Haptic Devices Actuation: Functionnal Overview and Typology

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Abstract

This article presents a general analysis on the actuators of haptic devices. This analysis aims first at clarifying the status of this component among the various aspects of haptic devices functions and performances. The functional structure of the actuation system is introduced. This basic structure is then used to establish a general typology that attempts to encompass most of the current and historical haptic technologies. Within the proposed classification, the strength and limitations of the different actuation technologies are discussed.

1 Introduction

The actuator is an essential and critical element of an HD: it constitutes with the mechanical linkages the part of the haptic device that supports the physical constrains/mechanical energy flow that are inherent to the haptic interaction [5].

The haptic device actuator role has been associated to the concept of force feedback and linked to some aspects of the human perception. According to this theoretical guideline the mainframe of haptic actuator performance criteria were based on human tactile-kinaesthetic perception analysis [4]. In addition haptic actuation concept inherited from the classical approach of robotics that situated it in a field of effects and active behaviour. But contrarily to a robot the primary specification of a haptic device is to be a substitute of an object and then to behave mostly passively. The actuator function in this case must be precised since the use of classical actuation concepts may lead to neglect important feature when high precision haptic systems have to be designed.

In the following we firstly examine the functional aspects of the haptic devices actuators and then establish from this model a typology of the actuation systems whose main properties are compared. The objective is to find functional relationships between the existing technical solutions with a quest of genericity for new developments.

2 Functional overview of actuation

In a general functional diagram of an haptic device sensing and actuation blocks are two "ports" elements each provided with one side a mechanical port an on the other side, a signal output or input port

These two components constitute the core of the interface between the user's physical real world and the "informational" domain of the virtual models calculation. The sensor function corresponds to a usual concept of measurement, its produces a signal from its physical interaction with the other parts of the device whose meaning (type of sensed variable) is not a completely intrinsic property of the sensor but is conventional and related to a representation system.

The actuator cannot be considered as the reciprocal of a sensor since it is not possible to set a measurable effect from an input signal without violating a simple causality principle. Then it is more appropriate to consider that the primary function of the actuator input signal is to determine a physical constrain like a temporary structural property. This can be schematically represented by the formula:

$$F(f,v) = T(e)$$

where F represents the instantaneous *(f,v)* relation and T is a temporal operator that represents the causal dependency of this relation on the input.

2.1 The energy flow modulation

In the general case the actuation system is at least constituted of two parts

1) A power supply or "buffer" that produces or absorbs the effective mechanical power of the haptic interaction.
2) A passive modulator that insures the control of the power flow by the input signal. The simpler conceptual component that allows obtaining such a control from a low or null energy input signal is a non-accumulative dipole, i.e. a pure dissipative element.

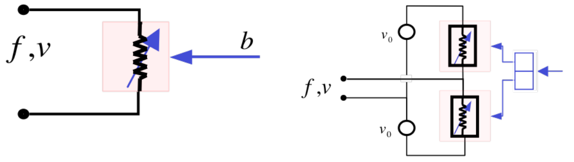


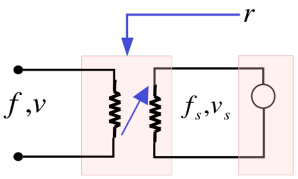
Figure 1. Circuit representation of a controlled brake, and the half bridge push-pull modulator configuration

Then the electric circuit representation of the corresponding actuator structure is a rheostatic circuit whose a symmetric combination allows to cover the four regions of the *(f,v)* plane that correspond to the

Proceedings of ENACTIVE/07
4th International Conference on Enactive Interfaces
Grenoble, France, November 19th-22nd, 2007

different combinations of positive and negative power and speed. That leads to the classical half bridge push-pull (Figure 1).

Another modulator type can be obtained from a non dissipative, energy conservative, transformer whose ratio *r(e)* is controlled by an input signal *e*. This quadripole element is interposed between a power supply and the actuator load (Figure 2). In this case the resulting *(f,v)* curve family is the image of the power supply *(f,v)* curve, by a transformation of the controlled impedance ratio *v/f* .



$$f = r.f_s$$
$$v_s = r.v$$

Figure 2. Circuit representation of impedance ratio actuation

In the first case of a dissipative modulator the power supply provides always a positive power. Then the totality of the ingoing power from the physical environment is dissipated by the modulator.

