ControllAR: Design and Fabrication of a Universal Parametric Low-Profile Hand Wearable for Augmented Reality Interactions*

The rapidly emerging Augmented Reality (AR) devices, especially head mounted displays (HMD), show great potential to enhance human capabilities. Yet the most of the HMD rely on on hand held input controllers for interactions. On the other hand, the advancing wearable technologies enlighten new opportunities to develop comfortable input devices for AR. Our motivation is to design and develop a lightweight, unobtrusive interactive device that is easy to fabricate, and suitable for interactions in many environments. We introduce ControllAR, a parametrically sized glove, which offers a comfortable and low profile design that eases the interactions with AR head mounted devices. ControllAR provides a parametrizing interface, simple and accessible fabrication workflow with no soldering or sewing involved, and a pressure sensor using a soft piezoresistive elastomer material. Through a series of experiments and use cases, we confirm that ControllAR achieves an accuracy of 82.4 for a uniform speed of navigation between users, notably comfortable, and hands-free interaction with its personalized fit while using Augmented Reality. Moreover, we obtain improvements in the settling time and response of the soft pressure sensor while achieving a more relaxed, and pleasant experience with AR.

CCS Concepts: • **Human-centered computing → Human computer interaction (HCI)**; **Interaction devices**;

Additional Key Words and Phrases: Wireless sensor networks, media access control, multi-channel, radio interference, time synchronization

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1 INTRODUCTION

Augmented reality (AR) technology is increasing in use in recent years. It presents a superposition of holographic images over real world settings, which is one of its strengths. AR allow users to interact with an augmented environment, that has been virtually modified. Holograms can be seen by using a head mounted device, or a mobile phone with AR capabilities enable. Hear mounted devices (HMD) allow users to obtain an immersion into the AR environment and leaving their hands free interact with it. The most common input modalities are complicated interactions for common navigation in AR environments, such as head gaze, gestures and hand-held clickers [40, 42]. These input modalities allow the user to navigate using head movements around the augmented world, and to access options using a 'clicking' hand-gesture or a hand-held controller. These selections are enabled by the tracking system embedded into HMD. However, the method of head movement as a selection mechanism is not practical, and reduces users ' experience and performance when combined with the hand gestures, or hand-held controllers. To enable tracking, hands need to be in front of the HMD, blocking the users from their activities and a pleasant interaction. Accuracy in tracking systems together with device price and an social

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acceptance become prominent issues that this AR technology presents. Thus, AR becomes a complex tool, rather than a practical one which could be used daily, and discourages developers from creating more applications.

Head mounted devices are considered as wearable technology, the advantage of them is that you can carry them to any place without the need of power source, or an additional computing equipment. A goal of wearable technology is to enhance user capabilities, improve user experience, provide internet connectivity, or boost social interactions. Some of these wearables have already become mainstream use, such as health trackers or smart watches. These devices can be carried everywhere, and be personalized. Wearables opened a space where normal user interactions can be improved, and new forms of interactions can be created. Wearables provide users with the capability to interact with the environment and technology at the same time, without impeding normal activities. Many wearable devices have been applied to industrial and social settings such as RealWear HMT-1, which is a voice controller user interface to operate tools, and HUMON HEX, which measures oxygen levels within the muscle [27, 61]. Researchers have also pursued the development of new technologies to explore input modalities, interactions, personalization, cost, fitting, fabrication, and locations on the body [34].

In this paper, we introduce ControllAR, a hand wearable device capable of sensing user inputs and providing an interaction modality that encourages the universal use of AR in HMDs. ControllAR is a glove made by combining different layers, which enable a low-profile wearable that contours a user's index finger and hand. Unlike prior gloves used for interaction and gesture recognition technology [16, 33, 34, 75], our wearable presents simplified fabrication workflow, which allows the user to create their own glove without stitching or soldering, our method combine fabrics, conductive inks, and piezoelectric materials.

With this fabrication approach, we plan to make every user be able to fit their hands in ControllAR, so a sizing app was developed to create a pattern for every user's hand size. The users need to input the required hand measurements into the application, and they will obtain a glove pattern that will fit their hands. In that way, we synthesize and embed the complicated glove fabrication into a One-Design-Fits-All. With this fabricated size personalized wearable, the users will be able to interact with AR scenarios in a quick and natural way compared to the current interaction inputs. To achieve the interactions, the glove uses pressure sensing principles to create various forms of inputs. By reducing the settling time and correcting the initial zero value after each interaction of a piezoelectric elastomer, we were able to achieve interactions like fast continuous clicks, selections, swipe, scroll, and long press detection.

To confirm and validate our approach, ControllAR was tested in three different settings. First, an evaluation of the pressure sensor. The sensor was evaluated using a blind test with users and by applying controlled pressures and recording the response. The tests provide insights of user preferences in terms of size, settling time, pressure response values, which shows how our sensor improves interaction, and comfort compared with others. Second, the evaluation of the parametric sizing application. The application was tested by making users input their measurements and fabricating the base of the wearable glove and wearing it. The insights from this test reveal the good fitting of our approach, the simple fabrication of a perfect fit glove, and the big range of hands sizes that can be fabricated without any knowledge of ergonomics, or clothing design methods. Finally, we conducted an evaluation of the wearable glove as a complete system. The evaluation was performed between two common techniques of interaction in AR scenarios and ControllAR. Tests evaluating text input, menu navigation, social inclusion, and small spaces were tested to analyze the performance of the three interaction modes. Overall, our study shows how ControllAR can improve user interaction with AR-head-mounted devices, and how it will help to facilitate the immersion of this technology into our day-to-day lives. Providing a great amount of applications such as assembly assistance and instructions, interactions with home appliances, maintenance and repair in industrial settings, or an interaction technique for outdoors and social environments.

The contributions of this work are the following: (1) a fast and low-cost accessible fabrication workflow for a hand wearable device, that allows the user to create a glove in a fast and easy way without the need of stitching or soldering; (2) a parametric sizing app, which enables the user to create a personalized glove that will fit perfectly on their hands and accommodate for the folding and hand movements. No extra knowledge about geometry, or ergonomics is needed to achieve a glove with perfect fit; (3) improvement of settling time and pressure response for a piezoresistive elastomer based pressure sensor, that is implemented as an input metaphor to drive the interaction mode to create click, select, scroll, slide, and x, y navigation. (4) results from a user study using the system, with additional application examples that prove the evaluation of the experience of interacting in common scenarios using augmented reality head mounted devices.

2 RELATED WORK

Our work lies at the intersection of multiple areas, including personalized wearable devices, AR interaction methods, and wearables fabrication techniques. The intersection of these areas serves as poiny-of-views to develop and understand ControllAR.

2.1 Personalized wearable devices

In terms of wearable devices, the capability for personalization becomes an important factor to make the technology more useful. As for e-textiles technology, research and industry have focused on developing manufacturing techniques that will allow the integration and adaptation of innovative material as wearables that people will be willing to try on daily basis [28, 53]. We focused on three approaches to promote personalization of our wearable: precise interaction, sizing, and fitting.

