Contactless Haptic Feedback: State of the Art

Faisal Arafsha, Longyu Zhang, Haiwei Dong, and Abdulmotaleb El Saddik
Multimedia Computing Research Lab (MCRLab)
University of Ottawa
Ottawa, Canada
{farafsha, lzhan121, hdong, elsaddik}@uottawa.ca

***Abstract*—This paper discusses some of the recent advances in contactless haptic feedback. We mainly discuss two research methods to produce haptic feedback in 3D space: Air-jet and ultrasound. We discuss and compare technical basics of each technology, and then give a literature review of some of the research done that is closely related to this field. This paper also surveys the stages of the design and implementation of airborne ultrasonic tactile displays (AUTD) by researchers in the University of Tokyo, as well as an application of this research done in the University of Bristol. A comparison is presented showing the main advances in the Tokyo research and the technical tests and implementation differences. A discussion follows covering possible improvements and safety issues on the contactless haptic feedback research in general. We show comments and drawbacks of the current technology. For future work in the field of mid-air haptic feedback, we propose a design method to build a "Touchable Avatar", which is a holographic display with contactless haptic feedback properties. Finally, a conclusion is provided including an outlook of the future applications in the field of contactless haptic feedback.**

Keywords— contactless haptic; air-jet; ultrasonic haptic; acoustic radiation pressure; survey; holograms; touchable avatar

I. Introduction

There are mainly three strategies to produce haptic feedback in free space [1]. The first strategy is through the conventional direct-contact wearable devices, such as gloves [2] or haptic jackets [3-5]. The second is manipulating the location of the haptic actuators themselves such that they only touch the user when feedback is required. An example of this strategy is the electrotactile display discussed in [6]. The third strategy, contactless haptic feedback, is to produce the haptic feedback to the user from a distance without direct skin contact. This means that the user does not have to wear gloves or hold a device to feel the motion or the tactile surface, but rather perceive the intended output of the system in mid-air.

Contactless haptic feedback discussed here is produced using two main techniques: air-jet, and ultrasonic radiation pressure. Several studies suggest that haptic feedback can be correlated with sound waves [7, 8], while others focus only on pressurized air. There are other studies that utilize the effects of laser to produce tactile sensation at a distance [9-11].

Utilizing the characteristics of pressurized air, air-jet is used as one method to stimulate haptic perception. Researchers show that this can be exploited to feel virtual tactile surfaces, either by holding a receiver (a paddle) or with bare hands. Disney research show a prototype that produces air vortices directed at the user's palms with the help of Microsoft Kinect. This research has high potential in the future of interactive videogames. In contrast, airborne ultrasound displays are being developed in the University of Tokyo, which utilizes high frequency sound waves to stimulate haptic perception. These displays show that ultrasound can produce contactless haptic feedback in a much higher resolution than air-jet.

II. Technologies

Two methods are discussed for producing contactless haptic feedback: Air-Jet, and Acoustic Radiation Pressure.

A. Air-Jet

Air-jet tactile feedback in this survey can be summarized into using one of two methods: direct compressed air through focused nozzles, and vortex based tactile actuation. The former method is utilized by connecting a tank of pressurized air through valves to focused outputs. These valves can be controlled using pressure sensors and servo-pneumatic valves [12]. The latter method uses air vortices by controlling the pressure difference between the nozzle and the outside medium [13, 14]. This method allows the produced air vortices to reach further distances while preserving form and speed [15].

An example of the air vortex generator is the AIREAL device designed by Disney Research [15]. It is composed of an 8x8x8 cm cubic enclosure, a 4 cm flexible nozzle, and pan/tilt motors. Apart from the output nozzle side, each side has an inward facing 2-inch 15W subwoofer that, all together, act as an actuator that produces the pressurized air (Figure 1).

B. Acoustic Radiation Pressure

Producing tactile sensation using ultrasound is based on the principle of acoustic radiation force [16]. Acoustic waves propagate through a medium (i.e. air), which undergoes a steady force called the acoustic radiation force. This force is generated from the transfer of momentum of sound in the medium [17]. In haptic technologies, acoustic radiation pressure principles are exploited by using electronic ultrasound transducers. These transducers are controlled digitally with a high-voltage driving signal to produce the ultrasonic waves that can reflect on the human skin [18, 19].

