6th IEEE RAS/EMBS International Conference on
Biomedical Robotics and Biomechatronics (BioRob)
June 26-29, 2016. UTown, Singapore

Design and Preliminary Evaluation of Haptic Devices for Upper Limb Stimulation and Integration within a Virtual Reality Cave

Francesca Sorgini[1] *Student Member, IEEE*, Rohan Ghosh[2] *Student Member, IEEE*, Justus F. Huebotter[2], Renato Caliò[2], Carmen Galassi[3], Calogero Maria Oddo[1,†], *Member, IEEE* and Sunil L. Kukreja[2,†] *Senior Member, IEEE*

***Abstract*— During the last decade significant advances have been made in vibrotactile actuator design that are leading to the development of novel haptic technologies. Similarly, important innovations have been made in the area of virtual reality for scene rendering and user tracking. However, the integration of these technologies has not been well explored.**

In this paper, we outline a broad design philosophy and integration plan of these tools. In addition, we give an overview of applications for such a cohesive set of technologies. Preliminary results are provided to demonstrate their critical importance and future widespread use.

I. INTRODUCTION

The transmission of force perception from a physical or virtual object to an operator who may be in a remote location has significance in virtual reality and telerobotic operation [1]. Immersive virtual reality (VR) has the ability to envelope an operator into a simulated world with the effect of altering the user's perception of reality [2]. The Occlus Rift and Google Glass (Google Cardboard) have the advantage of relative low cost but with limited functionality [3]. The immersive capability of these devices is encompassing but they have limitations. The restrictions are due to safety concerns since the user cannot see outside the goggles, creating trip and fall hazards.

A cave automatic virtual environment (CAVE) is an alternative immersive environment [4]. The CAVE uses projectors to create a virtual world on three to six walls of a room-sized cube. This approach avoids safety issues related to wearing goggles.

Fig. 1 shows our CAVE system. A user is able to step into this space to experience a virtual environment. Optical tracking cameras are used to track and understand the operator's movements or gestures. The gesture kinematics are transmitted to a real world robot for tasks such as advanced control and manipulation.

Fig. 1. Four-wall CAVE system with optical tracking cameras.

A. Touch Augmentation

Tactile augmentation combines touch of the real environment with synthetic touch stimuli, which serves to enhance haptic perception of an object [5]. This fused approach has the promise to provide a more realistic tactile perception of an object with the ability to alter its characteristics. Traditionally, haptic augmentation and feedback have been used for training and rehabilitation purposes, e.g. surgical training [6], [7] and impairments following stroke [8], [9]. Inspiration from these approaches has lead to the development of augmented haptic methods to palpate tissue for tumor exploration during surgery [10] and object shape representation and determining its pose [11].

B. Visual Augmentation

Visual search is an important task for target pursuit in many applications. In an augmented reality (AR) environment a user's ability to search a scene can be augmented to help him/her rapidly assess the setting through the use of virtual cues [12].

C. Integrated Platform

The state-of-the-art in augmented reality is primarily limited to visual augmentation and basic haptic feedback. To the best of the authors knowledge, the integration and development of technologies to enable a virtual reality CAVE platform to be used as a master-slave system with augmented tools such as vision, touch and gesture recognition has not

This research is funded by the Ministry of Defence, Singapore, Grant Number: R-719-004-102-232.

This study was funded in part by the Italian Ministry for Education, Universities and Research, within the Technological Clusters Initiative, project 1 of the Intelligent Factory Cluster (grant number CTN01_00163_148175).

[1]Francesca Sorgini, Renato Caliò and Calogero Maria Oddo are with the Scuola Superiore Sant'Anna (SSSA), The BioRobotics Institute, Pisa, Italy. oddoc@sssup.it

[2]Rohan Ghosh, Justus F. Huebotter and Sunil Kukreja are with the Singapore Institute for Neurotechnology (SINAPSE), National University of Singapore (NUS), Singapore sunilkukreja.sinapse@gmail.com

[3]Carmen Galassi is with Consiglio Nazionale delle Ricerche (CNR), ISTEC, Faenza, Italy. carmen.galassi@istec.cnr.it

[†]Share senior authorship based on equal contribution.

been implemented yet. In this paper, we describe our design principles, which include haptic and visual feedback and gesture identification within a virtual field.

