Non-intrusive Haptic Interfaces: State-of-the Art Survey

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Abstract. Haptic rendering technologies are becoming a strategic component of the new Human-Machines Interfaces. However, many existing devices generally operate with intrusive mechanical structures that limit rendering and transparency of haptic interaction. Several studies have addressed these constraints with different stimulation technologies. According to the nature of contacts between the device and the user, three main strategies were identified. This paper proposes to detail them and to highlight their advantages and drawbacks.

Keywords: haptic interface, intrusive device, workspace, stimulation strategies.

1 Introduction

Today, haptic technologies are involved in different fields. For instance, in the Product Lifecycle Management (PLM), where haptic based VR approaches have increased both speed and accuracy of human-computer interactions for the edition and the assembly of the 3D CAD models [Bordegoni, 2009]. In the field of the training and rehabilitation, haptics plays an important role for the training of sensory motor skills and to alleviate the motor system impairments [Broeren, et al.,]. Education, games, and entertainment can be also quoted as disciplines where several studies have shown the role of haptics to improve the learning and the interactivity though serious games approach [Sourina, 2011]. However, the deployment of haptic devices in public and industrial applications is still limited. This is due to the intrusiveness and the limit of some performance factors of existing haptic devices.

Astley and Hayward have listed a number of measures relating the performance of haptic devices [Hayward and Astley, 1996]. Among these, we can find the number of degrees of freedom, the nature of the contact between the user and the device, the amplitude of movement, the instantaneous and continuous forces, the peak acceleration, the inertia and damping of the device, the sensor resolution, the accuracy of the generated force, the stability of interaction and rendering, the environmental factors (such as noise), and the weight of the device.

The human haptic perception is extended in space and sensitivity range. Therefore, the haptic device design has to respond to workspace constraints and dynamics of sensory feedback. Moreover, all aspects of risk management related to the use of haptic devices have to be taken into account.

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The workspace of most actual haptic interfaces is often restricted even to making simple gestures. Moreover, haptic devices based on articulated robotic structures like exoskeletons [Nakai et al., 1998], or cable systems [Sato, 1992] have several limitations. In fact, these strategies adopt devices that must be physically connected to the user through mechanical systems to interact with the virtual object. These systems are often intrusive, limiting the comfort and the transparency of interaction with the environment. This survey aims at highlighting studies and new actuation technologies that address workspace and intrusiveness constraints.

2 State of the Art

According to the nature of contacts between the device and the user, we identified three main classes of strategies for non-intrusive haptic stimulation. The first approach corresponds to attached or wearable haptic devices. The second approach provides a limited contact only when tactile feedback is required. The last approach does not require direct contacts with the material device. We propose to detail these strategies in the following sections.

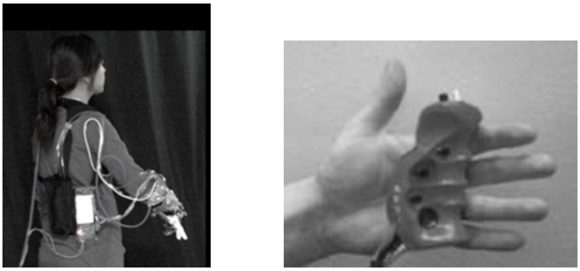
2.1 Attached Haptic Devices

The first strategies consisted in attaching tactile devices to the user's fingers or palms. For example, the CyberTouch device [CyberTouch, 2010] involves wearing a data glove equipped with vibrators that individually stimulate the fingers and palms (see Fig 1.a). Dave Anderson et al., [Anderson et al., 1999] developed a wearable tactile interface for virtual reality (Fig 1.b). This device consists in a pin-matrix of 2 × 3 electromagnetic actuators, mounted on a frame, and fixed on the finger of the user. Each actuator operates in the range of frequency of 8–100Hz, is at a maximum pressure of 1.2N/cm².

(a) (b)

Fig. 1. (a) Vibrotactile Glove device (CyberTouch). (b) Sandia National Laboratories Tactile.

Kim et al. [Kim, 2008] proposed a wearable, small, and lightweight tactile display system composed of piezoelectric ultrasonic actuator arrays (see Fig 2.a). In these strategies, the skin and the device are always in contact, which leads to undesired touch feelings. The Salford university group developed The ARRL, a pneumatic haptic interface (Fig 2b). It integrates three pneumatic actuators, in order to reproduce simple tactile feedback, when the hand (or the user virtual cursor) enters in contact with a virtual object [Stone, 2001]. However, even though data gloves allow more freedom of movement, they provide low spatial and force resolutions.

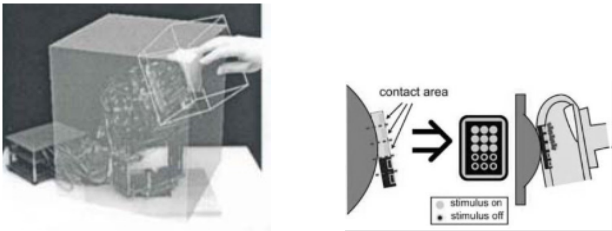


(a) (b)

Fig. 2. (a) Piezoelectric ultrasonic tactile display. (b) ARRL Interface.