E-textiles for interaction incorporates capabilities to fabrics and yarns that serve as an input method to generate interactions. Yoon's approach in wearable fabrication modifies a piece of Lycra with a piezoresistive elastomer and conductive yarns to create a multimodal sensing input device [78]. This kind of approach expands with other works that create stitch based stretch sensors allowing different novel ways of interactions [36, 54, 55]. Adding to the list, the use of piezoresistive materials to create hover, touch, and pressure as input modalities [53, 67]. Thus, expand the textile fabrication where embroidery or weaving is used to embed electronics into clothing [23, 32]. This allows one to enrich the interaction modes of the users with many different environments such as phones, tables, AR, computers, or illumination. *Fitting e-textiles* into an arm, chest, hand, or other body part is another challenge for researchers. In the textile area, the exploration of geometrical approach the generation of flat patterns from 3D shapes is a very important contribution [12, 37, 73, 82, 83]. These approaches do not consider the creation of e-textiles but contribute to the personalization of size and shape of wearables in general. In this study, the importance of considering comfort of the wearables as a requirement for design is demonstrated. To acquire a higher level of customization, *personalization apps* are based on patterns of fabrication or interaction configurations. There are approaches that simulate the integration of electronics and current apparel industry to allow to scale of e-textiles [44]. Additionally, iSoft presents an interface to create wearable and personalizable interactive objects [79]. Similarly, Multi-Touch Skin, although not using a modified fabric, enables the creation of interactive surfaces for many body parts [49]. Other tattoo and hand wearable approaches, which creates interactive surfaces also inspire our work [29, 30]. Our work creates a novel sizing parametric app, which provides the user the possibility to fabricate a personalized electronic glove (e-glove). We relieve the user from the design knowledge, circuit creation and method for placement electronics and connections.

2.2 AR input methods

Head mounted displays (HMD) preset capabilities such as the display digital information on users environment, augment your surroundings as a setting for applications, and create applications that can be used everywhere. However,interacting with head mounted AR devices is still cumbersome. While types of interaction utilized on smart glasses have been making progress [34], only recently have we made progress on interaction methods, and fisnger worn devices [34, 64]. In this survey, it clearly identifies how smart gloves have been used for hands-free interactions, specifically, for touch-less inputs such as hand gestures, head, and body movements. ControllAR falls in a hybrid classification because it is a hand worn device, using touch input modality, and generating a hands-free interaction. The current interactions that have been demonstrated with AR-head-mounted devices conduct are: gestures, sensor based interactions, and voice commands. The most popular type of interaction is gesture-based, such as gloves with tags for hand tracking to interpret a set of gestures as inputs[25, 33, 58].Other types of interaction only use hand tracking systems to translate movements into commands [38, 41], and others use wearables distributed on the body, thumb tracking, or sensor inputs to describe different distributed interactions [70, 74, 81].

To achieve a socially acceptable wearable device and the integration of AR into daily activities, Hsieh introduces the design of a haptic glove integrated with smart glasses targeting scenarios such as text entry, scrolling, pointing, and selection in public spaces [26]. Likewise, we analyze DigiTouch , which presents a re-configurable, two hands entry glove with continuous touch input based on thumb-finger interactions [75]. The glove design presents the detection of continuous touch inputs between thumb and other hand areas. For ControllAR, the goal is to achieve a wearable device that alleviates camera tracking obstructions to create simpler, repeatable, accurate, and easy to remember interactions for AR-head-mounted devices. Adding the social acceptance and reducing the cognitive load in the interactions to focus more on the AR than the input mode.

2.3 Wearables fabrication techniques

Fabrication methods for interactive wearable devices are progressively growing. However, there is still a gap between fabricating comfortable wearable devices and easy fabricating working electronic devices. This is due to the difficulty in integrating electronics into flexible fabric based wearables [5, 13, 46, 52]. A variety of soft e-textiles and the development of software applications that will scale current manufacturing methods also help fill this gap [23, 44]. For circuit creation, current trends have explored electronic elements interconnection with flexible materials that can be used instead of textiles to create interactive wearables such as conductive inks, electric threads, capacitive sensors, and screen touch-pads [20, 30, 49, 50]. Others use conductive fabrics, which provides the integration of current fabrication techniques and wearable fabrication [7, 55, 56, 78]. Expanding to current studied methods, SketchStitch allows the interconnection of electronic components placed on fabric using conductive thread and a computer vision based approach[23]. DigiTouch [75], on the other hand, uses conductive fabrics to modify a commercial glove with the purpose to obtain the interactivity for the user. For e-textile wearables the conventional techniques for fabrication are buttons to plug devices into the substrates, knitting, stitching, and sewing to make the connections[7, 45, 60, 63]. Inspired by this work, we move beyond to bring a full pipeline for an accessible low profile, interactive e-glove with highly accessible tools. We emphasize, integrating all hardware in the same design, personalizing the size for each user, and fabricating the glove at low cost without any soldering, or stitching.

3 GLOVE DESIGN GOALS

3.1 Fabrication

We are motivated by the need of a low profile, socially acceptable and low cost glove for head mounted AR device interactions. Further, the gloveshould be easily fabricated by any user and without any special equipment or expert previous knowledge. First, to achieve low profile, the materials should maintain a small form factor. Specially, thickness of textiles, electronics, and sensors are the most relevant elements. Second, to maintain a fabrication simple and easy to reproduce by every user and in any moment, we aim to create a workflow that optimizes the use of materials to reduce the cost, avoids complicated fabrication methods like soldering or stitching, and eliminates the configuration requirements.

3.2 Glove Form Factor

The existence of a wide variety of hand sizes, producing a one size fits all glove becomes a very challenging design constraint. The fact that a hand can have around 27 degrees of freedom (dof)[19], creates many limitations related to movement constraints, location of articulation points, wearability, and range of motion. We propose the creation of an app that has the capabilities to generate a glove pattern ready to fabricate based on the size measurements of the user's finger.

3.3 Soft pressure sensor

Since flexibility, stickiness, and deformation properties of elastomer piezoresistive materials, the restoration time and pressure values range is affected in measurements. We propose an improvement of the fabrication process, to reduce the settling time of the elastomer, remove the stickiness and obtain always the full range of pressure values after a deformation. This approach, considers, curing times, thickness, and contact surface shape with the electrode. We reduce the curing time. This will obtain the best response in our sensor without adding additional sensing layers, or other types of sensing reading techniques that can increase the size of our design..

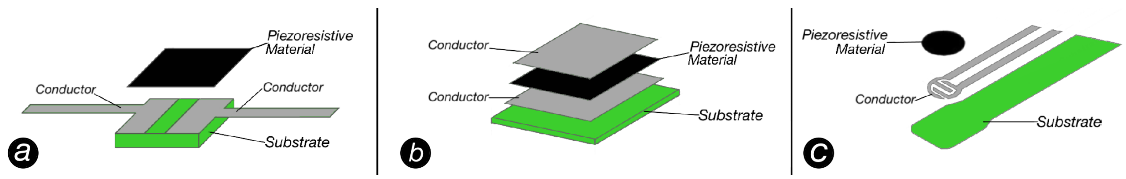

Fig. 1. a) Parallel pressure sensor, b) sandwich pressure sensor, and c) interdigitate pressure sensor

4 MATERIALS SELECTION ANALYSIS

This section explores the materials, elements, and fabrication techniques required to achieve the proposed design goals. First, the e-textile, then the piezoresistive pressure sensor.

4.1 E-Textile

In this phase, the goal was to achieve the creation of an e-textile without using soldering or stitching, in a fast mode, and with the minimum possible cost. To all this, the exploration to achieve the best performance from the glove. The exploration was based on finding the best compatibility between the substrate layer and the conductive layer. As general guidelines, ControllAR needs a substrate that could conform the hand and still be comfortable and not intrusive, and at the same time support hand movements such as finger flexing. Substrate and conductive layer should present a very good bonding, so the created circuit is not destroyed by the hand movements. A comparison between multiple substrates and conductive options were analyzed to achieve the goal. For substrate, the materials considered were **nylon**, polyester, Lycra, and silicone rubber [17].For the conductive materials, there were considered carbon based paint [8], silver paint [66], nickel paint [48] and conductive yarn [11] to evaluate the compatibility. This materials selections were based on the low profile, low cost, and easy fabrication.