The paper is concerned with broad design principles and philosophy of a master-slave system for performing advanced human augmentation with a virtual environment for applications such as telerobotics. In the remainder of this paper we describe our conceptual system and present results for two subcomponents; namely, haptic feedback for hand and wrist augmentation. System level integration and evaluation will be presented in future studies, as a follow-up of the present preliminary assessment of these individual subcomponents.

The organization of this paper is as follows. Section II provides a description of the overall system and its components. Section III discusses the haptic and visual feedback technologies we currently have under development. Gesture recognition is described in section IV. Our experimental paradigm and materials used to investigate haptic feedback are given in Section V while the results of the studies are provided in Section VI. Section VII provides concluding remarks and future directions.

II. System Overview

Human-machine interface (HMI) is the integration of a human controller with a machine. Typically, switches, keypads and touch screens are used as the physical part of a HMI. However, the availability of virtual reality systems such as the CAVE integrated with haptic and visual feedback and gesture recognition has made robust and intuitive HMI a possibility [13].

Figure 2 shows a conceptual sketch of the system. The goal of this project is to develop an AR/VR room for experimenting advanced object recognition and manipulation algorithms suitable for extreme surroundings to control remote robots or vehicles for search-rescue and rehabilitation. This platform will allow a user to remotely operate a robot/vehicle using natural and intuitive body motions (e.g. movement of upper limbs, natural hand gestures, etc.) with high flexibility, accuracy, and low latency. We are in the preliminary stages of developing haptic feedback technology to be used with this platform.

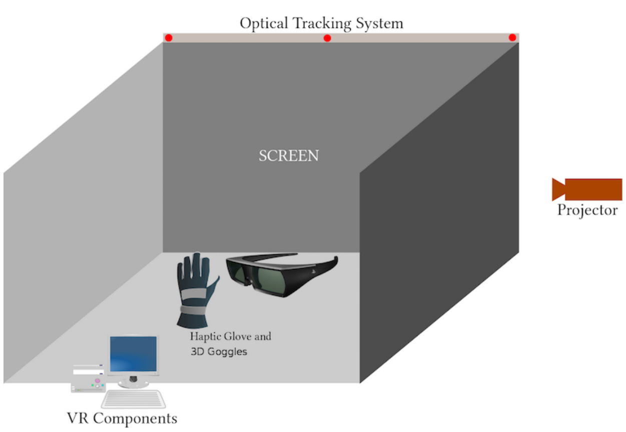


Fig. 2. General schematic overview of our advanced HMI system. General components are: (a) CAVE, (b) haptic gloves, (c) optical tracking cameras and (d) computer hardware and software for visual and haptic feedback and gesture recognition.

Assuming robots or other devices are equipped with advanced high-density e-skin, tactile information generated from the interaction between robot/vehicle and physical objects will be transmitted to the operator inside the VR room through wireless communication channels. Similarly, we will enable haptic capabilities for interactions with avatars within this environment.

III. Haptic and Visual Feedback

A. Haptic Feedback

Force is one of the first sensory events felt by humans. However, it is challenging to replicate and render force feedback accurately, particularly in confined spaces such as surgery. In addition, force feedback is faced with robustness and control issues leading to high costs [14].

For haptic rendering, we use a sensory substitution approach, which transforms pressure characteristics to vibratory stimuli. This design approach reduces size and bulkiness of a haptic device [15]. However, a vibrotactile feedback strategy is limited by actuator size and a desire for flexibility, which restricts the number of actuation (sensing) points. This reduces spatial precision and range of stimulus presentation. Therefore, we aspire to develop an advanced high-density vibrotactile glove that is exceptionally compact and formfitting, permitting more precise localization, possibly leading to a wide range of stimuli rendering. The tactile sensing glove will be used to remotely assess an object's properties, possibly leading to recognition in some applications. We will also investigate whether the current level of precision allows the representation of complex tactile perception in an intuitive manner.

