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Vincent Hayward
Pierre and Marie Curie University - Paris 6

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Performance Measures for Haptic Interfaces

Vincent Hayward and Oliver R. Astley

McGill University
Center for Intelligent Machines
3480 University Street, Montréal, Qc, H3A 2A7, Canada

Abstract

A haptic interface is distinct from other display devices because it is bi-directional; it is capable of both reading and writing input to and from a human user. Due to both the direct human interaction and bi-directionality there has been much ambiguity in describing and evaluating these devices, making evaluation and comparison difficult. The goal of this paper is to set out requirements and guidelines for the performance measures of haptic devices and to hopefully lead towards resolving the current equivocal situation. In particular, performance measures are introduced which have so far not been pertinent in traditional robotics; these include, peak force, peak acceleration and frequency dependent measurements. Performance measures often quoted in traditional robotics are also discussed, however, the focus and relevance of these measures are different in haptic devices. Each of the suggested performance measures in this paper is discussed with respect to its importance, its measurabilty and the condition under which it should be measured.

1 Introduction

Many kinds of haptic devices and force-reflecting hand controllers have been created over the past decades. The earliest ones, devised for telemanipulation of hazardous materials, are mechanically connected to a slave manipulator. Newer ones, instrumented and powered, are connected to a slave manipulator via analog or digital control. Virtual environments, made possible by the recent availability of inexpensive computing power, replace a slave system and the task by a computational model. From this perspective, the development of hand controllers spans almost half a century.[1]

This paper is written in an attempt to progress toward collecting a set of device-specific quantitative measures. It is hoped that this work might lead to a practical means to measure progress in the art of designing and building haptic devices (defined in next section). The availability of such widely accepted set of measures would have numerous important advantages in the field of teleoperation and virtual environments.

Most industries (computer, aerospace, vehicles, electroacoustic, etc.) have already developed such commonly accepted sets of performance measures. The benefits that follow from these measures are numerous, for example:

- Device performance (and price) can be matched in an informed fashion to the tasks they are meant to address.
- Devices can be specified before they are built.
- The improvements applied to a particular device or technology can be tracked in a systematic fashion.
- Devices with different designs can be compared.

[1]Flateau, Greeb and Booker in an article dated from 1973 state in the introduction that [7]: "Teleoperator Technology (TOT) as an independent discipline was originated over 25 years ago. While this is quite ancient by today's standards of technology lifetimes, TOT still shows a considerable amount of infantilism by the degree of empiricism involved in all of its aspects not directly borrowed from the many neighbouring disciplines involved.

The advantage of this infantilicism is that activity in the field has not yet been segregated into theoretical and applied specialities whose intense activities contribute to widening the communication gap between those two groups."

These statements ring strangely up-to-date and it can be safely predicted that they will remain so for the foreseeable future.

- The importance of certain particular factors can be ascertained with respect to application areas.

- Progress in the field can be monitored.

No set of quantitative measures will replace the litmus test of actual practice (not any more than for any other technology); nevertheless, these specifications must be attempted.

The identification of single performance numbers is the key to concise reporting of characteristics. Whenever possible, one single characteristic will be associated to a single number in an attempt to clarify the associated significance. This will result in a sizeable amount of such numbers. In this spirit, we will make no attempt at specifying an ideal device given the strong dependency on applications and operating conditions.

In the paper we will make use of the concept of "ground device". This refers to the intrinsic physical characteristics of the device unchanged by control. This will not only be useful to evaluate the device before control, but also to evaluate the performance improvement and the ability of the device to modify its parameters once controlled.

This will be useful to specify the performance of the control. Conversely, it will be useful to specific the ability of the device to modify its apparent properties under control.

2 The Haptic Channel vs. Other Channels

Haptics refers to that part of physiology pertaining to the sense of touch; it has become the standard term to qualify studies and technologies concerned with this sense. Haptic feedback relates to two cognitive senses: the tactile sense that gives an awareness to stimuli on the surface of the body, and the kinesthetic sense that provides information on body position and movement. Bidirectionality is the most prominent characteristic of the haptic channel. Haptic perception always involves exchange of (mechanical) energy—and therefore of information—between the body and the world outside.

The word 'display' emphasises the uni-directional nature of information transfer, as such, it is probably not the best word to be qualified by 'haptic', as opposed to 'graphic' or 'audio'. In addition to vision and audition, vestibular perception informing humans of mechanical signals related to body motion is also uni-directional in this sense. In the case of, vision, audition and the vestibular sense, body motion is of course intimately linked to perception, which is why all these three channels can elicit vection, or sensation of motion. However, none of these channels is linked to a somatic means of modifying one's immediate physical neighbourhood. In other terms, with vision, audition or vestibular perception, there is no significant exchange of energy between the body and the world outside.