2.2 Haptic Devices with Limited Contact

The second strategy consisted in controlling the positions of tactile devices so that they make contact with the skin only when tactile feedback is required. Hirota, and Hirose [Hirota, and Hirose, 1995] investigated the implementation of a haptic feedback for universal surface display (see Fig 3.a). The interface consists of 4×4 pins, on a square surface with a dimension of 20mm². Each pin has a stroke of 50mm. The different combinations of the pins' amplitudes produce different 3D surfaces that can be explored. Sato et al. [Sato, 2007] have proposed a multi-fingered master-slave robotic system featuring electrotactile displays on each finger of the master hand (Fig 3.b). The position of the electrotactile display is controlled so that it is in contact with the user's finger only when the slave robot grasps or touches objects. Major drawbacks of such systems are that they require bulky robot arms and a complicated control method. Drif et al. [Drif, 2004] proposed an alternative approach through a multi-level display concept. The kinesthetic feedback is based on moving and orienting a mobile surface on the contact point when a collision between the real finger and the virtual surface is detected. This approach makes it possible to touch an object without handling or wearing an intrusive mechanical structure. Moreover, it provides a good haptic interaction transparency. The main drawback of this strategy concerns the reactivity of the system and the limit of working space.

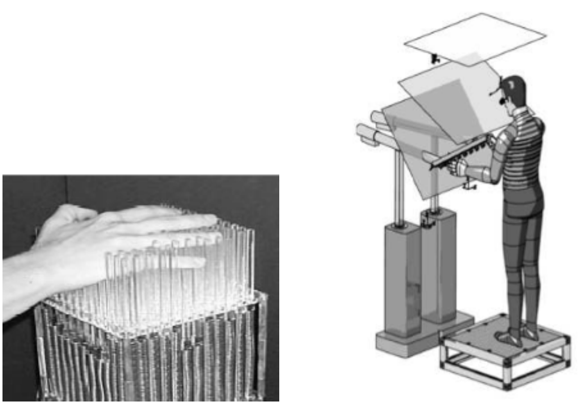


(a) (b)

Fig. 3. (a) Tactile interface based on returned of form. (b) Conceptual representation of the electrotactile system.

Bordegoni et al. [Bordegoni, 2010] proposed the use of an active tangible interface for the evaluation of virtual shapes of aesthetic products (SATIN). The system consists of two MOOG haptic devices which position and rotate a robotic spline. The user can modify the shape of the spline by applying local pressures (see Fig 4.b). The main advantage of this approach is the realism of the interaction with the 3D models. However, it cannot display an arbitrary surface.

The MATRIX (Fig 4.a) developed by Overholt et al. [Overholt et al., 2001], is a device that offers real-time control of a deformable surface, enabling the manipulation of a wide range of audiovisual effects. Interface consists of 144 rods which move vertically in a 12 by 12 grid, and are held up by springs at rest. The device uses this bed of rods to provide a large number of continuous control points, thereby improving the communication bandwidth with the computer. But, this device provides a limited workspace.



(a) (b)

Fig. 4. (a) MATRIX (A Multipurpose Array of Tactile Rods for Interactive eXpression). (b) Conceptual representation of the SATIN system.

2.3 Haptic Devices without Direct Contact

The last strategy consists in providing tactile feedback from a distance without any direct contact. Two approaches have been explored: air-jet-based strategies and acoustic-radiation-based strategies.

Air Jet Based Strategies. Several groups have explored the use of air jets as a means of conveying kinesthetic or tactile information. In the following sections we summarize the main strategies.

Haptic Feedback with Direct Contact with the Air Jet. Bianchi et al. [Bianchi, 2011] studied an air jet approach for generating a lump percept. This work aims to develop a tactile feedback system to enhance palpation using robot-assisted minimally invasive surgery (RMIS) (see Fig 5.a). The proposed approach consists of directing a thin stream of air through an aperture directly on the finger pad, which indents the skin in a hemispherical manner, producing a compelling lump percept. This work investigated the relationship between aperture size and air supply pressure by means of tactile sensor measurements and psychophysical experiments to understand how they affect the perceived pressure on the finger pad. The results suggested that the JND of air pressure on the finger pad is constant, regardless of aperture size. Moreover, this study clearly shows the effectiveness of well-prototyped air jets for tactile feedback. The main limit of this work concerns the stimulation distance, which does not exceed 2 cm. Recently, in the context of the design of a novel non-contact haptic device providing an important work space, Tsalamlal et al. [Tsalamlal et al., 2013] have proposed to use the air jet for direct tactile stimulation with greater distances (>10 cm). This configuration provides an important workspace for a better freedom of movement (Fig 5.b). It can also provide a greater stimulation area with a good force resolution. In this work, authors carried out psychophysical experiments in order to characterize the human perception of the air jet tactile stimulation.