B. Visual Feedback

Typically, virtual cues are presented in an overt manner and results in excessive visual clutter [16]. The clutter leads to degradation in search ability [17]. In addition, explicit visual cueing may have the unintended consequence of reducing a user's concentration on a specific task that may supersede the cued task. For this reason, alternatives to explicit cueing are being explored. The use of subtle (lightweight) cues is an emerging area that often relies on heuristic approaches for stimulus presentation and remains largely unexplored [18].

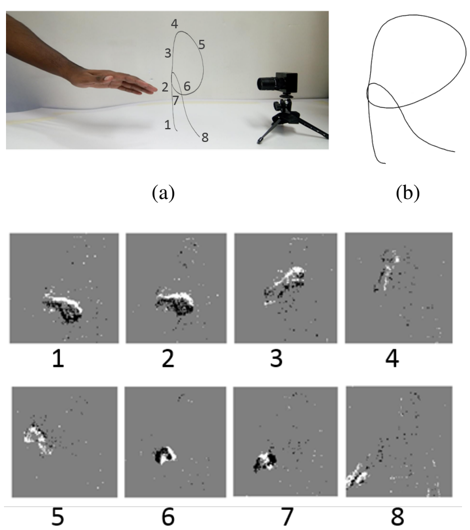
IV. Gesture Recognition

Gesture recognition is concerned with the identification of a pattern from data. It is often characterized by short spurts of activity with an underlying meaning and intention. Algorithms developed to recognize gestures need to be capable of processing large amounts of data in real-time and be precise [19], [20].

The patterns identified need to be mapped from the user coordinates to a robot operating outside the master environment. The mapping needs to be highly accurate and transmitted with minimal latency.

To accomplish the task of mapping an optical-tracking human motion capture method is under development. Optical markers are attached on a user's hands, upper-limbs and head to track motion and enable control of a remote robot. A marker-based system alleviates the significant computational burden of marker-less methods. In addition, a platform with multiple cameras minimizes occlusion and permits marker detection robustly. The proposed method will solve problems related to unnatural hand and arm motions required by mechanical device (e.g. joysticks) based motion capture techniques and concerns related to human body part occlusion.

However, a consequence to using multiple optical trackers is the high computational load due to continuous processing of marker locations, even when they are static. Neuromorphic asynchronous marker-less sensors may offer a solution to this issue because they only respond to dynamic changes in the visual scene. This approach consumes significantly less power than conventional cameras. In addition, they operate at a microsecond temporal resolution, providing appreciably faster responses to changes in tracker position without the need for Kalman-smoothing and prediction. Fig. 3 shows an example of a marker-less hand tracking application with a dynamic vision sensor (DVS) [21].



(c)

Fig. 3. (a) DVS setup with super-imposed hand motion trajectory for the letter R in the order of occurrence. (b) Output of the tracking algorithm. (c) Sensor output from the DVS at each point of the recording.

The figure shows that a DVS is able to generate smooth trajectories using it's high temporal resolution in the presence of noisy distractors and, hence, it may be useful for gesture recognition.

V. Materials and Methods

A. Glove

We designed and fabricated a first generation haptic glove that is lightweight, flexible and capable of delivering haptic information with high spatial precision and intensity. A prototype of the haptic glove is shown in Fig. 4 [22]. The

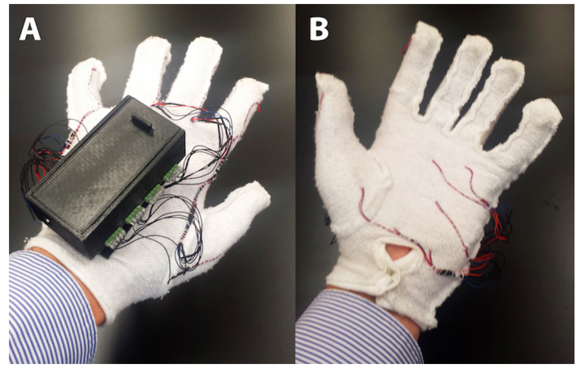


Fig. 4. Haptic glove: (A) back, (B) front.

glove had 18 vibratory eccentric rotating mass actuators. It was controlled by an Arduino microcontroller and two pulse width modulation drivers encased in a 3D-printed box on the back of the glove.