As shown in Table 1, the results of the combinations between substrates and conductors are presented. These tests show how the elements behave with each other. for instance, Lycra is a material that stretches and is very comfortable for long periods of time and can manage large ranges of movement. The limitation of Lycra comes when it is mixed with the conductive paints. Lycra stretchability is higher than the conductive, so when it is stretched, the paint cracks which breaks the designed circuit. An option to use it is to stretch the Lycra before painting, but it is needed more space between circuit lines to completely avoid short circuits. On the other hand,

Table 1. Material Combinations for Substrates and Conductive Layer

	Carbon Coating	**Silver Paint**
Lycra	Paint cracks when stretched When stretched, Lycra leaves gaps	Paint cracks when stretched When stretched Lycra leaves gaps
Polyester	Paint cracked while bending	Compatible for short term
Nylon	Paint cracked while bending	**Compatible and good bonding for long term**
Silicon Rubber	Paints do not stay on substrate	Paints do not stay on substrate
	Conductive Yarn	**Nickel Coating**
Lycra	Requires more fabrication effort When stretched, Lycra leaves gaps	Paint cracks when stretched When stretched Lycra leaves gaps
Polyester	Polyester shrinks	Compatible for short term
Nylon	Nylon shrinks	Paint cracked while bending
Silicon Rubber	Complicated implementation	Does not stay on

using the conductive yarn allows the possibility of stretching if the yarn is placed creating a sinusoidal pattern while stitching [60], but this requires more effort in the fabrication, thus it is time consuming, and requires additional equipment for a good result. Dragon Skin silicon, presents excellent properties such as wearable, breathable, flexible, fast curing time, and can be molded [17]. The incompatibility to retain the conductive paints and complicated fabrication for yarns were principal reasons to discard this option. Polyester presents a better compatibility with the conductive layer. The issue with this material is that the paints only last for a couple of minutes and then start cracking. While using conductive yarn, the fabric shrinks, which makes very uncomfortable to wear and create the sensors. In the same way, Nylon presents better characteristics of bonding, specially with the silver ink. Carbon and nickel paints crack with some minutes of use. This can be attributed to the stretchability property of paints when it is dry. The compatibility with silver ink allow users to wear the glove and remove the glove multiple times without compromising the conductivity and functionality of ControllAR. After all that, silver paint was the most optimal option, despite of its cost was higher than the other options.

4.2 Piezoresistive Sensor

For the design of the piezoresistive sensor, which is used as an input metaphor in ControllAR, we explore the design of the electrode and the piezoresistive layer. Distribution and geometry were the main focus that were analyzed in two tests described in the sensor evaluation section.

4.2.1 Electrode Design. To create a pressure sensor using a piezoelectric material requires two minimum components. A piezoresistive element and two conductive layers that will be separated by the piezoresistive material. In Figure 1 we can see the most common configurations for a pressure sensor of this type.

ControllAR uses circular interdigitated electrodes (Figure 1 C) [9] because this pattern of electrode helps to reduce the volume of the sensor, improve **sensor response**, reduce material, and reduce number of layers. This simplifies the design and fabrication of the sensors in the glove, and allows to fabricate electrodes and conductors in a single layer.

Table 2. Context evaluation of piezoresistive materials materials (evaluate cost, manufacturing compatibility etc to decide which sensors to tests)

	Commercial Pressure Sensor	**Velostat**	**ELASTOSIL LR 3162**
Additional information	FlexiForce A201 Sensor 9.53 mm diameter, thickness 0.203 mm	11"x11" (28cm x 28cm) 4mil (0.1mm) thick piece	
Price	$81.70 / 4 sensors	$3.95 each	$40/lb ($0.44/5 grams)
Resisivity		<500 $\Omega.cm$	11Ωcm
Malleable	NO	2D shapes only	Moldable thickness control
Additional equipment or process	Not need	Cutting	Heat curing
Compatible with fabric and silver paint	NOT COMPLETELY	YES	YES
Can be used with any non conductive elements?	YES	YES	YES
Passive feedback	NO	NO	YES
	Carbon nano-tubes(CNTs)	**Capacitive electrodes**	
Additional information			
Price	$.010/gram	$1.25/gram	
Resisivity	1-200 Ωcm	0.010 ohms/square at 1.0 mil	
Malleable	Moldable, resistivity control thickness control	YES thickness control	
Additional equipment or process	Substrate special mixers	NO	
Compatible with fabric and silver paint	Fabric YES, Silver paint NO	YES	
Can be used with any non conductive elements?	YES	NO	
Passive feedback	YES	NO	

4.2.2 Conductive piezoresistive layer. For the piezoresistive layer, an exploration of four elements of easy access were considered. We considered a commercial pressure sensors [21], Velostat [71], capacitive electrodes [66], Carbon based silicone rubber from WAKER [18], and Multi-Walled Carbon Nanotubes [47]. These materials were considered to achieve sensing performance and response, low cost, malleable, comfortable, easy to find, easy to apply, and compatible with the substrate and electrodes. Table 2 shows the summary of the comparison of the elements mentioned such as cost, accessible, comfortable, compatible with the electrodes, and able to deliver the expected performance.

4.2.3 Sensor Evaluation. From the materials comparisons and the geometry selected, the tests use the top three materials ([18, 21, 71]. The capacitive sensing was omitted due to the fact that it only reacts with conductive elements, and one of our requirements was the ability to perform under any circumstances, for example, while using protective gloves. On the other hand, the use of Carbon nanotubes was costly, and it require additional equipment for fabrication.

Four conditions were considered to perform the experiments. 1) Geometry constrained by maximum electrode diameter, which was limited by the minimum hand size supported by the design [10]. 2) Sensor fabrication and placement 3) Sensor must be easy to attach to the polyester substrate. 4) User experience.

We conduct two experiments to determine the optimum sensor, in performance and according to user preferences. We measure pressure vs voltage relationship to evaluate response of the sensors and maximum load limits, and a blind test to evaluate the user experience with the different sensor thickness.

First, We execute the loading test to evaluate the response of the sensor due to different loads, materials, thickness, and with different electrode leads separation. To construct this experiment we leverage on [9] tests. As shown in Figure 2a , we use SHIMPO Digital Force Gauge FGE-50X [65] to apply and control the amount of load applied to the sensors, and a Digital Multimeter Agilent 34401A [15] to obtain the respective voltage

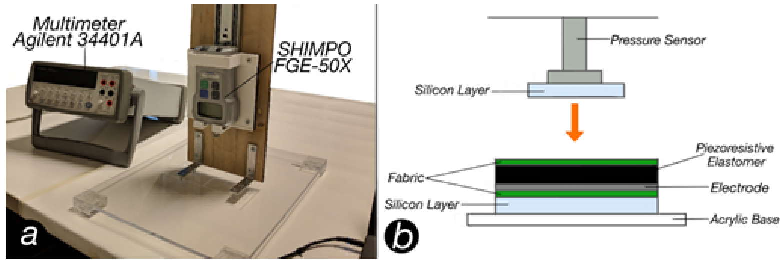

Fig. 2. a) Pressure and Voltage measurements test setup. b) Setup layers for finger pressure simulation