This distinction is most apparent if one considers that visual, auditory or vestibular signals (olfactory too) can be recorded and replayed (people watch movies, listen to audio recordings, or have rides in vehicle simulators). On the other hand, recording and replaying kinesthetic and tactile sensations does not make sense, except possibly for the display of textures and certain material properties.[2]

A large proportion of modifications made to one's environment involves the use of the hand. This is particularly true of the interaction with machines and the majority of haptic devices so far available.

To summarise, bi-directionality is the single most distinguishing feature of haptic devices when compared to other machine interfaces. A haptic device must be designed to "read and write" to and from the human hand (or foot, or other). As it turns out, the "read" part is relatively easy to achieve and a great many types of devices already exist (knobs, keys, joysticks, pointing devices, etc.) although many issues are still unresolved. The "write part" is comparatively much more difficult to achieve. More specifically, the function of the haptic display is to recreate constitutive properties (relationships between variables of flow and effort).[3]

These observations are at the root of a set of measures proposed here. They bear much analogy with specifications for graphic screens or electroacoustic equipment but have two major differences: they must deal with multiple dimensions and refer to both efferent and afferent channels.

In order to clarify the scope of the discussion, we will refer to any device, thereafter called a haptic device, having these two characteristics: (1) apply mechanical signals at distinct areas of the body (2) measure mechanical signals at the

[2] In effect, the perception of thermal conductivity cannot be replayed: it involves the transfer of heat from the hand to the item being touched, to measure head diffusion.

[3] That holds for the thermal conductivity example too.

same distinct areas of the body. Whether these signals refer to forces, displacements, or a combination of these and their time derivatives, is not specified in the definition. This definition also excludes tactile displays in the form of fine pitched active arrays of actuators.

The proposed performance measures are directed toward isotonic devices. This term refers to devices which in their nominal mode of operation are designed to display forces are read position variables. Thus, an ideal device nominally has neither mass nor dissipation, and is a perfect force and position transducer in the respective directions. Many of the measures about to be dicussed will suggest a 'distance' of an actual device to the ideal device. Conversely, isometric devices are designed to display displacement variables and read back forces. Thus, an ideal device nominally has infinite stiffness and is a perfect position and force transducer in the respective directions.

There has been comparatively few isometric devices developed and they would require separate performance measures to do them justice. For these reasons isometric devices are not considered, but clearly, a corresponding set of measures could easily be mirrored from those discussed for isotonic devices.

3 A Plethora of Performance Measures

Walking into the local haptic devices store, one could be forgiven for being overwhelmed by the diversity of performance specifications. What is more, performance indices which appear the same, may not be comparable with each other due to incompatible testing conditions. In this section we comment on the performance specifications of approximately twenty haptic devices, both in academia and industry.

For any robotic mechanical system, such as a hand controller, there are several essential criteria for describing the system, e.g. inertia, friction, weight and backlash. However, the duality of the hand controller to drive and to be driven causes discrepancies as to from where these measures should be taken. For example, is inertia measured as seen from the actuators, or from the output device itself? Out of the devices surveyed, only the Phantom specifications defined that inertia was taken as "Inertia at the tip." [17].

Measurements such as precision, resolution, force output, and backlash are rarely specified as to where they were taken from. For regular robots these measures have traditionally been taken at the individual joints. However for a haptic device, in which a user directly interacts with its output, the choice is not so clear. For this reason when reading performance specifications such as these, there is much ambiguity and hence confusion when evaluating the pros and cons of one device over and other. Until such time that there are recognised standards, there is a need for more specificity in such measures.

The interaction of human and machine implies that the bandwidth of the device is of great importance. This critical factor is inexplicitly overlooked in the specifications of the various haptic devices. Out of the devices we studied only Salcudean's MAG-LEV [22], and the Harwell U.K Hand Controller [23] gave any reference to position and force frequency response. Another largely overlooked factor is maximum acceleration. In emulating stiff walls, for example, the maximum acceleration is critical yet only a couple of the haptic devices we studied gave this performance measure [6].

From the lack of detail, to the miscellaneous specifications which despite their validity defy comparison because they appear in just the one data-sheet. The only reference that could be found comparing several devices by means of well defined parameters is by McAffee and Fiorini [18]. Examples of these miscellaneous measures include: interaction force resolution, effort return gain, deflection, no load accelerations, and play. This highlights the need for a common set of performance characteristics which will bring out the best and worst in individual devices and make meaningful comparison possible.

4 Gross Features

4.1 General Rule

One common difficulty with single number performance measures is their dependency on the operating point. It is proposed that for all single number measures, specifications be provided in terms of best and worst cases over the entire operating motion range of the device. In effect, best case figures are not only of limited importance in the absence of further information, but at the same can be quite misleading. A further suggestion is to specify the maximum value of the rate of change (max gradient) of the measure under scrutiny over spatial variables of displacement and orientation, whatever the case may be.