An ultrasonic transducer is mainly composed of a piezoelectric material attached at the face of a metal casing with an inner acoustic insulator. The transducer produces ultrasonic waves by applying alternating current across the piezoelectric material, which in turn, vibrates at a high speed. With this high-frequency vibration, ultrasonic waves are produced (piezoelectric effect).

978-1-4673-9175-7/15/$31.00 ©2015 IEEE

Table 1 shows a comparison between the above basic technologies. The air-jet method appears to be simpler to design and implement in comparison to the ultrasound method. In addition, the haptic feedback produced by an air-jet device can reach a further distance. However, it has a lower spatial resolution and is slower in reaching the targeted focal point in contrast with an ultrasound-method device.

TABLE I. TECHNOLOGIES COMPARISON

	Air-jet	**Ultrasound**
Advantages	• Easy to implement • Long travel distances	• Small size • High spatial accuracy
Disadvantages	• Bulky • Low spatial resolution • Slower transfer through medium	• Noise • Short travel distance
Power consumption	Very low in most cases (control signals only)	Relatively high (typically 40 W [25])

III. CONTACTLESS HAPTIC SYSTEMS

A. *Air-jet Haptic Feedback*

Suzuki et al. [20, 21] first introduced a force feedback display driven by air-jet in 2005. In their prototype, they used an air compressor connected to 100 nozzles (10x10 grid) embedded on the surface of a table. Each nozzle is controlled by an electric valve. They all have the same pressure, but only one operates at a time to utilize the overall pressure. The system is implemented on a virtual reality system with force feedback. The user holds a paddle-like air receiver whose location is monitored by the system. When the user places the paddle on the virtual object, the corresponding valve operates to produce force feedback felt by the user. The stimulation that this system produces is compared to holding a stick and moving it over a real object to feel its force feedback. In other words, the user does not feel the air-jet, but feels the pressure produced on the paddle. It is debatable whether this type of haptic feedback can be considered as purely contactless or contact-based. The reason is the fact that the user is required to hold a device that receives the haptic feedback, which, in turn, transfers the sensation of touch to the user’s hand. However, it is categorized here as “contactless” because the handheld device is not physically attached to the overall system.

Sodhi et al. from Disney Research [15] present a new air-jet based contactless haptic device that can be used along with Kinect in entertainment based applications (Figure 1). Their device, called AIREAL, uses compressed air pressure and shoots it in the form of rings in order for it to reach further distances while keeping its form and speed. The device is able to target a field in the range of 75-degrees, and uses flexible actuated diaphragms to push air out of it. The rate of displacement is controlled to create the flow of air going out of the device. The AIREAL device combines a tilt motor with an embedded flexible nozzle along with a small 3D depth camera for vortex control. It measured to perform at 90% accuracy at a distance of 1 meter covering the 75-degree field [15].

Tsalamlal et al. [22] conducted an experimental study on air-jet based tactile stimulation on users' hands. They used an air-jet diffusion nozzle with an air compressor and a flow controller to study the human tactile perception. The objective was to determine the absolute threshold, which is the minimum detectable intensity, and the differential threshold, which is the minimal detectable change in applied intensity (the noticeable difference). The test nozzle is placed at a 350 mm distance from the user's palm and 25 variations of air pressure intensities are tested. The intensity is decreased upon a positive response, and slightly increased upon a negative response. Finally, the researchers provided a model function to control the haptic rendering and calculation for airflow rate.

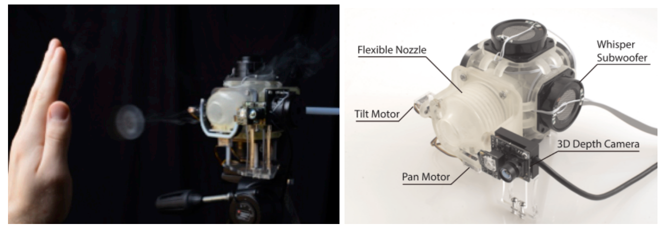

Fig. 1. AIREAL tactile device [15].

B. *Airborne Ultrasonic Haptic Feedback*

The leading research in the area of airborne ultrasonic haptic feedback is conducted in the University of Tokyo, Japan, and in the University of Bristol, UK. Below are some of the latest published research papers in this field.