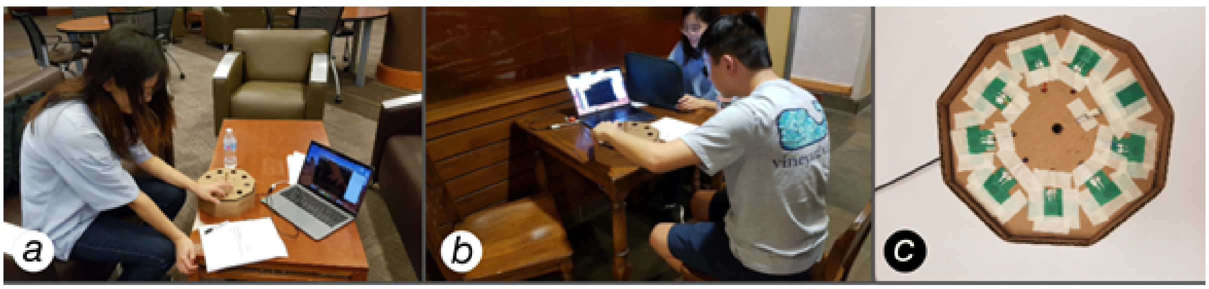

Fig. 3. a) Blind test setup and user testing, b) Blind test users preference, c) User blind test sensor setup

readings with the same loads. To perform this text we build a tester setup that approximates the response of the sensor pressed by a finger. In Figure 2b we can see the layering built to evaluate the sensor response with the soft deformation of a finger. At the end of SHIMPO pressure sensor and the second layer of the base of the sensor a 3mm layer of DragonSkin silicon [17] is deposited. We range the value of the load between 0.3 pounds to 4.3 pounds. The upper range of the sensors was defined based on their response to the load magnitude and due to previous research in thumb against index finger forces[14, 80]. The test consists on applying discrete controlled amounts of pressure over the fabricated sensors. The sensors fabricated were using electrodes with interdigital separations of 0.65mm related to a pin standard thickness. Additionally 0.5 mm, and 1mm separations were tested, which were selected to obtain an evaluation of upper and a lower level of separation. The test was performed between a commercial pressure sensor, Velostat and the carbon based elastomer using the mentioned interdigitated eledtrode. Thanks to the carbon filled elastomer properties, we add different thickness for the piezoresistive layer. The results shown in the Figure 4. correspond to the tests made for the main sizes of sensors .

For the blind test, the sensors were divided in nine different versions (1mm, 2mm, 3mm, 0.1mm, 0.3mm, 0.4mm, 0.6mm) using 0.65mm separation between conductive leads, selected from previous tests, and were distributed in a radius (Figure 3c). Twelve random participants were asked to interact with the sensors one by one. After each interaction they were asked to give comments and to evaluate the sensors. To end the experiment, the users were asked to touch the sensors in any order and to rank the top three of their choice. Figure 5 shows the sensor selection made by the users

4.2.4 Results. Across the twelve users tested for the sensor thickness and performance selection, we express in Figure 4 the results of the sensors using 0.65mm electrodes. Figure 4 shows the the valid range of values. These values represent if the user can have control over the pressure. Velostat sensor and the 3mm thickness sensor present an almost constant output, which means that the user is not going to be able to control the output of its

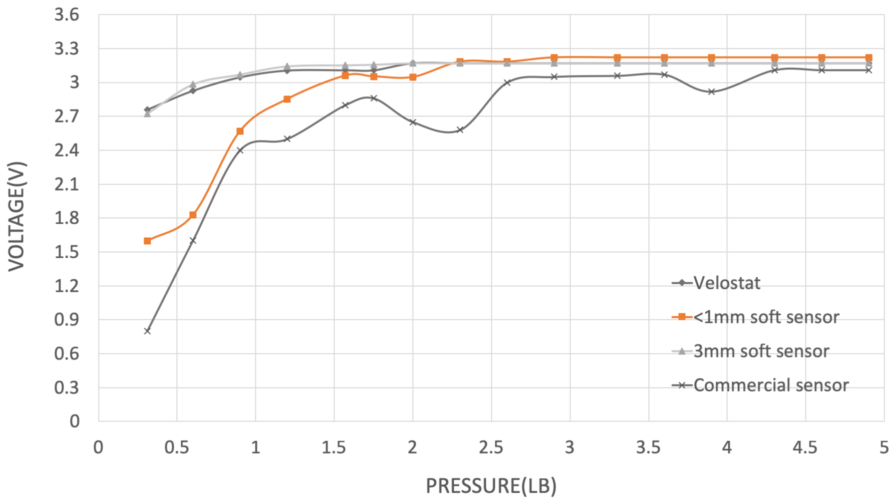

Fig. 4. Pressure vs Voltage from Loading Test (0.65mm electrode)

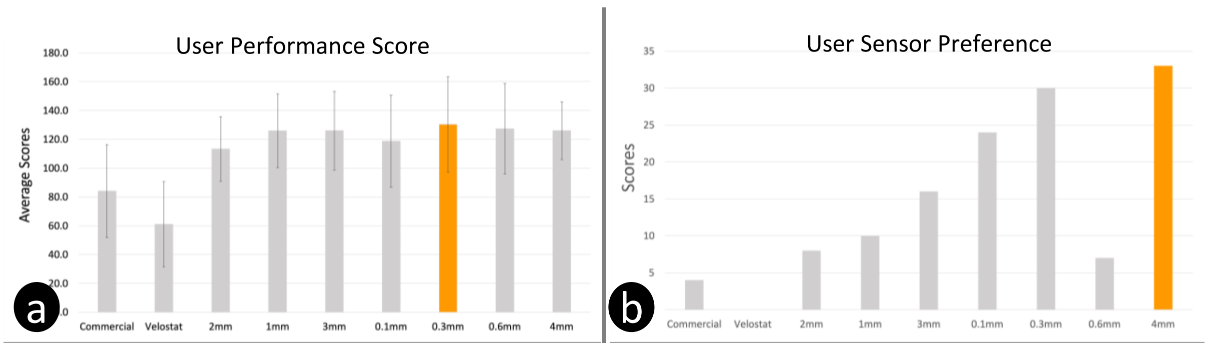

Fig. 5. a) User sensor preferences. b) User performance test results

pressure. On the other hand, the commercial sensor and the carbol elastomer sensor of less than 1mm thickness present a controllable range of pressure until two pounds of pressure. 83% of participants mentioned that the range between 0.3mm and 0.4mm provides the most comfortable experience, and 50% chose the sensor of 0.1 mm as the second option. It is worth mentioning that commercial sensor and Velostat with 25% and 42% of the votes respectively were the least desired sensor experience.

5 GLOVE DESIGN AND FABRICATION

In this section, we describe the overall steps to achieve the fabrication of ControllAR, a personalized low-profile hand wearable for interactions with Augmented Reality. By integrating all the previous material selected, we start describing the distribution of sensors and electronics on the hand, which was based on hand interactions, anatomical reachability, and anthropometric measurements. Next, the description of the parametrization design tool, and lastly the complete fabrication workflow.

Fig. 6. Common way to hold controllers

5.1 Sensor and electronics distribution

Three parameters were used to define the design of ControllAR. Interaction types, hand size and shapes, and common input methods. The information extracted from the analysis of these three parameters was used to define the final positions of the sensor on the glove. We consider first the basic interactions for users to navigate within digital devices (phones, tablets, computers, game consoles, and now Virtual and Augmented reality). The most common interactions are click, select, swipe, scroll, and navigate on the display. These basic interaction modalities are the ones that AR head mounted devices struggle the most. Second, we did an empirical analysis of common hand controllers used with interactive devices. We extract the common points between all the controllers, and as shown in Figure 6 all the controllers share the hand position. The holding shape and the ergonomic position of the hand while holding the devices present a initial guideline to build ControllAR. [22, 57].

Finally, we consider how hand anthropometrics affects hand wearable design. This provides the physical and positional constraints for the hand wearable, and the necessary guidelines and standard measurements for our design [57]. As shown in Figure 7, the triangle pink zones on the hands represent the zones that have minimal amount of movement when hand interactions are performed [24, 57], hence, those zones become potential areas for sensor placement. Zones marked with green elipses highlight areas that present bending, and the blue circle describes a zone that modifies its shape when the user is using the hands. Hands present twenty different measurements compared between people in antrhopometric data[57]. All this measurements present a variable to be considered for the design. This makes it very complicated to create a glove that creates a one size that fits all.