In the case of the impedance ratio modulator the environment power flows is identical to the supply power flow

The two types of modulator present different properties regarding the resulting internal impedance of the actuator. In the first case (a) this impedance is always highly dissipative. In the second case (b) this impedance is an image of the power supply internal impedance and when several modulators share a same supply the different channels are coupled through this supply bus ; this properties is exploited in the cobots for providing a controlled cinematic constrain (§3.4)

2.2 Alternate energy flow modulation

The conceptually simpler actuation system would consists in a complete mechanical realisation of the above schemes. However in the usual context of industrial servo-controlled systems and robotics the technology of such systems could be relatively complex. For this reason, and because of the availability of mature technologies in the domains of energy conversion and power control, alternate energies, mainly electric in lesser extend pneumatic and hydraulic, have been employed in most haptic actuators.

The energy conversion is realized by an additional component at the end of the chain. This component is ideally a non-dissipative and non-accumulative "transducer" Its role is to convey in the most transparent way the physical constrains generated by the electric or fluid modulator into a mechanical constrain. In a electric circuit representation this transducer is a transformer whose ratio defines the relationships that link the electric or fluid variables (voltages/ intensity, pressure/flow) to the mechanical variables (speed/force) .

A particular issue that concerns energy conversion is the commutation: In order to perform the infinite cyclic motions that are natural in the mechanical motion space, the transducer may include a commutation principle. This is one of the basic features of the classical electric DC machines It consists in a mechanical combination of several elementary transducers each operating on a limited portion of the motion space. The commutation system may be independent on the modulator (electric brush motors) or integrated with it (electric brushless motors). Commutation leads to a variation of the actuation characteristic at each commutation step. This drawback named "cogging" is particularly sensitive at low or null speeds.

2.3 Local control loop

In practice the (f,v) curve families of the actuation system are not convenient for the type of control signal that is issued from the calculation. In addition these characteristics may be sensitive to external parameters. To overcome these limitation a local feedback is set up to control the (f,v) /input signal according to the desired type of control (Figure 3).

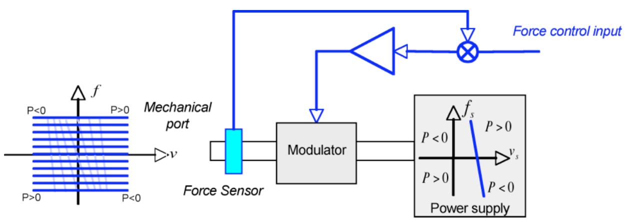


Figure 3 Example of local loop of a force controlled actuator

The use of a control loop leads to a new family of (fv) curves but the availability of these new physical characteristics is limited by the cut-off frequency of the control system, itself depending on the actuator load (the physical environment).

The particular actuators like force actuators or motion actuators are necessarily based on such a local control loop.

3 Typology of actuation

Depending on the type of alternate energy, type of modulator and technology, a wide diversity of actuation systems may exist.

3.1 Electro-magnetic actuators

The electric systems are the most commonly employed because of the suitability of electronics technology in making high performance/ low cost electric modulators. This leads to shift the focus on the electromechanical transducer that is more critical component of the actuation chain. Different physical conversion principles exist. The Laplace force based electro-magnetic devices are the most widespread with DC motors and linear or rotating electro-dynamic transducers. The haptic DC motor are generally commercial devices except some that have specially been developed for high performance haptic/robotic usages[6](§5.3.2). The electro-dynamic systems are specific devices: the ACROE ERGOS shared flux modular multi-axis device [7], the special 2 axis rotating actuator of UW [12] designed for 2 Dofs fingertip haptic.

The essential limitation of the electromagnetic transducers *is quantitative* and related to their maximum specific power and specific force that are determined by the physical properties of the active materials (conductors and magnets)[11]. The force limitation is the most critical for the haptic usage.

Their strengths are their intrinsic linearity, high bandwidth and the obvious advantage of the Laplace force is its ability to circulate through a gap of air thus avoiding material link between the actuated parts. This property that greatly simplifies the structure of the cyclic commuted actuators (the classical DC motors) has also made it possible to design efficient active levitation systems like the CMU Maglev [8].

3.2 Piezzo-electric actuators

Unlike electro-magnetic motors the piezzo-electric transducers provide great forces under low volume. That could be a significant advantage for haptic actuation. On the contrary since they work by deformation, their displacements are restrained. This last limitation is overcome in some miniaturized high torque motors by the use of cyclic operation of several elementary cells with alternate contact /release phases [6]§5.3.6. However these technologies are not still completely convenient for haptics because of the too limited speed and hard non-linear properties of these devices. Finally the haptic uses of piezzo-actuation are mainly limited to the very small working space of tactile stimulators. In this case the actuator consists of sets of independent elementary piezzo-transducers.