Iwamoto et al. [19, 23] described their first prototype implementation of an airborne ultrasonic tactile display that is designed to provide tactile feedback for 3D modeling software and video games. Their implementation does not require the user to wear anything. They compared their implementation with CyberTouch [2] that uses vibrotactile actuators on fingers and palms to stimulate tactile feedback. Iwamoto's display, however, radiates airborne ultrasound that exerts pressure directly onto the user's skin. They state that approximately "99.9% of the incident acoustic energy is reflected on the surface of the skin" and, therefore, the user does not need to wear special gloves. The prototype includes an array of 91 ultrasound transducers arranged in a hexagonal arrangement, a 12-channel amplifier circuit, and a PC. Each transducer is 10 mm in diameter with a frequency of 40 kHz and a sound pressure of 20 Pa, 300 mm far from its surface. The total force of this prototype was measured by placing it upside down on an electronic scale with input amplitude of 15 V. The measured force was 0.8 gf (gram-force) at a 250 mm distance, and 2.9 gf at a 0 mm distance from the electronic scale.

Hoshi et al. [1] further improved on Iwamoto's work in [19] and [23] by developing an interactive holographic system with tactile feedback. It mainly consists of a holographic display, a hand tracker, and their developed tactile display. The aim of this experiment was to intensify the pressure of haptic feedback provided in their previous research. They combined 4 ultrasound transducer arrays that summed up 364 piezoelectric transducers, and arranged them such that their haptic output meet at a single focal point in the middle of the space between them (Figure 2, left). They also increased individual sound pressure by increasing the input voltage to 10 Vrms. They tested the system by asking volunteers to put their hands at 250 mm distance from the main transducer array. Finally, they show the results of their experiment and explain the effect of different pulse widths and input voltages on the perceived haptic feedback.

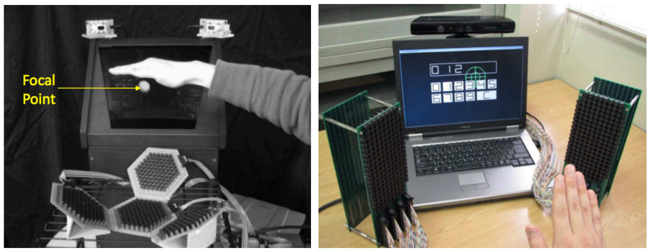

Fig. 2. Hoshi et al. interactive holographic system [1].

Hoshi et al. conducted another experiment [18] using a square array of 324 ultrasound transducers driven by 9 amplifier circuits (36-channel) and a master circuit. The force feedback was again measured by placing the unit upside down on an electronic scale at a distance of 200 mm. The input signal amplitude was set to 24 Vp-p (peak-to-peak voltage) and the force was measured to be 1.6 gf. Later, Takahashi and Shinoda performed different simulations and performance tests to improve the performance of this airborne ultrasound tactile display by improving spatial resolution, force pressure, and refresh rate [16]. In 2010 and 2011, Hoshi et al. published more extensive technical details and performance studies about this implementation [24, 25]. One of which is an aerial-input aerial-tactile-output system that utilizes a Kinect device and ultrasound to produce tactile feedback in mid-air. The tactile display system is composed of a PC, a master-slave system and two transducer arrays driven by two 96-channel amplifier circuits. The target area is 200x200x200 mm, and is divided into 5x5x12.5 mm sub-areas. Each of these sub-areas can be a target focal point that can stimulate tactile feedback in mid-air [25] (Figure 3, right). In 2013, Hasegawa and Shinoda from the University of Tokyo widened this ultrasonic tactile display into a 9-times bigger display filled with a total of 2,241 ultrasound transducers. They combined 9 units together and tested the system that produced a gross force that reached 7.4 gf [26].

Carter et al. [27] from the University of Bristol designed a system to produce multi-point haptic feedback for interactive screens. Their system, UltraHaptics, requires no direct contact or tools to feel haptic force. They use ultrasonic transducers arranged under the surface of the projected display to produce acoustic radiation force. The projection surface is also designed such that it allows ultrasonic radiation to pass through it, while still having a decent projection surface. A prototype was built following this design, and a psychophysical study was carried on to ensure distinguishable tactile properties.

Yoshino and Shinoda [28] also explain their contactless tactile touch screen with a similar concept to Carter's. They designed a visio-acoustic screen, made by acrylic material, which allows airborne ultrasonic pressure to pass through it while holding projected light beams for display. In their case, the projection of media comes from behind the screen (compared to front projection by Carter et al.). They utilized their lab's airborne ultrasonic tactile display described in [24] for contactless haptic feedback in this system.