A custom made graphical user interface (GUI) (see Fig. 5) was used to assess the ability to render precise vibratory touch perception in two different ways: (1) intensity and (2) spatial locality.

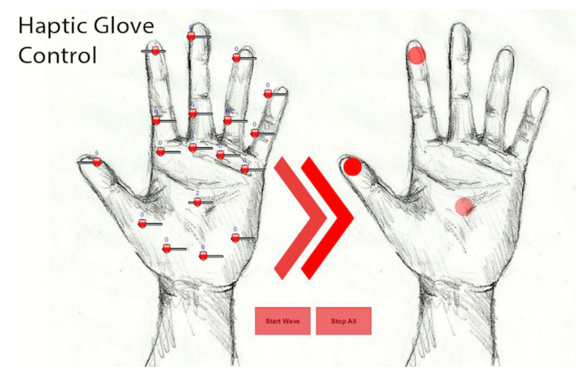


Fig. 5. GUI to control individual actuators during evaluation.

Forty untrained subjects were asked to distinguish stimulation region and intensities. Specifically, each subject was asked to identify the location of a single active actuator while vibration intensity was varied as $\pm$ 0, 20 and 40% of the actuators maximum. In addition the subjects were asked to identify the quantity and location of 2 to 5 simultaneously active actuators with varying area of stimulation.

B. Wristband

Piezoelectric transducers were integrated in a wearable device to be used in a virtual reality environment with the purpose of providing haptic feedback (see Fig. 6 A-B). The signals of the haptic wristband can be coupled with those of the haptic glove's to enhance user experience.

The transducers used in this device were piezoelectric disks (7BB-12-9, MuRata) with 12 mm diameter and 220 μm thickness. The piezoelectric element underwent a custom manufacturing process that integrated it in a polymeric

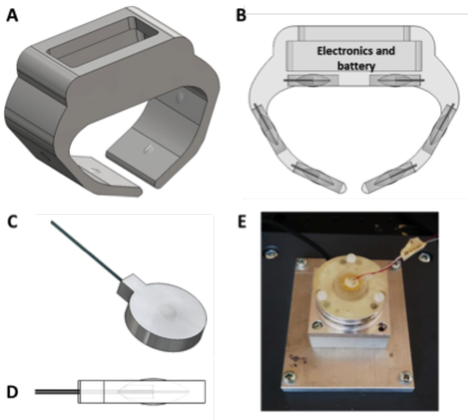


Fig. 6. Piezoelectric transducer integration and experimental measurement system. (A-B) Haptic wristband with embedded transducers. (C) Piezoelectric transducer embedded in a PDMS matrix. (D) Lateral view of piezoelectric transducer. (E) Measurement system setup with load cell and 3D printed holder for transducer placement.

matrix (PDMS, Dow Corning 184 - Silicone Elastomer). The PDMS encapsulation served dual mechanical and electrical roles. It allowed electric contacts to be encapsulated, providing electrical insulation of the element. In addition, it achieved the goal of designing a system that can be easily inserted in a wearable haptic device such as the wristband. After customization the transducer was 18 mm in diameter and 4 mm in thickness. The shape of the embedded system was characterized by two spherical cups that protruded out 250 μm from the upper and lower levels of the polymeric matrix (Fig. 6 C-D). These elements allowed skin stimulation at a specific contact point. The transducers were actuated by means of a piezo-haptic driver (DRV2667 Evaluation module, Texas Instruments) using a GUI (LabVIEW, National Instruments) that activated the driver through an electronic board (SB-RIO 9636, National Instruments).

Before human evaluation of the system, we assessed the ability of the haptic interface to deliver perceptible and discriminable stimuli using a load cell (Nano 43, ATI Industrial Automation) to provide input stimulus and record its resultant vibrations (Fig. 6 E).

The selection of stimulation parameters included amplitude and frequency values that resulted in significant vibrations of the transducer. Previous work has shown skin sensitivity to vibrotactile frequencies up to several hundred Hertz [23]–[26].