5.1.1 Hand Parameters Selection. Considering the anthropometric measurements of a hand [57], we notice that a personalized e-glove becomes very complicated and time consuming to design and fabricate, and it is problematic to find a glove that completely fits your hand measurements. Different factors of the standard gloves such as size, uncomfortable to wear and flex, limited range of motion, and constrained interactions with the environment. All this hand characteristics, are variables between different people, for example the finger length can be the same between two people, but the phalanges measurements may be different.

We needed to simplify the design process. While satisfying the constraints from the previous sections, and the interactions expected. To design ControllAR, we define a series of parameters that helped to reduce the measurement constraints and obtain a more generalized pattern for fabrication. First, to overcome the finger length constraint, the glove should be open on the finger tips, flexing points should be adjustable to each user, hand palm should should be free for interactions with other objects, electronics should be located on areas of minimum movement, fingers accessible to interact with keyboards and phones, comfortable hand movements to interact with the input sensors, provide all the required interactions, be low profile and be attached close to the

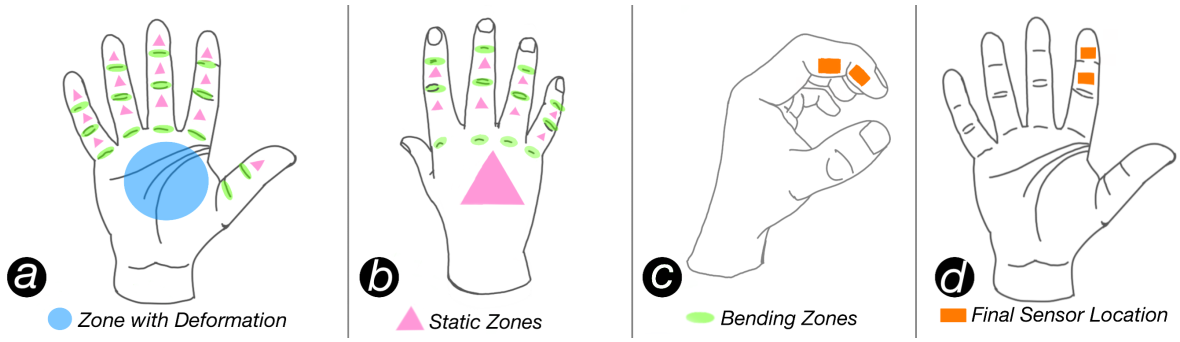

Fig. 7. Hand critical zones and final sensor locations

Table 3. Minimum number of sensors needed to create the interaction

	Click	Select (hold)	Scroll	Swipe	Navigation (up, down, left, right)
Sensors needed	1	1	2	2	4

hand, so it is not obtrusive in the activities. To simplify the design according to our needs, we start to define the number of interactions supported.Then, for our 5 types of interaction, the maximum number of sensors needed to perform an action is four as shown in Table 3. In case, each interaction was assigned a single sensor, the result would be a bulky 10 sensor wearable device. The user will have to wear a bulky full hand glove, memorize the input for ten sensors, and whewthey are located on the glove. ControllAR uses four sensors to achieve all ten input modalities with a series of simple combinations of the sensors. As shown in Figure 7 the distribution for the four sensors over only the index finger reduces our design anthropomentric constraints to only three (index finger length, hand breadth, hand thickness). This number of parameters reduce the size, complexity, and material required.

5.1.2 Sensor fabrication. To fabricate the sensor, we start mixing two parts of ELASTOSIL LR 3162[18] on one to one ratio by hand. Due to the black color of the carbon based elastomer, it is recommended to mix for three to ten minutes depending on the volume of the elastomer, to ensure a perfect mix. For 4 electrodes we use two grams of each part (4g total), and it was mixed for three minutes. We molded the elastomer with 3D printed mold fabricated using ABS-P430 material [4] , and a MOJO 3D printer. This thermoplastic for 3D printer was selected because it can handle the curing time required for the elastomer. We tested with other plastics like PLA [69] that failed to handle the temperature for the curing time required. The elastomer thickness on the contact area was 300 microns (Figure 8). We apply the elastomer into the desired rounded molds using a palette or a knife, and then place a layer of nylon fabric over to attach the substrate to the elastomer while preheating a toaster oven (Mainstays 4-Slice Toaster Oven) to 65 C. After preheating the oven, we place the mold with the elastomer for 12 minutes in the oven for curing. Remove from the oven and wait until it cools down before manipulating. Once the material is cold, remove from the mold. As a note, if after exposing the elastomer to the respective curing time, it is still soft and not retaining its shape when pressed, it means that the mixing in not sufficent. On the other hand, if the elastomer is stuck in the mold, means that the curing time was excessive for that thickness. This molding processes using 3D printer provide an additional benefit. Due to the layering fabrication process that 3D printers use, the finished surface is not completely smooth. The lines left on the surface by the filament

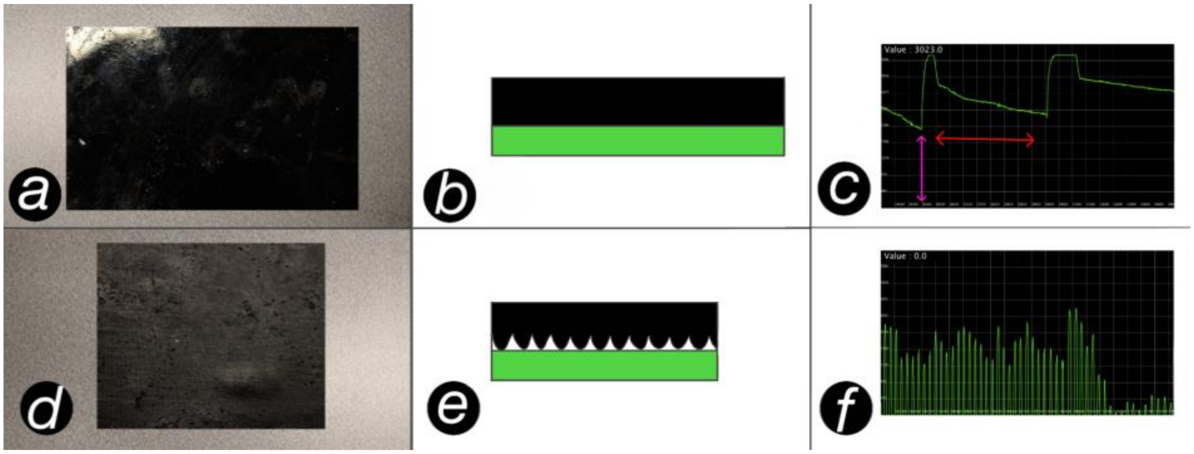

Fig. 8. a) Sensor with original fabrication method, b) Cut view illustration of original sensor, c) original sensor response signal to pressure, d) Improved sensor fabrication, e) Illustration of the improved sensor fabrication with the pattern provided by the mold , f) Improved response signal to pressure.

creates a zig-zag pattern ou our sensor. This pattern reduc the settling time because the area of contact between the elastomer and the electrodes was reduced. Therefore, after each pressing the sensor recovering time is not registered by the measuring system. The sensor presents a better performance, however, it is not a constant behaviour. The stickiness characteristic of the material keeps affecting the response of the sensror To achieve an even better performance , before we assemble the sensor, we sand lightly (using a 3M Sandblaster Pro (320) sandpaper) the patterned surface of the elastomer until no shiny sections are left. This was sufficient to obtain a sensor with the required characteristics.

5.2 Sensing Approach and Data Processing

To enable users to replicate a functional e-glove with the interaction capabilities, we include in the design all the needed for it such as sensors, signal conditioning, and the sensor data processing.

