Haptic feedback: from force-reflecting robots to tactile interfaces

Michaël Wiertlewski
Aix-Marseille Université, CNRS, ISM UMR 7287, 13009, Marseille, France

Abstract:
During the last century, technical means of broadcasting sounds and pictures came into existence. And today, many scientific and industrial efforts are being made to develop means of broadcasting tactile and haptic sensations. This review covers the latest technological systems and smart actuators used to stimulate the sense of touch and deliver programmable haptic sensations.

Keywords: Haptics, Tactile feedback, Vibrotactile, Actuators, Surface Haptics

Introduction

More than a decade ago, Hayward et al. observed that before computers became a common workplace fixture, most human tasks used to involve fine sensory-motor skills, whereas little use has been made so far of the sense of touch in human-computer interactions [1]. Haptic interfaces restore the tangibility of the interface with a computer and are beginning to transit from the laboratory to the industrial world in the context of concrete applications such as virtual reality, gaming and wearable electronics.
However, most human-computer interfaces are still devoid of tactile and haptic feedback and their performances therefore fall far short of our exquisitely complex human sensorimotor skills. Whenever we use a keyboard, mouse, or touchscreen to interact with a machine, the mechanical cues that we perceive are not in the least interactive. The resistance of a click will be identical, whether or not the virtual button has been disabled, and the frictional drag of the user's finger on the touchscreen will not reflect the shapes conveyed by a visual display.
Haptic interfaces bridge this gap by providing bi-directional interactions in which the user can touch the artificial environment and the computer will respond by providing tactile and/or kinesthetic feedback. The force levels fed back to the user can be correlated with the displacement, velocity and acceleration of a limb and generate realistic dynamic environments that have elastic, viscous or inertial properties.

Human sensory-motor abilities

Haptic interfaces strive to mimick the mechanical interactions occurring in the real world. Actions such as pushing an object, sensing the texture of a fabric and handling a cup generate forces that vary in time and space. The effects of these forces on the muscles contribute to our kinesthetic perception of the environment and the deformation of the skin, which also occurs in the vicinity of the contact between the body, and an object constitutes the basis of tactile (cutaneous) perception.
The somatosensory system combines these mechanical stimuli along with the motor commands to create a haptic representation of the surroundings, Perception of friction, stiffness, curvature and other attributes of held objects play a central role in planning fine motor actions. Because the properties of the contact often cannot be assessed visually –for instance because vision is occluded by the hand– tactile cues are absolutely necessary for guiding movement.

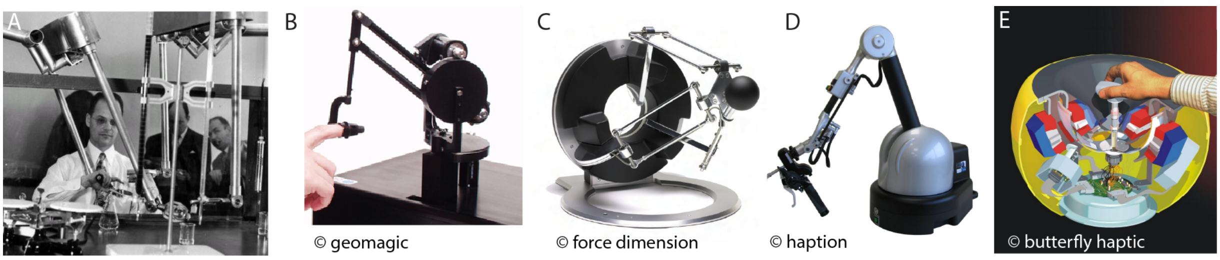

Figure 1: A. First teleoperation apparatus [5]. B. The PHANToM, one of the first commercial haptic interfaces to be developed [7]. C. Parallel robots with greater stiffness and a wider frequency bandwidth. D. Serial implementation for larger workspaces. E. Magnetic levitation replaces linkages and effectively removes friction.