Specifically, the experimental protocol was based on stimuli lasting 500 ms with a constant amplitude within each trial (3 peak-to-peak amplitudes across the entire protocol, as shown in Table I) and two frequency levels, each one lasting 250 ms. The chosen central frequency was 450 Hz, with lower and upper limits of 100 Hz and 800 Hz (see Table I for frequency combinations). Two series of stimuli were generated to test increasing and decreasing frequencies.

Psychophysical experiments with subjects were structured according to the protocol described below, that is a 2-Alternative Forced-Choice (2AFC) paradigm. One of the main methods used in psychophysical literature to describe the correlation between a quality of a stimulus and its perceptual effect [27]. The complete sequence of 42 stimuli (Table I) was delivered to the piezoelectric element while it was held between the thumb and index finger of the subject. Each sequence was randomized and repeated in 5 sessions with a pause of approximately two minutes between sessions, for a total duration of about 40 minutes for the whole protocol. Within each sequence, the stimuli were spaced in time with 8 s intervals, during which the subject was asked to judge whether the frequency variation Δf of the preceding vibrotactile trial was increasing ($\Delta f > 0$) or decreasing ($\Delta f < 0$). The subjects were wearing a headset with white noise for being acoustically shielded from the environment.

VI. Results

A. Glove

The results show that we had a 64-93% rate of success to identify an active actuator location (see Fig. 7). Actuators at

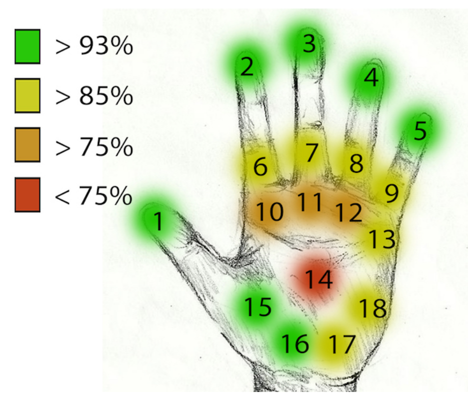


Fig. 7. Precise actuator localization.

the fingertips were more accurately identifiable than at the palm.

The findings in Fig. 8 illustrate that the intensity variation was easily identified with a 78-93% rate of accurate association.

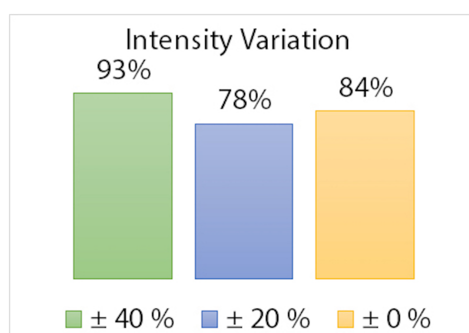


Fig. 8. Stimulus magnitude perception.

The region of active stimulation had a 60-100% rate of correct identification (see Fig. 9). The results indicate that a

TABLE I

EXPERIMENTAL STIMULATION PARAMETERS.

Stimulation amplitude $[V_{pp}]$		
100	150	200

X

Frequency variation Δf=f2-f1 [Hz]														
Δf	-700	-600	-500	-400	-300	-200	-100	100	200	300	400	500	600	700
f1	800	750	700	650	600	550	500	400	350	300	250	200	150	100
f2	100	150	200	250	300	350	400	500	550	600	650	700	750	800

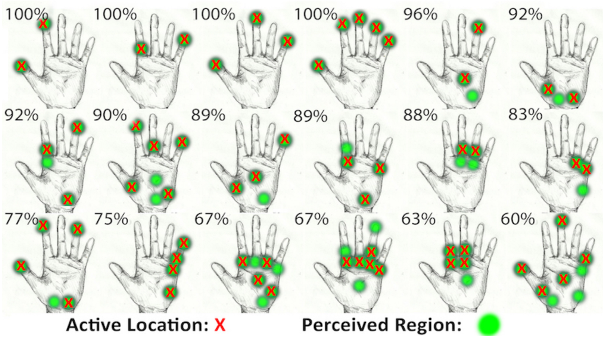


Fig. 9. Perception of active region.

higher quantity of localized stimulation reduces precise actuator identification accuracy. However, the region of activation was well recognizable.

