmentation software streams the rear camera images in its 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 [16] 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.

IV. Experimental Evaluation

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 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.

Then the user was asked to place the virtual finger on the three levers to sense the weight of the three spheres (Fig. 4c).

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 did 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[1] 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 [17]. The *"Manipulability"* block analyses the participants physical efforts and comfort during the task, given the smartphone montage. The last block is referred as *"Embodiment"*, and is aimed to evaluate participants' impressions about the realism provided by the haptic feedback, and the feeling of having the virtual hand displaced from to the real one.

V. Results and Discussions

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. 5.

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 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.

[1]http://sirslab.dii.unisi.it/wristbandhaptics/

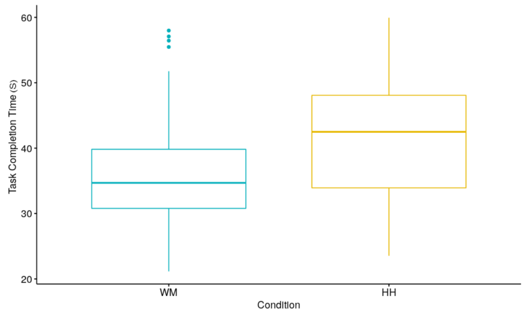


Fig. 5: Completion time boxplot representation for wrist-mounted and hand-held condition, respectively.

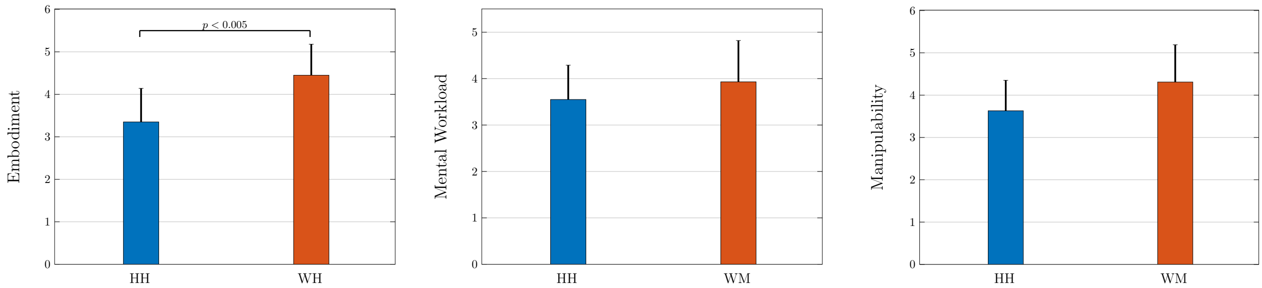
Regarding the questionnaire, Shapiro-Wilk test confirmed the normality of scores distributions, for each block and condition. From Leneve's test conducted on the four quantities emerged no significant difference in variance homogeneity between the two conditions. The average scores for the HH condition 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 depicted in Fig. 6.

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 self-perception of Mental Workload ($t(17) = 1.65$, $p = 0.12$). In average, the Manipulability items were rated higher for the WM condition ($t(17) = 2.07$, $p = 0.053$). Visual representations are reported in Fig.6.

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 0-3N).

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 were getting used to the wrist-mounted modality and were exploring different strategies to easily control the system. In particular, most of them decided to exploit 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 [18], as the haptic feedback fosters the embodiment of a virtual hand moving in accordance to the



(a) (b) (c)

Fig. 6: The boxplot report the average ratings for the two experimental conditions, divided by questionnaire subsection: a) Embodiment, b) Mental Workload and c) Manipulability.

real one. Questionnaire results support the more realistic feeling of ownership of the virtual hand in the WM condition. All participants reported that the haptic 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.

VI. Conclusions and Future Work

In this paper, we improved a previously presented idea for interacting with Augmented Reality in a portable and immersive way, and provided a careful evaluation along with a dedicated haptic device. We described a system embedding 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 perceiving 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.

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