Table II shows the stages of the research done on airborne ultrasonic tactile displays in the University of Tokyo. It compares the main characteristics of each design, output force, input signal amplitude, control method, total number of transducers, and spatial resolution (accuracy) of the contactless haptic feedback. In all of these designs, researchers used ultrasound transducers model number T4010A1, from Nippon Ceramic Co., Ltd. These transducers have a diameter of 10 mm, and a resonant frequency of 40 kHz. They can produce a sound pressure output of 20 Pa at 300 mm distance, and an output force of 2.9 gf (28 mN) at 0 distance from the transducers.

C. *Other Studies*

Other implementations discussed in this section cannot be specifically categorized as contactless or contact-based haptic feedback, but are closely related to the main idea of contactless haptic feedback. For example, the research by Alexander et al. [29] in the University of Bristol describes the implementation features of the UltraTV, which is a mobile media device with haptic features. Haptic features implemented by adding mid-air and multi-point ultrasonic haptic feedback to the back of the tablet device. In addition to audio-visual streaming of media, ultrasonic air pressure waves are added to create vibration feedback. Various vibration components are presented by controlling the pulse, duration and frequency parameters of the haptic feedback actuators. The user's hands feel a change of intensity by sensing the change in frequency in these actuators. The paper suggests that haptic feedback is sensed by the user's hands when the input frequency is within the range of 40-1000Hz, and that the hands are most sensitive to vibrations around 250Hz. Therefore, intensity is controlled by controlling vibration frequencies around this value. The haptic feedback feature in the UltraTV supplements audio-visual streaming in the device. It uses ultrasonic transducers and makes use of the radiation pressure to create tactile sensation to the user. However, the device must be held by hands in specific areas in order to perceive the ultrasonic haptic feedback.

Hollis [30-33] explained Butterfly Haptics' magnetic levitation haptic interface device that was developed at Carnegie Mellon University and manufactured for commercial use by Butterfly Haptics. Their device is described to be very similar to a computer mouse with six degrees of freedom, and magnetic-based haptic feedback. A handle is attached to the center of a bowl-shaped surface. When the user interacts with a 3D virtual object using this handle, electric currents are directed through embedded coils. These currents interact with permanent magnets fixed along the devices inner walls to give the force feedback sensation. Here, the produced haptic feedback is done via magnets (i.e. contactless). However, the user feels the pressure on the handheld handle and not directly into their skin, which presents direct contact and incomplete mobility up to some extent.

O'Hara et al. [34] discussed contactless interaction with medical images in 3D space. They state the fact that surgeons, during surgery, are unable to physically and directly interact with non-sterile equipment, such as a computer mouse or keyboard. Several approaches are discussed to overcome the contactless interaction in the article including an example of a system used in Sunnybrook Hospital in Toronto, Canada that uses the Kinect sensor and simple gestures to navigate through a pre-defined stack of medical images. O'Hara et al. discuss their developed system that is used in Guy's and St. Thomas' Hospital in London, U.K. which also uses a Kinect-based system but with the addition of collaborative control, system engagement/disengagement functions, and a one-hand, two-hands or hands-free control.

There exist other related studies that are concerned with direct-contact haptic feedback for such applications. An example is the CyberTouch [2] that uses vibrotactile actuators embedded in wearable gloves to simulate touch in virtual environments. In addition, Sato et al. [6] implemented a master-slave robotic system that directly contacts each finger with electro-tactile displays on the user's hand. These systems are either bulky or require direct contact with the haptic interface and, therefore, are not considered "contactless".