B. Wristband

Spectral analysis was performed using a wavelet coherence package [28] on normal forces (Fz) recorded by the load cell during actuation. This analysis showed coherence with nominal stimulation parameters. Vibratory changes were substantial for different peak-to-peak amplitudes and frequency differences (see example analyses in Fig. 10). Hence, the device delivered vibrotactile stimuli in a reliable manner. In addition, we evaluated the efficacy of the system to deliver accurate tactile feedback using a 2-alternative forced-choice (2AFC) psychophysical protocol.

Results of the psychophysical tests show that the detection rate increased almost monotonically with frequency variation, Δf. The results had a typical appearance of a psychometric curve of a 2AFC experiment, where 'increasing frequency' responses were almost random around the origin of Δf axis, and tended to 100% for strongly increasing frequency changes and to 0% for strongly decreasing ones (Fig. 11). Since modulation of the parameters of vibrotactile stimulation are well reflected in subject perception, with a monotonic mapping between stimuli difference and discrimination performance, the system can be used to provide meaningful sensory feedback to a wearer by means of sensory substitution.

VII. CONCLUSIONS AND FUTURE DIRECTION

Our study of the vibrotactile glove shows that the volunteer subjects were able to successfully perceive stimulus. Our glove is easy to use and permits a wide range of haptic perception. Although multiple actuator identification is less precise, single activation are easily perceived. To address the non-ideal properties of this first generation glove, we aspire to develop an advanced high-density vibrotactile glove that is exceptionally compact and formfitting, permitting more precise localization. We plan to increase perception using precise haptic actuators such as the Haptuator^{TM} Planar (TactileLabs). In addition, we plan to evaluate the ability to render multimodal tactile information using our second-generation glove.

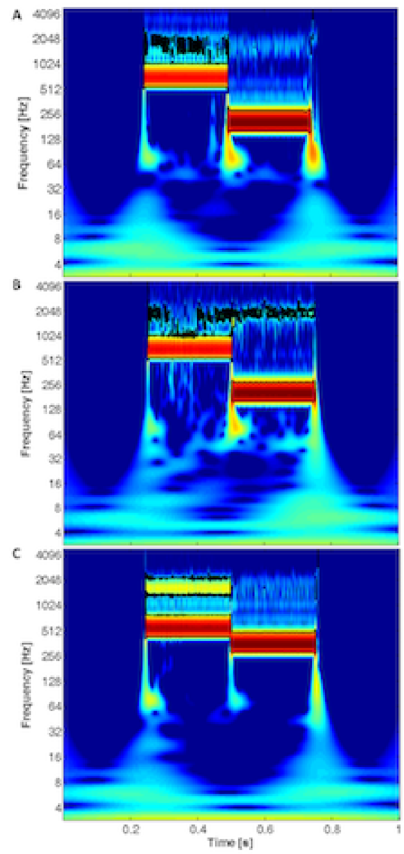


Fig. 10. Spectral analysis on the normal force recorded by the load cell while activating a piezoelectric actuator (Figure 6 E). The red regions show the spectral frequencies bringing highest signal power and point out their occurrence with time as the stimulation starts. See [29] for detailed methods. (A) Results for 200 Vpp and 700-200 Hz frequency change (-500 Hz Δf). (B) Results for 100 Vpp and 700-200 Hz frequency change (-500 Hz Δf); (C) Results for 200 Vpp and 550-350 Hz frequency change (-200 Hz Δf).