Just as designing loudspeakers requires a thorough understanding of the human auditory system, designing haptic interfaces requires detailed knowledge of the processes underlying human sensorimotor skills. The forces exerted by humans interacting with the environment with their arms can be as large as 100 N [2]. In contrast, the smallest force detectable is four orders of magnitude smaller under quasi-static conditions [3] and six orders of magnitude smaller when the stimulation is dynamic [4]. The changes in forces that are perceived include frequencies ranging from quasi-static to about 800 Hz, and a peak in the sensitivity occurs at around 250 Hz [5]. The vast dynamic range of haptic perception makes it difficult to emulate the entire repertoire of human haptic sensations with a single artificial device.

Force-reflecting robots

One of the methods most commonly used to simulate haptic interaction is force feedback. The user holds the manipulandum of what is essentially a small robot. The force applied to the end-effector varies according to the user's motion, resulting in realistic sensations of collision or the frictional sliding of objects on virtual walls. Force-reflecting robots originated from remote control devices developed in the nuclear and spatial sectors [6,7,8] for dealing with issues of conveying a force sensed by a slave robot back to an operator (see Fig. 1A). In the context of virtual reality, a physical simulation replaces the remote robot.

An ideal force-feedback device would accurately reflect the force levels computed by the simulation or sensed by the remote apparatus, and thus have an infinite stiffness and virtually no mass or damping between the motor and the end effector. In practice, however, structural deformation and the inertia of the linkages have to be taken into account to ensure the transparency of the interface.

The simplest force-feedback system is one with a single degree of freedom. In this simple case, a virtual environment can be explored by performing either linear or rotational movements and simulate complex responses to events such as the puncture of the skin during the insertion of a virtual needle or the resistance of a virtual steering wheel. The number of degrees of freedom can be increased in order to simulate more complex virtual environments. Planar and 3-D interfaces use linkages between the end effector and the actuators, which are often located in the base. The main disadvantage of these linkages is that they increase the weight and the inertia, which is detrimental to the sensation produced. In the PHANToM [9], one of the first mainstream devices to become available on the market, a near-perfect balance was reached between the weight of the end effector and that of the DC-motors, so that there was no longer any need for a gravity compensation process (see Fig.1B). To create stiffer interfaces, parallel structure such as the planar 5-bar [10] and Delta configurations [11] presented in Fig. 1C have been adopted. Serial configurations such as that shown in Fig. 1D are offer less stiffness in return for a vastly larger workspace in which whole arm interactions can take place.

Actuators and power requirements

The majority of force-feedback devices rely on coreless brushed motors for actuation. Electric motors of this kind boast low rotational inertia and ease of control. And contrary to brushless motors, which may seem at first sight to be more suitable because of their low speed and high torque, coreless DC motors do not exhibit torque-cogging [12]. Non-homogeneity of the torque throughout the angular range creates ripples that are responsible for undesirable oscillations, which usually have frequency components of around 100 Hz, to which the human perceptual system is particularly sensitive. Some efforts have been made to compensate for cogging [13]. Butterfly Haptics use Laplace-force motors inducing multi-axis magnetic levitation to produce force feedback (Fig. 1E). Since this application is devoid of linkages, it involves remarkably low levels of friction [14]. In order to