5.2.1 Interface and Data Collection. ControllAR includes a microcontroller ESP32-WROOM-32 from ESPRESSIF Systems on board of the hand, which includes Analog inputs and WI-FI connection. The pressure sensor raw values are read using four 12bits resolution from the on-board microcontroller and a voltage divider. The data obtained is then processed on-board and organized to recognize the user input interactions and then transmitted to the AR head mounted device. The advantage is that ControllAR presents the interface for the data processing on board of the e-glove and with only 11 grams even less than the HoloLens clicker (17gr)

The data processing recognizes the users input and generates a command that later is interpreted by the AR application as a click. hold, swipe, and scroll. These interactions are possible despite the limited number of sensors and the type of sensors. The interpretation of the analog values was implemented using a set-point. The set-point was assigned after an evaluation of the blind test analysis and the user studies pressure values. With this, the users can simply wear the glove and interact with it, avoiding the calibration for each one.

5.2.2 Connections. The mix of fabric, silver ink as a conductor, and rigid electronics is a challenge. We avoid sewing and soldering to achieve highly accessibility fabrication for end users. Hence, to attach these elements to each other we paint the ink over the fabric and heat cure it. For the solid electronics we use z-conductive tape

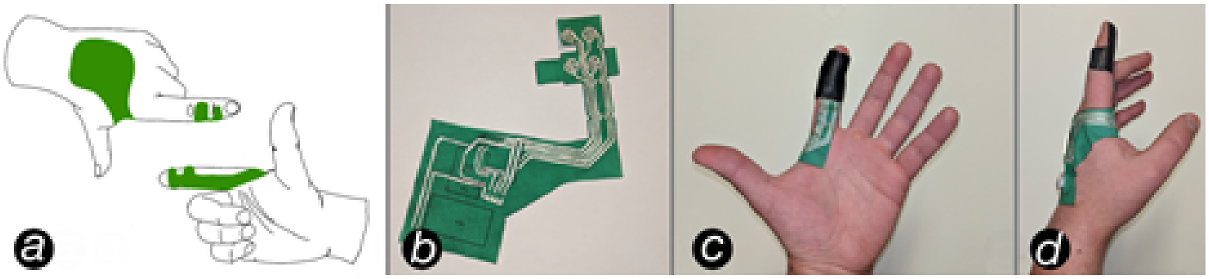

Fig. 9. a) Final form factor design sketch, b) Final design printed on fabric, c) and d) ControllAR om hand

Fig. 10. User interface for phalanges input

that allows a connection with the painted points on the fabric. Electronics were placed on zones with minimal movements when performing activities with hands. However, to avoid any unexpected or undesired movements, the edges of the microcontroller are glued to the fabric. In the case of the swipe and scroll interactions, we record two values, and we store them for a fraction of time before making the comparison to determine the outcome. This fraction of time was set considering the reaction time that the users need. They perceive it as a immediate reaction to their command.

5.3 Wearable Parametrization

The main constraint to create a personalized glove and even harder a personalized electronic glove, is the hand size for each one of the users. This provides a double constraint, knowledge about electronics and garments fabrication, and skills on how to integrate both areas into a functional glove that will provide with the desired output with no help. Therefore, parametrizing hand measurements becomes a core function of this goal, and create an e-glove that can be fabricated with a method that can fit each user. For this, ControllAR developed an application that parametrizes finger measurements and ensures that the glove will fit each user with just a simple input of user's measurements. The interface has been developed in Qt framework [59]. This interface shows graphically what measurements are needed, and where those values need to be placed. First the user measures the phalanx lengths of their index finger, and inserts the corresponding values into the interface input boxes as shown on Figure 10.

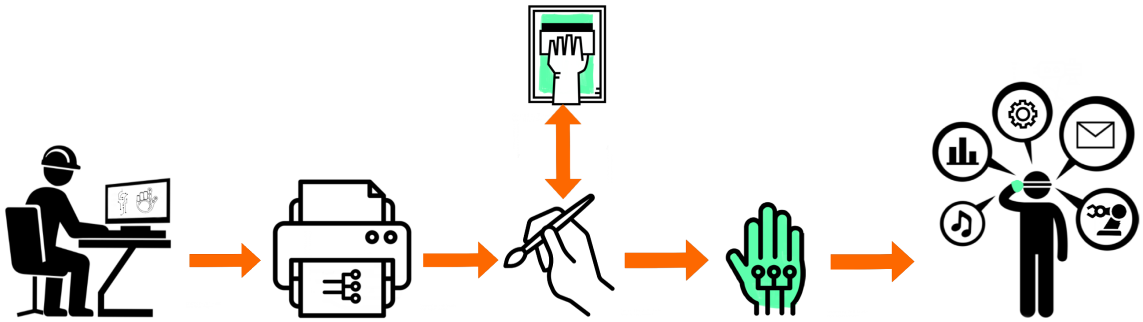

Fig. 11. Fabrication workflow with a screen printing alternative

After the measurements are inserted and the user press **CREATE** on the interface, a rendering of the circuit, made on OpenGL [51] will be displayed as a visual feedback for the user. Additionally to the circuit render on the display, a DXF file is also generated as an output file from the system. This file is used as a template for the fabrication. The interface uses the index finger phalanx lengths to parametrize the electronic circuit, the location of the sensors and the flexing points on the user hand. This parametrization is made with respect to the measurement of the first phalange that starts at the base of the index finger. Now, the user can use the template to transfer the electronic circuit into the nylon substrate by hand painting or by screen printing with silver ink. This template is exactly the size of the users hands, if s/he input the right measurements.

5.4 Fabrication Workflow

ControllAR presents an optimized workflow for the fabrication of a wearable e-glove, which can be personalized for each user hand size. After the elements analysis and selection, a combination of steps created a workflow that allows users to be able to fabricate low cost, low profile, easy to fabricate, personal size hand wearable. The fabrication is distributed in 4 different layers as shown in Figure 12

First, the user measure the three phlanges of their index finger and write it in ControllAR sizing application. Then the software generates the new glove template with the correct dimensions to fit the user's hand.

The parametric glove and circuit design obtained from the software has to be reproduced onto the fabric substrate. This can either be done by screen printing the circuit onto the fabric, or simply by hand painting with a brush, using CI-1036 silver ink[66]. For hand painting, the user can print the generated template directly on to the nylon fabric. And for the screen printing process the pattern has to be printed over a transparent film that will be used to generate the screen pattern for the process, in both cases using a regular laser printer. These techniques allow to obtain a slim and thin design.

Screen printing as well as inkjet printing has been very useful for embedding circuits on fabrics [31, 49, 62]. We decided to fabricate ControllAR using hand painting but also providing the user the possibility to use screen printing. Inkjet printing method was not considered for this project because the other two methods requires less modifications and equipment Hand painting the circuit is even cheaper and more convenient, but time consuming in terms of repetability. After the conductive ink is on the substrate, it needs a 5 minutes heat curing under 65°C.

While the curing is happening, we can create the conductive layer for the pressure sensors. Using the conductive rubber which provides us with the piezoresistive characteristic, we start by mixing part A and Part B of ELASTOSIL LR 3162 in 1:1 ratio as indicated by manufacturer [18]. To do this, we mix the two parts by hand for three minutes for our case (three to ten minutes is recommended). Then we prepare the mold with the elastomer and the fabric substrate to create the piezoresistive layer and prepare for the curing time.