3.3 Circulating fluid actuators

The main properties of these types of actuation are described in [6]§5.3.Their common interest is the lightness of the transducer (cylinder) that makes them suitable for portable haptic interfaces[3]. Pneumatic is more convenient for low cost systems. Its major limitations are the poor bandwidth due to the compressibility of the air and the important dry friction of the air cylinders. The hydraulic technology although hard to set-up is potentially highly efficient for haptics Hydraulic cylinders present high force capability, high bandwidth, high stiffness, and low inertia. Unlike electric actuators the only physical properties that limit the power of a hydraulic converting device are the mechanical limits of the material. As a consequence at equivalent power and force capability the hydraulic device is lighter and smaller than the most efficient electric transducer. Then direct joint actuation is possible thus avoiding gear reduction and commutation.

There is still an open field for adapting the hydraulic technology to haptics and overcoming its technical drawbacks that concerns essentially the availability of high bandwidth servo-valves. Then the hydraulic technology could be an alternate solution to electric actuation for medium and large size systems.

3.4 Mechanical systems

The direct modulation of a mechanical energy flow is possible in two different ways:

1. By controlling the friction coefficient of special clutches or brakes. In this case the mechanical modulator is a push-pull of two such clutches combined with mechanical power supply. The recent advances in smart materials, in particular magneto-rheological fluids is a way to overcome the limits of the traditional electro-magnetic powders in the design of such controllable brakes and clutches [2].

2. By using a continuous variable ratio transmission system as CVT that links the load to a constant speed supply. Such variable ratio transmission systems were employed on an active 6-DoF device called active cobot. This device allows obtaining very high stiffness with low inertia [10].

The limitations of the two types of mechanical modulators are:

1.The use of a constant speed rotating motor is be a source of sensitive vibrations.

2. Their input bandwidth is generally limited by the input electromechanical conversion device.

Their main advantages are:

1. The dynamical limitations inherent to the energy transducer are avoided.

2 Both dissipative and CVT modulators present high dynamical performances in their direct open loop physical properties.

3. The mechanical control of an infinite cyclic motion is natural in the mechanical motion space and does not require any commutation system.

4 Unlike in energy conversion systems the absence conversion losses allows designing efficient passive actuators with the 2 types of modulators

(dissipative & CVT). The power supply is then replaced either by a null motion ground, like in the direct contact MR fluid devices[9], or by a 1dof free motion mechanical buss that allows the passive inter-axis coupling, like in the passive cobots [10].

3.5 Compared properties

Several categorizing properties appear between the different technologies. The first concerns the transfer characteristics related to the control input. The second concerns the physical property the device is able to exhibit out of control or in stationary control mode.

Regarding the haptic requirements the first properties defines the ability of the actuator to follow the closed loop control from the virtual objects calculation. The versatility of the system and the field of variability of the provided behaviour will depend also on this property that refers to the "Z width" concept. The second will define the sizing limits (forces and speeds) of the haptic device and it's out of control behaviour.

Then the mains 3 classes of actuators examined above can be compared according to these criteria: Electric systems present poor intrinsic physical properties (high inertia and limited stiffness) but high control capabilities. On the opposite mechanical system present very interesting physical properties but reduced control bandwidth that limits their usage to specialized application where the desired behaviour fits with their intrinsic physical properties. Hydraulic actuation although rarely used in haptics presents promising features for high performance and large size haptic devices.

4 Conclusion

We have proposed a functional representation of the actuator system with the attempt to clarify its role in the haptic interface functions. From this representation we have proposed a typology of the different technologies encountered in the today haptic devices domain. This typology allows establishing various types of similarities between haptic devices and new criteria for the comparison of the different technologies for a better understanding of the encountered bottlenecks. It appears that a majority of haptic devices are built from the current actuation technologies that had been developed in the various domains of controlled mechanical systems. These devices are generally convenient for large or medium work space where spatial and geometrical constrains are predominant. Several specialized systems are more focused on high performance dynamics or very special usages where specific performances are required (passivity, high bandwidth). These developments have leaded to original actuation solutions whose design is based on a deeper analysis regarding specific haptic issues. Although initially focused on very specific usages these components may constitute alternate solution to the classical systems in the cases where their technology has reached its physical limits. Besides these cases a wide landscape of non explored solution exists either in the field of converting systems or in direct mechanical modulators.

Systematic exploration and comparison of the different actuation technologies could result in a better knowledge of the limits of actuation and provide realistic guideline for future researches in haptic interfaces.

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