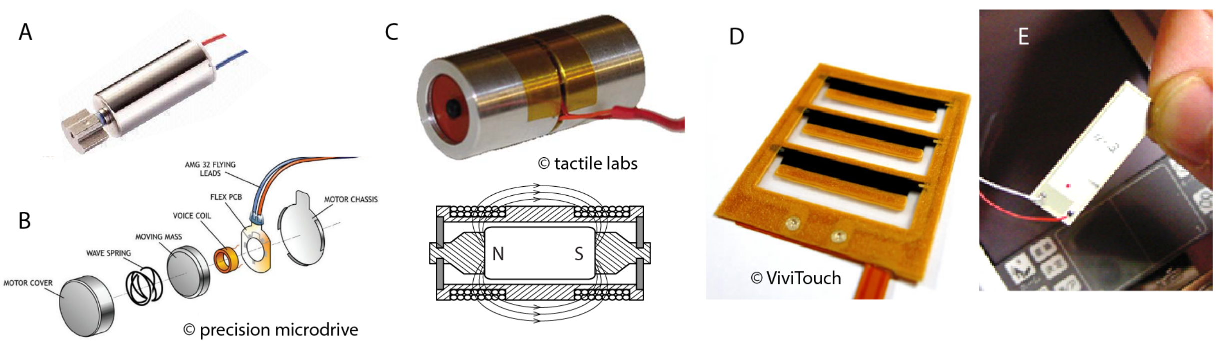

Figure 2: A. Excentric rotating motor suitable for simple rumble. B. Exploded view of a linear resonant actuator (LRA). C. The Haptuator provides a tactile stimulation with a 50 to 500 Hz frequency bandwidth using Laplace force actuation [21]. D. Example of a vibrotactile stimulator made of electroactive polymer. E. Owing to its fast response time, piezoelectric bimorph is another popular choice of material.

the ensure a compatible with MRI, some haptic interfaces specifically made for neuroscientific inquiry, use pneumatic pistons or traveling-wave piezoelectric motors instead of electromagnetic actuators [15,16].
All actuators alike suffer from the fact that a tradeoff has to be made between the maximum force they can deliver and their inertia. The ideal motor would have a large torque output while showing low rotational inertia. To overcome this physical limitation, some authors have combined a fast, light actuator producing the transients of the signals with a larger, more powerful motor that is capable of delivering large tactile forces [3]. In addition, to ensure that the control loop will always be passive and reduce the power consumption, some interfaces combine brakes and actuators [17,18].

Vibrotactile feedback

In spite of the wealth of sensations now being mediated by force-feedback interfaces, recent scientific and technological developments have focused on improving the performances of vibrotactile devices. The main reason for this development has to do with the progress made in the field of mobile electronics. Eccentric rotating-mass motors, which take advantage of humans' acute sensitivity to vibration, provide a cost-effective solution for communicating tactile signals. However these motors suffer from a coupling between the amplitude and frequency of the stimulation which both depend on the rotational velocity. It limits the range of stimulation possible with eccentric rotating-mass motor to simple rumbles (see Fig. 2A). The latency due to the acceleration of the motor is also a serious limitation. Instead of relying on the rotation of a mass, linear resonant actuators (LRAs) have a linear suspension actuated by electromagnetic forces, which resonates strongly at one particular frequency. Exciting the actuator at a high-Q resonance triggers a sharp vibratory tone, which typically falls around 200Hz. This construction allows for faster response time than pager motors. Because of the low power consumption required thanks to the resonance, these actuators are well suited for mobile electronic applications. More complex signals, which include multiple frequencies, can be generated by modulating the amplitude of the resonant frequency [19]. To produce richer signals, linear voice-coil systems, such as the one shown figure 2B, have been designed to damp the resonances, offering a wide frequency range of stimulation [20,21]. Because of the additional dissipation, however, more energy is required to generate a given signal amplitude. The high quality of these devices is at the expense of the consumption and the compactness. When driven by an appropriate vibration synthesis algorithm, these high-fidelity vibrotactile actuators are able to simulate the subtle vibrations of a virtual guitar string, the texture of a fabric or the sensation of a ball rolling over a rough surface [22,23,24].
While most of the vibrotactile stimulators available use electromagnetic forces to impart vibrations, some others have been designed using electro-active polymers (see Fig. 2D) or piezoelectric bi-morph materials (see Fig. 2E). These actuators have the advantage of being thin, solid-state materials and often boast higher energy densities at the expense of higher operating voltages [25].
A single vibrotactile actuator can be used to send complex transient and vibratory signals back to the user. However, the user's perceptual experience can be greatly enhanced by distributing multiple actuators across the skin in order to produce spatially patterned sensations. By tuning the timing and the relative amplitude suitably in each of the cells in the array of vibrators, the discreteness of the