TABLE II. AIRBORNE ULTRASOUND TACTILE DISPLAY: RESEARCH PHASES COMPARISON

Prototype Description [ref] (year)	Main Characteristics	Output Force @ Test Distance	Input Signal Amplitude	Control Method	Total Number of Transducers	Spatial Resolution (Focal Point Diameter)
12-channel annular array [19, 23] (2008)	• First prototype using acoustic pressure as tectile feedback. • Anular array of ultrasound transducers	0.8 gf (8 mN) @ 250 mm	15 V	Digitally through 12-channel amplifier circuit.	91	20 mm
4 focused annular arrays [1] (2009)	• Holographic tactile display: multiple annular arrays from first prototype. • Combined focal point Increased individual sound pressure.	4.8 gf (47 mN) @ 250 mm	17.7 V (50 Vpp)	N/A	364	20 mm
18x18 ultrasound transducer array (AUTD) [18, 24] (2009-10)	• AUTD: second prototype: bigger square board. • Reduced power	1.6 gf (16 mN) @ 200 mm	8.5 V (24 Vpp)	Master-slave system (9 slaves). Each slave drives 36 transducers through a 36-channel amplifier circuit.	324	20 mm
Multiple AUTD unit system in a 1 square meter environment [16, 26] (2010-13)	• 9x Synchronized AUTD units	7.4 gf (73 mN) @ 600 mm	N/A	9x master-slave systems composed of multiple entities of the previous prototype	2241	20 mm
Aerial input/output system [25] (2011)	• 2x rectangular ultrasound transducers arrays	1.2 gf (12 mN) @ 300 mm	8.5 V (24 Vpp)	Master-slave system (4 slaves). Each slave drives 96 transducers trhough a 96-channel amplifier circuit.	384	36.4 mm[a]
Tactile visio-acoustic screen [7] (2013)	• Touch screen with contactless tactile features	1.6 gf (16 mN) @ 240 mm	N/A	N/A	249	10 mm

**Focal point diameter is calculated as the square root of horizontal diameter x vertical diameter*

IV. IMPROVEMENTS DISCUSSION

There are some drawbacks from using the above methods to produce contactless haptic feedback. The air-jet method is a straightforward implementation and can give relatively acceptable force feedback as can be seen from the above review. However, due to the physical properties of air, this method lacks spatial and temporal qualities that are necessary for multimedia applications [25]. The ultrasonic method, on the other hand, overcomes these drawbacks, however, it is not ideal either. Hoshi et al. [1] mentioned in their research that in order to test their system, they had to ask volunteers to place their hands very close to the ultrasonic tactile display (250 mm). Another issue that raises concerns in the ultrasonic method is the audible sound produced by the ultrasonic transducers when utilizing radiation pressure. The volunteers in Hoshi's work were asked to wear headphones playing white noise to block transducers' sounds, which is a concern in some applications.

Hoshi et al. [18] also discussed the possibility to improve spatial resolution in their prototype. Higher frequency of ultrasound can minimize the focal point diameter, which is preferred in most haptic applications. However, the lossy characteristics of the transfer medium of ultrasound (i.e. air), does not work in favor of our case study. Hoshi shows that there is an energy-loss/frequency trade-off; the higher the frequency used, the higher percentage of energy is lost.

Dangers affecting the safety of the human body when experimenting with waves cannot be ignored. Skin tissue can suffer from heat damage if extensive power is applied, i.e. 100 mW/cm^2 (or >428 mN) [24]. In addition, the human skin can suffer from slight heating it was exposed to ultrasonic waves with power greater than 140-150 dB [35]. However, much less force is required for most contactless haptic related applications, which leaves a lot of room for improvement.

Howard et al. describe ultrasound as sound with frequency above 20 kHz. Their studies show that some side effects of long exposure to airborne ultrasound may include nausea, fatigue and headaches. While the maximum recommended sound pressure level is 110 dB, the sound pressure level at a 300 mm distance from a single transducer used in most of the above research is approximately 121.5 dB, which is higher than the maximum recommendation [24, 35]. Therefore, it is very important for researchers and users to take this into consideration and apply the necessary measurements to avoid accidents.

Below, we show a case study to build a touchable hologram using the reviewed ultrasound tactile displays. We suggest the use of a robotic manipulator placed at the center of the hologram in order to overcome the short distance issue in the reviewed work.

Case Study - Touchable Holograms: The studies discussed in this paper have very high potential in future applications, especially those related to virtual environments and gaming. The Multimedia Computing Research Lab in the University of Ottawa is considering the exploitation of the outcomes of these studies in building an interactive Touchable Avatar [36]. The proposed Touchable Avatar system is a contactless interactive haptic feedback system that consists of the following sub-systems.

The Real World Scaning System fuses information from different sensors such as a Kinect camera, ultrasound sensors, etc. to provide a 3D model of the scanned object that includes depth and stiffness properties in addition to color information. This can be done by transforming 3D objects into 2D images, and then re-normalize it into a 3D model for processing.

The Virtual World System is the outcome of the previous system as well as the interface of the overall system. Therefore, it would require a huge amount of processing and power. There have been some existing algorithms and applications that can reconstruct 3D models from real objects and scenes. For example, KinectFusion [37] by Newcombe et al., can track the global pose of a moving Kinect and fuse the streamed dense depth data into a 3D volumetric surface representation. To enhance user immersion, sonar sensors can be used to detect the stiffness of the scanned object.