Analysis of the piezoelectric actuator to be integrated in the wristband showed with human subjects that the sequence of stimuli presentation could affect perception of frequency

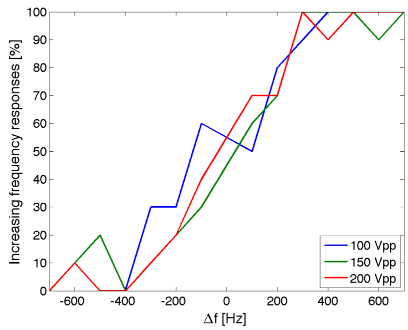


Fig. 11. Percentage of stimuli identified as having increasing frequency, as a function of the frequency variation Δf. The colors of the curves represent three amplitudes of stimulation.

changes. When stimulus with low Δf or Vpp, or both, was followed by one with high Δf and Vpp, subjects sometimes were not able to properly interpret the signal. Although preliminary results from psychophysical experiments showed that the single piezoelectric transducer is appropriate for the transmission of haptic information, further experiments must be performed to evaluate the best configuration for the entire device, in terms of number and spatial distribution of the embedded transducers. We expect the device to be comfortable, able to effectively transmit information to the wrists and work in a complementary manner with the haptic glove.

Future studies will address the quantification of the information content that can be provided by means of this haptic interface, also jointly with the virtual reality environment.

References

[1] G. Burdea and J. Zhuang, "Dextrous telerobotics with force feedback–an overview. part 1: Human factors," *Robotica*, vol. 9, no. 02, pp. 171–178, 1991.

[2] M. Slater and S. Wilbur, "A Framework for Immersive Virtual Environments (FIVE) - Speculations on the Role of Presence in Virtual Environments," *Presence: Teleoperators and Virtual Environments*, vol. 6, no. 6, pp. 603–616, Dec. 1997.

[3] A. Amer and P. Peralez, "Affordable altered perspectives: Making augmented and virtual reality technology accessible," in *Global Humanitarian Technology Conference (GHTC), 2014 IEEE*. IEEE, 2014, pp. 603–608.

[4] C. Cruz-Neira, D. J. Sandin, T. A. DeFanti, R. V. Kenyon, and J. C. Hart, "The cave: Audio visual experience automatic virtual environment," *Commun. ACM*, vol. 35, no. 6, pp. 64–72, Jun. 1992.

[5] S. Jeon and S. Choi, "Haptic augmented reality: Taxonomy and an example of stiffness modulation," *Presence*, vol. 18, no. 5, pp. 387–408, Oct 2009.

[6] A. S. Mathur, "Low cost virtual reality for medical training," in *Virtual Reality (VR), 2015 IEEE*, March 2015, pp. 345–346.

[7] J. Nishida, K. Nakai, A. Matsushita, and K. Suzuki, *Haptic Interaction: Perception, Devices and Applications*. Tokyo: Springer Japan, 2015, ch. Haptic Augmentation of Surgical Operation Using a Passive Hand Exoskeleton, pp. 237–243.

[8] A. S. Merians and G. G. Fluet, *Virtual Reality for Physical and Motor Rehabilitation*. New York, NY: Springer New York, 2014, ch. Rehabilitation Applications Using Virtual Reality for Persons with Residual Impairments Following Stroke, pp. 119–144.

[9] R. B. Hellman, E. Chang, J. Tanner, S. I. Helms Tillery, and V. J. Santos, "A robot hand testbed designed for enhancing embodiment and functional neurorehabilitation of body schema in subjects with upper limb impairment or loss," *Frontiers in Human Neuroscience*, vol. 9, no. 26, 2015.

[10] S. Jeon and M. Harders, "Haptic tumor augmentation: Exploring multi-point interaction," *IEEE Transactions on Haptics*, vol. 7, no. 4, pp. 477–485, Oct 2014.

[11] C. Strub, F. Wrgtter, H. Ritter, and Y. Sandamirskaya, "Using haptics to extract object shape from rotational manipulations," in *Intelligent Robots and Systems (IROS 2014), 2014 IEEE/RSJ International Conference on*, Sept 2014, pp. 2179–2186.

[12] G. Luo and E. Peli, "Use of an augmented-vision device for visual search by patients with tunnel vision," *Investigative Ophthalmology & Visual Science*, vol. 47, no. 9, p. 4152, 2006.

[13] M. A. Muhanna, "Virtual reality and the cave: Taxonomy, interaction challenges and research directions," *Journal of King Saud University - Computer and Information Sciences*, vol. 27, no. 3, pp. 344 – 361, 2015.

[14] P. Galambos and P. Baranyi, "Vibrotactile force feedback for telemanipulation: Concept and applications," in *Cognitive Infocommunications (CogInfoCom), 2011 2nd International Conference on*, July 2011, pp. 1–6.