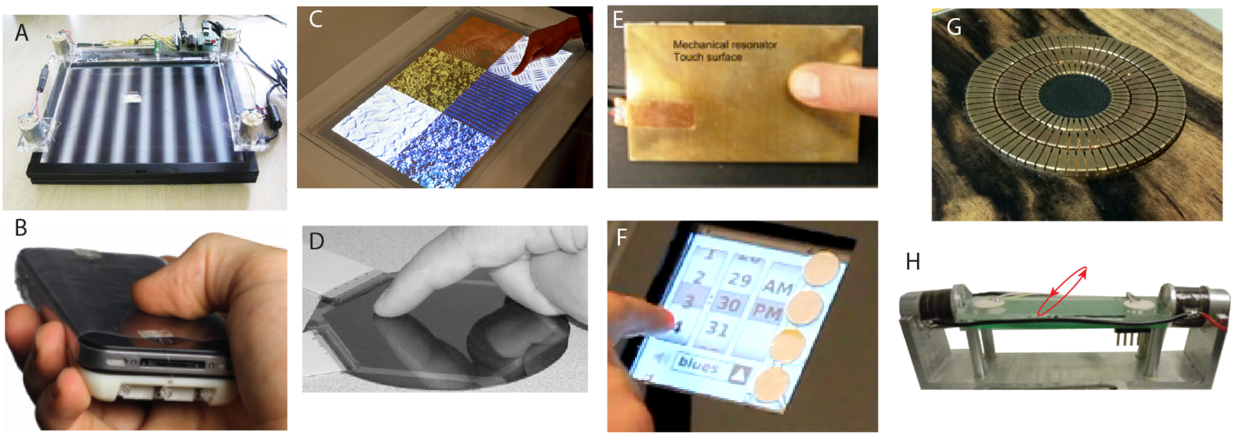

Figure 3: A. Cable-driven overlay [33]. B. Flexible wrap-around overlay [34]. C. Device using electrovibration to provide tactile texture [36]. D. Spatially distributed electrovibration device [37] E. Ultrasonic friction modulation on a metal resonator [41]. F. Transparent version of the ultrasonic friction modulation device. [42]. G. Travelling wave motor delivering shear forces to the static finger. H. 2-axis ultrasonic vibration delivers programmable lateral forces to the bare fingertip [46]

array can be made to disappear, leaving the user with an impression of a moving actuator. This effect was first observed by von Békésy [26] and used for non-intrusive navigation [27] and game-playing [28] purposes. Another technique worth mentioning is that in which two adjacent actuators are driven in anti-phase to produce a sharp edge at their boundary [29]. Lastly, a method has been developed in which asymmetrical stimulation is applied with an ungrounded actuator so that the maximum signal amplitude is greater during one part of the periodic motion, giving the user the perception of a net overall force [30].

Surface haptics

Vibrotactile actuators are especially suitable for simulating complex tactile interactions in mobile devices. However, by construction, their frequency range is limited to approximately 50 to 500 Hz, and does not include the low end of the spectrum, where force-feedback devices typically excel. Low-frequency forces, especially the continuous force component, are fundamental for simulating contact with virtual shapes, walls and switches [31]. When pressing on a virtual spring, for instance, since the force is a function of the displacement and not of time, the reaction force can be expected to persist as long as the pressure is maintained on the spring, even if the finger stops moving. Much research has focused during the last decade on designing means of delivering simulated force feedback directly to the bare fingertip, a class of device called surface-haptic. Some authors have used micro-fluidic approaches whereby dots are raised on the surface, providing the user's fingertip with a series of tangible bumps [32]. Other authors have provided force feedback on a touchpad via a moving overlay placed over a screen, which pushes and pulls the finger along [33]. The force is transmitted to the fingertip via a cable assembly (Fig. 3A) or using a flexible sheet of plastic wrapped around the device as shown in figure 3B [34].

However, solid-state devices, which modulate friction directly between a surface and the fingertip, are among the most promising applications. One implementation called electro-vibration, increases the normal force applied by a fingertip onto a surface by means an electrostatic attraction. The increase normal force therefore affects the friction force that is experienced by the user. Eletrovibration is achieved using a conductor covered by a thin insulator. The conductor will accumulate electric charges that will repel any opposite charges present in the skin contacting the insulator. Because of the insulation, no current flows, but an attractive force will make the skin adhere more firmly and thus increase the friction force [35]. Some devices derived from transparent touchscreen overlays, such as the 3M microTouch shown figure 3C, contain a large ITO conductor coated with a thin silica insulator and provide off-the-shelf solution for building elaborate computer-interfaces equipped with electro-vibration [36]. Patterned conductor arrays such as that shown in figure 3D make it possible to spatially distribute the effects and eliminate the need for a fingertip position sensor [37]. Electro-vibration is able to affect friction forces only by approximately 100 mN, which are perceptible only when the signals carry a high frequency component. The oscillating voltage is of the order of 100V with a maximum ac current of 5mA. Electro-adhesion, where a semi-conductor replaces the insulator, creates lateral forces as large as 4N, thus dramatically increasing the force range achievable while conserving the wide frequency bandwidth provided by electronic switching devices [38,39].