A significant part of the design of the Virtual World System is collision detection, which will be in charge of detecting interaction between the projected 3D hologram and the real user. It can convert interaction into haptic signals while offering a certain degree of force feedback to the proper collision location in the real world.

The objective of the Contactless Haptic Feedback is to make holographic projections touchable without using wearable devices. Based on the outcomes of some of the studies covered earlier in this paper, we propose a method to transfer the haptic feedback from the Virtual World System to the human's hands (the target).

To track the target, a tracking sensor, such as a Kinect [38] or Leap Motion [39], can be used to keep track of the user's hand and compare its 3D location with the projected 3D model in the Virtual World System. Haptic feedback is produced when collision is detected in the Virtual World System. The results of literature review show that airborne ultrasound tactile displays (AUTD) produce contactless haptic feedback using ultrasound up to a distance of 300 mm and with pressure of 20 Pa [16-18, 24-26]. One drawback is the maximum distance AUTD can reach. The large AUTD can reach a maximum of 600 mm with an acceptable spatial resolution of 20 mm [16, 26]. However, it is considered too large and bulky for our touchable avatar application. On the other hand, a small tactile display, such as the one in [19, 23], can reach a maximum of 250 mm with an acceptable spatial resolution of 20 mm. Another issue here is the direction to which these displays are to be embedded. The desired ultrasonic waves must come from within the hologram in order for the user's hand (the target) to be able to touch it from any side.

For these two reasons, we propose to use a manipulator that can keep directing at the user's hand while maintaining a fixed distance from it. This fixed distance is the maximum distance the AUTD display can reach with acceptable spatial resolution.

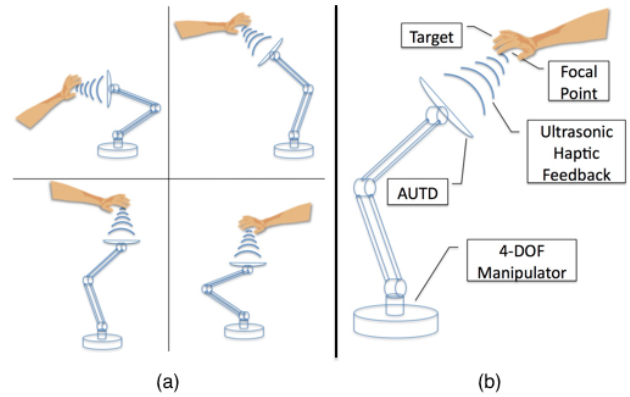

Fig. 3. Targeting contactless haptic feedback using Airborne Ultrasound Haptic Displays [18] and a 4-DOF manipulator. (a) shows different possible orientations of the manipulator, and (b) shows the basic parts

V. Conclusion and Outlook

Several studies, prototypes and designs that were discussed here prove that contactless haptic feedback can be used in today's wide range of multimedia applications [40-42]. We show two possible streams of research to produce haptic feedback in mid-air: air-jet and ultrasound. In addition, one other research shows the possibility of utilizing magnetic-field characteristics in future works.

The air-jet method shows a less expensive and relatively easier implementation, with the possibility of tactile feedback reaching further distances compared to the ultrasound method. However, the bulky designs might face some challenges in commercializing such products. Also, future studies may be able to improve its low spatial resolution and slow transfer through the medium. The ultrasound method, in comparison, shows more compact designs with high spatial resolution and accuracy at the focal points. However, the short travelling distance, unwanted noise, and safety issues should be considered for improvement in the future.

To the best of our knowledge, there is currently no system that allows the user to interact, manipulate, and feel the touch of holographic projections. This paper discussed the possibility and a proposed method to create, by combining available technologies, a complete system that will allow interaction with holograms. Applications for such systems can include video gaming, rehabilitation, social communication, command control, and many others.

Acknowledgment

The first author of this paper would like to thank the Saudi Arabian Cultural Bureau and the Saudi Ministry of Higher Education for sponsoring his graduate studies in Canada.

References

[1] T. Hoshi, D. Abe, and H. Shinoda, “Adding tactile reaction to hologram,” *Proceedings of the 18th IEEE International Symposium on Robot and Human Interactive Communication*, pp. 7–11, 2009.

[2] CyberGlove Systems, CyberTouch, http://www.cyberglovesystems.com

[3] F. Arafsha, K. M. Alam, and A. El Saddik, “Design and development of a user centric affective haptic jacket,” *Multimedia Tools and Applications*, 2013.