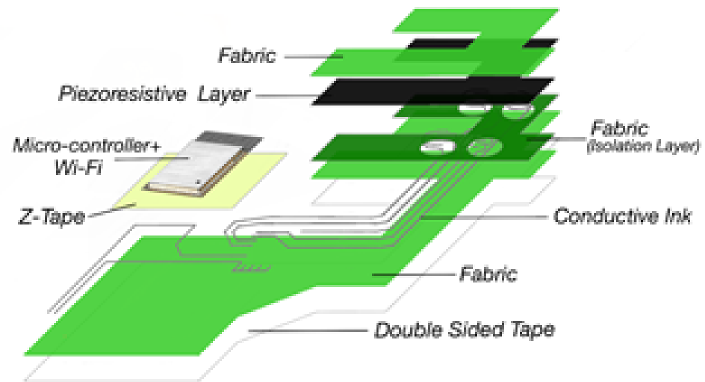

Fig. 12. Glove Layers Adhesive layer, nylon substrate layer, circuit layer, sensor division layer, elastomer layer, nylon layer

Remove the circuit printed on the nylon substrate from the oven and preheat the oven to 65°C. After preheating the oven, place the mold with the elastomer, and the nylon fabric for twelve minutes for curing. Once the curing time has ended, let the mold cool down, remove from the oven, remove the elastomer from the mold, and finally sand the elastomer to remove the shinny surface to ensure desired performance and surface characteristics.

Finally, to finish the e-glove, we proceed to layer a Z-conductive double sided tape [2] over the zones where the electronic elements are assigned. Then,we place the electronic elements and second layer of nylon to complete the circuit, paint the edges of the connections between pins and Z-tape to ensure the connection, and cure the e-glove for 5 more minutes. After the curing, we assemble the e-glove with the elastomer layer. Finally, we place the glove over 3M 1509 double sided tape [3] to use it as a method to attach the glove to the hand. This 3M 1509 tape is recommended because it can be worn for several days with the same tape. Other type of tapes were tested for this purpose such as MIILYE Dress Body double sided tape, and 3M 1522 clear tape [1, 43],which are as good as the recommended, but they can only sustain a day.

Our fabrication process aids in making the glove minimalist and unobtrusive. The use of conductive paint and z-axis conductive tape to make flexible, wire-free electronic circuits on a fabric substrate greatly reduces the size as well as increases comfort of the wearable and makes the fabrication possible for any user.

As seen in Figure 13, the four sensors distributed over the index finger. We can observe the distribution of the sensors on the hand and how the interactions have to be performed by the users. The interaction modes were distributed on the index finger using the four sensors, so the users can use the most common and repeated interaction modes such as click, long press, scroll up and down, and swipe left or right.

6 SYSTEM EVALUATION

Augmented reality interactions require precise and simple movements. What makes ControllAR special is 1) the fast input modality for navigation. 2) intuitive controls. 3) the possibility to execute activities in limited area, and 4) it is not obtrusive. To evaluate ControllAR, we create a series of experiments to compare it to current interaction modes. 9 voluntary participants (3 female, 6 male) were recruited to test the three input modalities: 1) Gaze + hand gestures, 2) Gaze + clicker, 3) ControllAR to interact with AR head mounted devices. The interaction modes were tested in randomized order to make sure that all the input modes have equal opportunities.

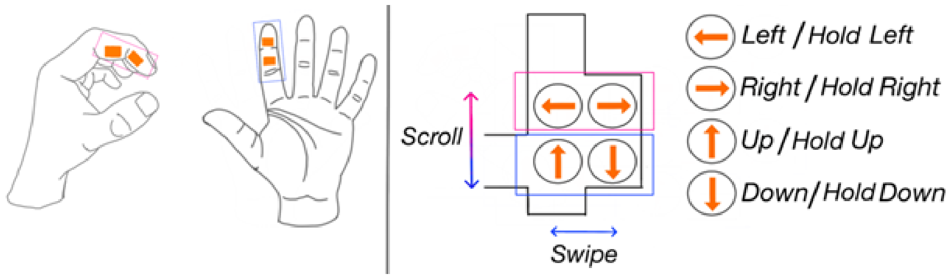

Fig. 13. ControllAR input modalities description

In every test, the users were ask to input two words with a holographic keyboard using the three input modes. This test evaluates precision, input speed, comfortability, user preference, errors made, and time to recover from the errors between the three methods. The tests were divided in two main scenarios. 1) static sitting scenario, and 2) reduced space scenario. First, the users were asked to type 2 words in a calm controlled environment. This part of the test was repeated with all the input modalities, in a random order. Test two was intended to represent a real live scenario. It simulates crowded area or a space constrained area such as an elevator, or working under a hood.

For the second part of the evaluation, the elevator experiment, the users had to type the same two words in a small area that limit their movements. The users were placed in a corner with a vertical cardboard placed 30cm in front of their chest simulating people or other objects, for example, under a vehicle while repairing.

To evaluate the study, we record videos of the users view point with the head mounted devices, external video, questionnaire after each interaction mode, and a questionnaire after all the interaction modes were completed. We collected data from the videos and questionnaires to evaluate users performance under the AR input modalities.

Before any experiment the users were exposed to a training session and practice with each one input modes. Additionally, after each set of evaluations with each modality, users were asked to answer a set of questions and at the end of the tests the users rank the three input modalities.

6.1 Results and Discussion

Figure 14b presents the precision for each input mode. As we expect, the use of an input mode with more control for the users increase the accuracy in the interactions. ControllAR provides an accuracy of 82.4% (ave errors=2.11, SD=0.81) while gesture interactions present a 33.3% (avg errors=8.00, SD=2.70), and the clicker a 44.9% (avg errors =6.61, SD=1.68). The lowest precision measured, was for the gesture + gazing interaction, which can be explained by the fact that a gesture has to be performed while making head movements to point the targets. Two main events affect the gesture based input, the fact that needs head movements for pointing and that it depends on a perfect tracking of the gesture to activate the input while the head is moving with the tracker. Something similar happens with the Clicker + gazing, which the advantage of a more solid controller is affected by the head gazing for pointing the targets.

This precision results can also be analyzed from the time required to complete a task. This time depends on how precise the interaction mode is, how fast you can move between targets, and how fast you can recover from errors. Two tasks of the evaluation were timed and the results are shown in Figure 14a. Participants time to complete the task were very different between input modalities. It took 84.94sec (SD=29) for the gesture, and around half of that time for clicker and ControllAR, 42.49sec (SD=8.68) and 47.42sec (SD=4.53) respectively. This demonstrates that the fastest input mode is the clicker + gaze. This result was not expected, however, it clearly describes the events. Gazing movements are faster than ControllAR input modalities. ControllAR present discrete