Another method based on ultrasonic vibration reduces the friction force induced by a finger sliding over a smooth or rough surface. This method makes use of the non-linear compression of the air trapped between the skin and the surface, causing the skin to levitate a few micrometers above the surface. Because of this slight levitation, the contact area between the skin and the surface is smaller and the user feels less frictional drag [40]. The friction force can be programmed to evolve according position and the velocity of the user's fingertip which give rise to sensations of bumps, holes, textures and gratings [41,42]. Examples of devices designed on the basis of this principle are presented in figures 3E and F. The range of lateral forces achievable starts at around 2N, but this value depends on the substrate material and can be decreased by one order of magnitude at vibration amplitudes higher than 2 μm. These devices are usually constructed around a rectangular glass plate that is excited by piezoelectric actuators bonded onto the plate. The expansion and contraction of the piezoelectric actuators produce a standing flexural wave that causes vertical oscillations of the plate. The power required to sustain the levitation has been estimated to be approximately 1W [43].

Variable friction is undoubtedly a strong candidate for providing modern touchscreen interfaces with the ability to produce programmable tactile features. Still, this approach has a major limitation. Since friction is modulated, the force experienced by the finger is always in the opposite direction to that of the user's motion. When simulating situations, such as moving over oblique gratings or going downhill, the force has to be in an arbitrary direction with respect to the motion of the finger. Forces also have to be applied independently of the motion of the finger in order to simulate elastic force fields, which are required even in the case of static interactions. By generating surface acoustic waves on a $LiNbO_3$ substrate, a net force can be exerted on a finger equipped with a slider [44] fitted with a bed of small steel spheres which couple with the surface wave traveling on the substrate. The traveling Rayleigh wave imparts an elliptical motion to the surface, which pushes the slider. However, at the amplitude and frequency levels used in these particular applications, the effects produced are rather weak, and it is not possible to transmit a force directly to a bare fingertip. Traveling wave ultrasonic rotary motors also produce an elliptical motion of its surface. Touching the stator with a bare finger creates forces that can push or pull the finger along the wave track [45]. Figure 3G shows 3 concentric travelling wave motors that can be adjusted by changing the position of the finger, giving rise to a complex and unique perceptual experience. Dai et al. create the elliptical motion required to exert active forces on the finger, using a combination of vertical and normal motion on a two-axis resonant system [46]. At specific phase relationships between the lateral and normal motion, forces of up to 200mN can be transmitted to a static finger (Fig. 3H).

Conclusion

Haptic is the perception of the mechanical events at work when we interact with the nearby environment. In order to simulate this perceptual experience, the most widely used approach consists in mechanically stimulating the user's limbs and skin. This gives actuators the central role in haptic technology. Consequently, a large body of work has been devoted to finding the combinations of linkages, actuators and physical processes that effectively to transform electric energy into programmable mechanical stimuli.

Just as loudspeakers have been optimized so that they produce auditory sensations with precise linearity, bandwidth and sharpness, designing haptic interfaces starts with selecting the most appropriate actuators, on which the quality of the forthcoming haptic experience depends.

To date, force feedback technology has permeated several markets, such as those dealing with virtual reality, tele-robotics, medical training, gaming, micromanipulation and minimally invasive surgery. However, because of their inherent complexity, the haptic devices are for the most part limited to industrial and medical applications. Vibrotactile simulation and surface haptics are now progressing towards bringing haptics onto the consumer market, in the hope of endowing our everyday electronic devices with tangibility and simulating the fine perceptual effects and which will allow us to leverage our fine sensorimotor skills when interacting with modern machines.

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