[4] F. Arafsha, K. M. Alam, and A. El Saddik, “EmoJacket: Consumer centric wearable affective jacket to enhance emotional immersion,” *Proceedings of the International Conference on Innovovations in Information Technology*, pp. 350–355, 2012.

[5] P. Lemmens, F. Crompvoets, D. Brokken, J. van den Eerenbeemd, and G. J. de Vries, "A body-conforming tactile jacket to enrich movie viewing," *Proceedings of Joint EuroHaptics Conference on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, 2009.

[6] K. Sato, H. Kajimoto, N. Kawakami, and S. Tachi, “Electrotactile display for integration with kinesthetic display,” *Proceedings of the 16th IEEE Internationsl Symposium on Robot and Human Interactive Communication*, pp. 3–8, 2007.

[7] S. C. Kim, S. C. Kang, and D. S. Kwon, “Sound generation for the haptic perception using an irregular primitive function,” *Proceedings of the 16th IEEE International Symposium on Robot and Human Interactive Communication*, pp. 19–24, 2007.

[8] S. C. Kim, K. U. Kyung, and D. S. Kwon, “The effect of sound on haptic perception,” *Proceedings of the 2nd Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environments and Teleoperator Systems*, pp. 354–360, 2007.

[9] H. Lee, J. S. Kim, S. Choi, J. H. Jun, J. R. Park, A. H. Kim, H. B. Oh, H. S. Kim, and S. C. Chung, “Mid-Air tactile stimulation using laser-induced thermoelastic effects: the first study for indirect radiation,” *Proceedings of World Haptics Conference*, pp. 374-380, 2015.

[10] F. Iannacci, E. Turnquist, D. Avrahami, and S. N. Patel, “The haptic laser: multi-sensation tactile feedback for at-a-distance physical space perception and interaction,” *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pp. 2047-2050, 2011.

[11] S. Knight, “Scientist create haptic holograms using femtosecond lasers,” *Tech Spot*, Internet: http://www.techspot.com/news/61207-scientists-create-haptic-holograms-using-femtosecond-lasers.html. 2015 [18 August 2015].

[12] H. Gurocak, S. Jayaram, B. Parrish, and U. Jayaram,"Weight sensation in virtual environments using a haptic device with air jets," *Journal of Computing and Information Science in Engineering*, vol. 3 no. 2, pp. 130-135, 2003.

[13] A. Glezer, "The formation of vortex rings," *Physics of Fluids*, pp. 3532-3542, 1988.

[14] R. A. Russell, "Air vortex ring communication between mobile robots," *Robotics and Autonomous Systems*, vol. 59, no. 2, pp. 65-73, 2011.

[15] R. Sodhi, I. Poupyrev, M. Glisson, and A. Israr, “AIREAL: interactive tactile experiences in free air,” *ACM Transactions on Graphics*, vol. 32, no. 4, pp. 134:1-134:10, 2013.

[16] M. Takahashi and H. Shinoda, “Large aperture airborne ultrasound tactile display using distributed array units,” *Proceedings of SICE Annual Conference*, pp. 359–362, 2010.

[17] D. Dalecki, S. Z. Child, C. H. Raeman, and E. L. Carstensen, “Tactile perception of ultrasound,” *The Journal of the Acoustical Society of America*, vol. 97, no. 5, pp. 3165–3170, 1995.

[18] T. Hoshi, T. Iwamoto, and H. Shinoda, “Non-contact tactile sensation synthesized by ultrasound transducers,” *Proceedings of the 3rd Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environments Teleoperator Systems*, pp. 256–260, 2009.

[19] T. Iwamoto, M. Tatezono, and H. Shinoda, “Non-contact method for producing tactile sensation using airborne ultrasound,” *Haptics: Perception, Devices and Scenarios*, Springer, pp. 504–513, 2008.

[20] Y. Suzuki and M. Kobayashi, “Air jet driven force feedback in virtual reality.,” *IEEE Computer Graphics and Applications*, vol. 25, no. 1, pp. 44–47, 2005.

[21] Y. Suzuki, M. Kobayashi, and S. Ishibashi, "Design of force feedback utilizing air pressure toward untethered human interface," *ACM Extended Abstracts on Human Factors in Computing Systems,* pp. 808-809, 2002.