[15] M. Bouzit, G. Burdea, G. Popescu, and R. Boian, "The rutgers master ii-new design force-feedback glove," *IEEE/ASME Transactions on Mechatronics*, vol. 7, no. 2, pp. 256–263, Jun 2002.

[16] J. Wither, S. DiVerdi, and T. Hllerer, "Annotation in outdoor augmented reality," *Computers & Graphics*, vol. 33, no. 6, pp. 679 – 689, 2009.

[17] R. Rosenholtz, Y. Li, and L. Nakano, "Measuring visual clutter," *Journal of Vision*, vol. 7, no. 2, p. 17, 2007.

[18] W. Lu, H. B.-L. Duh, S. Feiner, and Q. Zhao, "Attributes of subtle cues for facilitating visual search in augmented reality," *Visualization and Computer Graphics, IEEE Transactions on*, vol. 20, no. 3, pp. 404–412, 2014.

[19] L. O. Russo, G. A. Farulla, D. Pianu, A. R. Salgarella, M. Controzzi, C. Cipriani, C. M. Oddo, C. Geraci, S. Rosa, and M. Indaco, "Parloma-a novel human-robot interaction system for deaf-blind remote communication," *International Journal of Advanced Robotic Systems*, vol. 12, 2015.

[20] G. Airò Farulla, D. Pianu, M. Cempini, M. Cortese, L. O. Russo, M. Indaco, R. Nerino, A. Chimienti, C. M. Oddo, and N. Vitiello, "Vision-based pose estimation for robot-mediated hand telerehabilitation," *Sensors*, vol. 16, no. 2, p. 208, 2016.

[21] P. Lichtsteiner, C. Posch, and T. Delbruck, "A 128 times; 128 120 db 15 956;s latency asynchronous temporal contrast vision sensor," *Solid-State Circuits, IEEE Journal of*, vol. 43, no. 2, pp. 566–576, Feb 2008.

[22] J. Huebotter, J. Tung, N. Thakor, H. Yu, and S. Kukreja. (2016) A novel high density haptic glove for vibrotactile feedback. Abu Dhabi, UAE. [Online]. Available: http://www.sinapseinstitute.org/projects/neuromorphics/Kukreja-IEEE-LSGCC.pdf"

[23] R. T. Verrillo, "Psychophysics of vibrotactile stimulation," *Acoustical Society of America Journal*, vol. 77, pp. 225–232, Jan. 1985.

[24] R. S. Johansson and A. Vallbo, "Properties of Cutaneous Mechanoreceptors in the Human Hand Related to Touch Sensation," *Human Neurobiology*, 1984.

[25] S. Brewster and L. M. Brown, "Tactons: Structured tactile messages for non-visual information display," in *Proceedings of the Fifth Conference on Australasian User Interface - Volume 28*, ser. AUIC '04. Darlinghurst, Australia, Australia: Australian Computer Society, Inc., 2004, pp. 15–23.

[26] E. Gunther, G. Davenport, and S. O'Modhrain, "Cutaneous grooves: Composing for the sense of touch," in *Proceedings of the 2002 Conference on New Interfaces for Musical Expression*, ser. NIME '02. Singapore, Singapore: National University of Singapore, 2002, pp. 1–6.

[27] R. Bogacz, E. Brown, J. Moehlis, P. Holmes, and J. D. Cohen, "The physics of optimal decision making: a formal analysis of models of performance in two-alternative forced-choice tasks." *Psychological review*, vol. 113, no. 4, p. 700, 2006.

[28] A. Grinsted, J. C. Moore, and S. Jevrejeva, "Application of the cross wavelet transform and wavelet coherence to geophysical time series," *Nonlinear Processes in Geophysics*, vol. 11, no. 5/6, pp. 561–566, 2004.

[29] C. M. Oddo, M. Controzzi, L. Beccai, C. Cipriani, and M. C. Carrozza, "Roughness encoding for discrimination of surfaces in artificial active-touch," *IEEE Transactions on Robotics*, vol. 27, no. 3, pp. 522–533, June 2011.