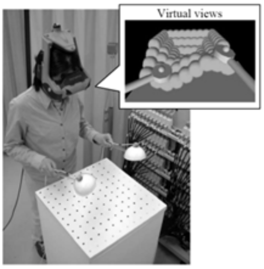
Haptic Feedback through a Flexible Intermediate Surface. Inoue et al. [Inoue, 2009] presented a haptic device using a flexible sheet and air jet. This approach presents the haptic sensation of virtual lumps under the skin to the user's finger. A tensioned flexible sheet is regarded as a virtual skin. The user touches the sheet directly with his or her finger. Then he or she feels the softness of normal skin as the sheet compliance. A nozzle fires a thin beam of an air jet onto the back of the sheet when the user touches the sheet at the location of a virtual lump. The main drawback of this strategy concerns the limit of working space, since the exploration of complex surfaces requires the translation/orientation of the flexible sheet.

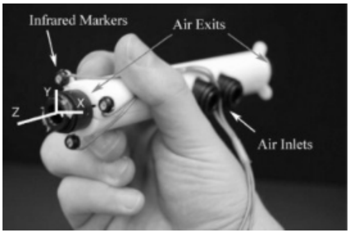
(a) (b)

Fig. 5. (a) Air lump display for RIMS. (b) Conceptual representation of long distance air jet stimulation.

Haptic Feedback through a Rigid End-Effector. Suzuki [Suzuki, 2005] proposed a haptic device consisting of multiple air jets arranged in a matrix and air receivers held by the user (Fig .a). The air jets from the nozzles hit the air receiver and apply forces on the user's hand. The purpose of the receiver is to act as an interface for receiving the air jets. This haptic device enables interaction with static or dynamic surfaces. This strategy presents different drawbacks, such as the limit of the force and position resolutions. Moreover, the user needs to handle an end-effector.

Haptic Feedback with Portable Jets. Xu et al. [Xu, 1991] developed a system where a single air jet was mounted on the wrist of a user, and short force perturbations were applied to the user's arm by quickly opening and closing the air jet valve. The system generates a binary force sequence with a steady state thrust of 4 N. The signal frequency varies between 75 Hz and 150 Hz. This system was mainly used for the study and identification of the mechanical properties of the human arm joint. Romano and Kuchenbecker [Romano, 2009] presented a portable haptic interface (AirWand) with one degree of freedom (DoF), which provides a large workspace (15 m3 instead 0.006 m3 with standard devices). The system is based on a 1-DoF tool that has two air jets aligned along the longitudinal axis of the tool, indicated as air exits (see Fig 6.b). These two jets are used to create forces along the longitudinal axis in both the positive and the negative Z direction. The maximum peak force experienced during trials was around 7.58 N and the maximum continuous force was F = 3.16 N. Gurocak et al. [Gurocak, 2003] proposed a 3-DoF version of the same concept. The system consists of six jets attached around the wrist and oriented along three orthogonal axes. By controlling the air flow through each valve, the system commands three degrees of force output at the user's wrist. The main advantage of this strategy concerns the generation of a real kinesthetic feedback with an important workspace. However, the user needs to handle an end-effector, which limits the transparency of the interaction.





(a) (b)

Fig. 6. (a) Air jets matrix array for virtual reality. (b) AirWand device.

Acoustic-Radiation-Based Strategies. The second candidate for providing haptic feedback in the free space without direct contact with a mechanical structure is based on the acoustic radiation pressure generated by ultrasound transducers (see Fig 7). Takayuki et al. [Takayuki, 2008] proposed the use of acoustic-radiation pressure to provide tactile feedback in 3D environment.

Fig. 7. Airborn ultrasound tactile display

The concept is based on controlling the phase delays of acoustic waves to generate a focal point. The prototype consists of 91 airborne ultrasound transducers controlled through a 12-channel driving circuit. The measured total output force within the focal region is 0.8 mN, the spatial resolution is 20 mm, and the prototype produces vibrations of up to 1 kHz. A recent version of this interface significantly increases the working space and provides an output force of 16 mN at the focal point [Takayuki, 2010]. The main drawback of this haptic technology concerns the limit of force intensity. Moreover, the authors highlight some medical risks of interactions with sensitive regions (e.g., head and face). Currently, the interface is used with the hand and arm only. A medical study is in progress.

3 Conclusion

Haptic interfaces are relatively recent devices. These interfaces physically stimulate a user through tactile and kinesthetic perception, which provides a better presence and immersion in virtual environments. For the user, the issues focus on comfort and fidelity of the interaction and perception.

Current haptic devices operate essentially with articulated robotic structures, or cable systems. Most of these systems are intrusive and are not practical in many fields such as games and desktop applications. A number of systems, using direct (e.g., data gloves) or limited contacts with the user, allow more freedom of movement but provide low spatial and force resolutions. Currently, other works investigate non-contact stimulation technologies. Two main strategies were investigated: the acoustic radiations tactile stimulation, and the air jets tactile or kinesthetic stimulations.

The use of acoustic radiations does not allow high intensity stimulations and could present a significant risk for the user. The air jet approaches seem more promising. But, existing works exploit either intermediate object for interaction with air jet (i.e., air receiver), or exploit very short stimulation distances, restricting the user's workspace. However, more recent works are investigating actuation technologies based on air jet stimulation with longer distances, and larger workspace.

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