[22] M. Tsalamlal, N. Ouarti, and M. Ammi, “Psychophysical study of air jet based tactile stimulation,” *Proceedings of the IEEE World Haptics Conference*, pp. 639–644, 2013.

[23] T. Iwamoto, M. Tatezono, T. Hoshi, and H. Shinoda, “Airborne ultrasound tactile display,” *Proceedings of the 35th International Conference and Exhibition on Computer Graphics and Interactive Techniques*, pp. 1, 2008.

[24] T. Hoshi, M. Takahashi, T. Iwamoto, and H. Shinoda, “Noncontact tactile display based on radiation pressure of airborne ultrasound,” *IEEE Transactions on Haptics*, vol. 3, no. 3, pp. 155–165, 2010.

[25] T. Hoshi, “Development of aerial-input and aerial-tactile-feedback system,” *Proceedings of World Haptics Conference*, pp. 569–573, 2011.

[26] K. Hasegawa and H. Shinoda, “Aerial display of vibrotactile sensation with high spatial-temporal resolution using large-aperture airborne ultrasound phased array,” *Proceedings of the IEEE World Haptics Conferance*, pp. 31–36, 2013.

[27] T. Carter, S. Seah, and B. Long, “UltraHaptics: multi-point mid-air haptic feedback for touch surfaces,” *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology*, pp. 505–514, 2013.

[28] K. Yoshino and H. Shinoda, “Visio-Acoustic screen for contactless touch interface with tactile sensation,” *Proceedings of World Haptics Conference*, pp. 419–423, 2013.

[29] J. Alexander, M. Marshall, and S. Subramanian, “Adding haptic feedback to mobile TV,” *Extended Abstract on Human Factors in Computing Systems*, pp. 1975–1980, 2011.

[30] R. Hollis, “Maglev haptics: butterfly haptic’s new user interface technology,” *Proceedings of the 35th International Conference and Exhibition on Computer Graphics and Interactive Techniques*, 2008.

[31] R. Hollis, “Butterfly haptics: a high-tech startup,” *IEEE Robotics & Automation Magazine*, pp. 14–17, 2010.

[32] R. L. Hollis, "Magnetic levitation haptic interface system," U.S. Patent No. 8,497,767. 30, 2013.

[33] B. King, "Computer graphics get a feel for real," Internet: http://www.technewsworld.com/story/61756.html, 2008 [Jun. 13, 2014].

[34] K. O’Hara, G. Gonzalez, and A. Sellen, “Touchless interaction in surgery,” *Communications of the ACM*, vol. 57, no. 1, pp. 70–77, 2014.

[35] C. Q. Howard, C. H. Hansen, and A. C. Zander, "A review of current ultrasound exposure limits," *The Journal of Occupational Health and Safety of Australia and New Zealand*, vol. 21, no. 3, pp. 253-257, 2005.

[36] "Touchable Avatar," MCRLab.net, Internet: http://www.mcrlab .net/research/touchable-avatar/, 2015 [17 April 2015].

[37] S. Izadi, D. Kim, O. Hilliges, D. Molyneaux, R. Newcombe, P. Kohli, J. Shotton, S. Hodges, D. Freeman, A. Davison, and A. Fitzgibbon, “Kinectfusion: real-time 3d reconstruction and interaction using a moving depth camera,” *Proceedings of the 24th Annual ACM Symposium on User Interface Software and Technology*, pp. 559-568, New York, NY, USA, 2011.

[38] J. Kang, D. Seo, and D. Jung, “A Study on the control Method of a 3-dimensional Space Application using KINECT System,” *International Journal of Computer Science and Network Security*, vol. 11 no. 9, 2011.

[39] F. Weichert, D. Bachmann, B. Rudak, and D. Fisseler, “Analysis of the Accuracy and Robustness of the Leap Motion Controller,” *Sensors*, vol. 13, pp. 6380-6393, 2013.

[40] M. Eid, “Haptogram: aerial display of 3D vibrotactile sensation,” *Proceedings of the International Conference on Multimedia and Expo Workshops*, pp. 1-5, 2014.

[41] S. Inoue, Y. Makino, and H. Shinoda, “Active touch perception produced by airborne ultrasonic haptic hologram,” *Proceedings of the IEEE World Haptics Conference*, pp. 362-367, 2015.

[42] D. B. Vo, and S. Brewster, “Touching the invisible:localizing ultrasonic haptic cues,” *Proceedings of the World Hap[tics Conference*, pp. 368-373, 2015.