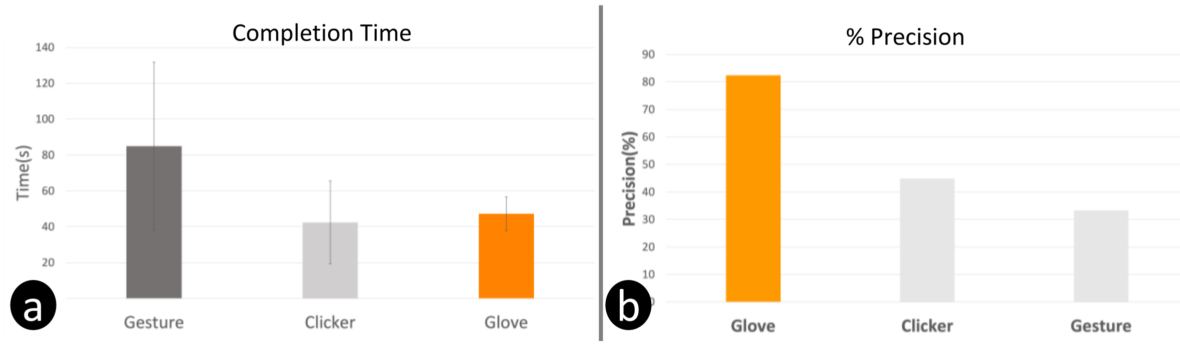

Fig. 14. a)Time completion, b) % Precision

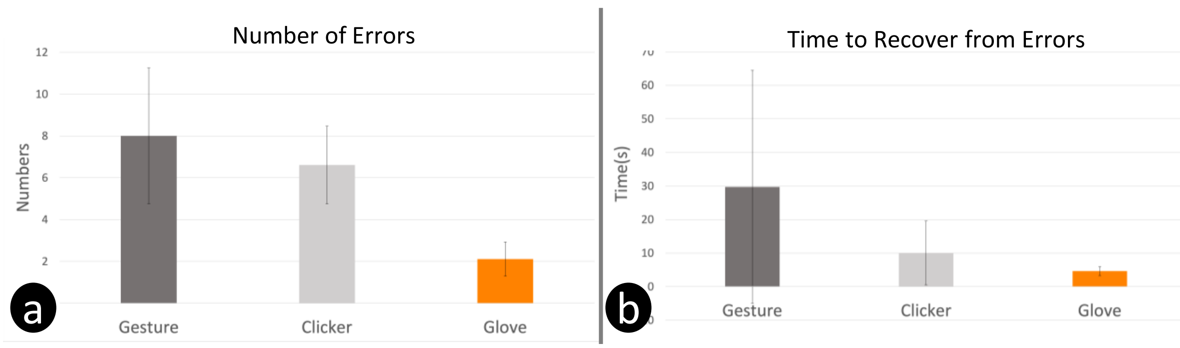

Fig. 15. a) Error made during the user studies b) Time to recover from the errors

inputs to generate discrete actions, while gazing is a more dynamic interaction. Requires less time to move from one option to another and make selections. A disadvantage of this speed is that it comes with sacrificing of the precision. For ControllAR, precision is first, the advantage comes to the point that the high precision obtained makes the method relatively slower, but at the same time makes the completion time of the actions more uniform between users. This effect is also reflected in the time the users take to recover from a mistake. Because the users make less mistakes, the error recovery also is reduced, which increments the amount of time that the user is having more accurate interactions (Figure 14c).

Additionally, as an additional feature, we compared the weight of the clicker and the glove. With the result that the clicker weights 17grams while ControllAR weights 11grams, and this last one is distributed around the hand, and leaves the hands free for other activities that not necessarily involve AR. With the type of input that ControllAR presents, even the size of the elements on the AR scene can be reduced because it presents a more precise modality allowing users to dismiss the size of the targets.

User feedback During the evaluations, we ask participants to provide their experience with the three input modalities. They commented about their preference of an element that allows discrete interactions, and the fact that it is soft. They also mentioned that they love the idea of not having wires. As suggestions, they recommended to add additional connectivity to other devices like smart watches and phones. They asked, if it can be washable and fancier, so it can last longer and can be worn with different outfits and occasions. Participants provide suggestions about applications. They mentioned, that can be worn in factories, real life interactive games.

Fig. 16. a) Quadcopter assembly, b) Cooking scenario

7 APPLICATION EXAMPLES

To showcase ControllAR and illustrate practical applications, we created four scenarios. Demonstrating the capabilities and interaction modes of our e-glove. This applications provide understanding of ControllAR as an unobtrusive, easy to use, fast interaction, intuitive, and comfortable glove in different settings.

7.1 Assembly instructions and Transfer learning

Inspired by all those assembly and instructional based toys [35, 39] and many AR instructional videos [72, 76, 77], we develop an application that guide users in the assembly of a quadcopter using animated holograms. This instructions explain step by step the sequence to assemble it from the beginning. The user is able to control the sequence, go back if a step needs to be repeated, play a small simulation of how to place a part. All this control is allowed by the use of the interaction modes provided by ControllAR, which allows the user to interact with the holographic scenario while manipulating the parts to be assembled and without any obstruction in a simple way, and without needing to gaze to point to the objects.

7.2 Everyday activities like Cooking

Inspired by everyday activities and with the purpose to encourage the immersion of AR head mounted devices into our every day, we develop a cooking application that can replace cookbooks, and video instructions. Previously, cooking has been implemented by using cameras on top of counter tops [6, 68]. This scenario allows the user to create its own salad while the user interacts with the cooking hologram experience and with knifes and bowls. We demonstrate how ControllAR facilitates the interaction with the scenes by clicking, long pressing, and swiping while it performs normally the actions on the real world without leaving the tools to interact.

Fig. 17. Rescue Animal Catcher App

SS.

Fig. 18. Keyboard Input and menu navigation

7.3 Dynamic scenarios in open environments

The immersion of AR applications on phones and games like Pokemon Go, that allow users to enhance reality with distraction activities, encourages this application. This animal catcher application, demonstrates how ControllAR and its non obtrusive and natural interactions allow users to interact with holograms while walking in an open space. This is another form how augmented reality can be encouraged to be used in everyday activities without obstructing our normal activities or limiting our hands interactions with the world.

7.4 Menu interaction for fast access and keyboard inputs.

As an important feature for AR head mounted devices is the menu navigation and text input. This kind of application has been approached [] to try to solve a troublesome system that is currently implemented. To test our system and to implement a set of interactions that allow users interact naturally and easy with this environment, we develop a simple qwerty holographic keyboard that allowed us to test ControllAR. This scenario is crucial because menus and text input are used to access any other application inside the AR environment. This applies menu navigation, long press, click, and swipe modes that provides ControllAR to interact with the environment.

8 LIMITATIONS AND FUTURE WORK

8.1 Scalability

During the evaluations and wearability tests we could detect that ControllAR had a constraint with the minimum hand size requirement perfectly fit all users. Hands sizes with hand breadth smaller than 5[cm], do not provide enough area to locate the electronics in current settings. This measurements affect mostly to children under 6 years old [10]. Despite head mounted devices cannot perfectly fit to them, we would like in the future to provide a personalized hand glove to all the users. This can be solved by creating more parameters on the glove.

8.2 Parametrization APP

The current parametrization tool consider limited number of parameters, based on most used interactions. Future versions will consider full control over the parameters of a partial or full hand glove, and control over the size and number of electronic elements included. Additionally, this app can be expanded to a full hand scan that allows to manage the shape of the desired glove. Additionally, It is going to be explored the possibility to increase the glove capabilities to enhance the current AR experience.

8.3 Fabrication

Our approach provides a no soldering and no sewing fabrication of electronic hand wearable, which provide users with no additional skills. We focus on an affordable personalized fabrication, which can be expanded and improved using laser cutters, 3D printing techniques, and other paint transfer techniques. This will make the fabrication process faster, easier, and can allow improvements in glove shapes. Additionally, an exploration on electronic elements protection against water, dust, and wear, to extend the lifespan of the e-gloves.

9 CONCLUSIONS

We present ControllAR, a parametric size, low profile, and interactive glove designed to enhance and encourage the use and interaction with Augmented Reality head mounted devices. It provides a sizing software interface, simple fabrication workflow with no soldering or sewing needed, and a pressure sensor based in a piezoresistive elastomer material. We conduct studies in three scenarios: 1) to evaluate the sensor response under the proposed fabrication improvement, 2) a user study of sensing guidelines for sensor size and response, and 3) a comparison evaluation with current most common input modes for Augmented Reality to evaluate the interaction improvements. We demonstrate that our e-glove can be used to interact with AR and improve the experience, precision, and comfortability with no obstructions, we obtain a soft pressure sensor response improvement in terms of settling time and speed response, and finally, the implemented results in the e-glove from the guidelines test. We hope that this work will encourage the use of Augmented reality in every day scenarios, promote future development of applications using our fabrication approach and create more input metaphors.

ACKNOWLEDGMENTS

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