4.2 Degrees of Freedom

The most prominent feature of a haptic device or hand controller is the number and the nature of the degrees of freedom (DOF) at the active end or ends.

4.3 Device-Body Interface

Unless the active end or ends are attached to the body via some bonding method, the hand or other concerned body parts must be connected to it. Unless the interaction is at all times unilateral, there are essentially two ways to achieve this. Therefore there are three cases of device-body interface: either the hand braces (holds) the device, or device braces the body, or else the interaction is unilateral. This gross distinguishing feature specifies which of the three cases the device in question is designed for. The complete specification will also include the concerned parts of the body: finger tips, parts of the fingers, forearms, heels, ball of the foot, etc.

It is also important to specify which mechanical freedom is active (A) and which is passive (P). For each degree of freedom we specify whether it is unilateral (U), bracing (B) or held (H).

4.4 Motion Range

The motion range specification (MR) poses several problems due to the possible lack of invariance and couplings. In addition, a detailed description may rapidly become very cumbersome.

In the case of low degrees of freedom devices discussed at the end of this section, it is possible and convenient to describe the operating volume inside which all other measures are taken as simple geometrical shapes, parallepideds, spheres, encompassing the reachable locations of the device-body interface(s).

For higher degree of freedom devices, involving combinations of translations and orientations, the specification is complicated due to the lack of metric for orientations with three degrees of freedom and the presence of couplings.

4.4.1 *Independent Specification of Orientation Range*

For one degree of orientation range, one angle suffices. For two, it is accurate to specify a solid angle, the section of which being described by a simple geometrical shape. For three, this scheme breaks down.

The proposal is as follows: presumably, the device-body interface will have a specific shape defining a preferred axis. Such is the case for most handles. Even spherical handles have such an axis being attached to a driving element by a stem. It is therefore natural to specify motion range with three orientations as a combination of a solid angle, angle inside which the preferred axis may reach, with an angle specifying the amount of rotation around the preferred axis. Once the nature of the solid angle is given, the complete orientation motion range can be given in 'steradian.degrees' with little ambiguity.

4.4.2 *Dependency of Orientation Range on Position*

The orientation motion range may depend on position in two ways.

The range can assume a different origin for each position. Such is the case for example, with wrist-partitioned manipulators, which have an orientation motion range amplitude independent from position, however the origin is not. For exoskeleton type devices, this may in fact be an advantage because this dependency can be made to match the human arm [26]. For the others, this dependency must be expressed in some fashion. Recalling what was discussed in the previous subsection, it is proposed here to specify the solid angle swept by a preferred axis through the position motion range when the relative orientation is kept constant.

For systems which are not partitioned, for example, parallel driven platforms, not only the origin of the orientation motion range may vary, but also its size and shape. A concise yet unsatisfactory report of this dependency is the specification of the maximum and minimum value of the orientation range in 'steradian.degrees'.

4.5 Peak Force

Much confusion is derived from published figures regarding peak force (PKF). Most prominently, the peak force should be specified where it matters, namely at the intended device body interface. This approach lifts the confusion due to specifications in terms of forces and torques which will depend on underlying coordinates. For example, a handle with six active degrees of freedom will be intended to be grasped in a number of ways but involving a limited numbers of areas of the hand. It is at these areas that the peak force should be specified. The resulting force being a combination of forces and torques generated at some other area of the handle.

The other source of confusion arises from duration. In many cases, the actuation system has losses resulting in heat (as exemplified in electric motors or amplifiers specifications) to be dissipated (actively of passively) eventually leading to a thermal equilibrium which must be below an acceptable limit. This defines the long term peak force (LTPKF).

As discussed further down the long term peak force may not matter much in some cases, so transient peak force must be specified independently. An excessive amplitude transient force may result in two effects. Either the device saturates causing large signal distortion (by design with current limiting circuits, mechanical torque limiters, or magnetic circuit saturation) or it sustains permanent damage. This limits the nature of meaningful transients. For example a true impulse will always be limited in amplitude by saturation. Instead, following the example of electroacoustic equipment testing specification, it is proposed to define a transient as one or several square signals of an agreed upon duration or durations. The proposal here is to define a short transient as a 10 ms square pulse (short enough to approximate a pure impulse for most devices), and a persistent transient as a square signal of one second duration.

This results in three specifications for peak force: long term (smoke test) (LTPKF), short transient (STPKF), and persistent transient (PTPKF). In each case, the measured peak output force is specified which will neither saturate nor damage the device at each intended area of contact with the body. For the long term smoke test, the time taken for the actuators to overheat should also be recorded. A concise specification, rather than painstakingly going through all the possible cases, might specify the worst cases only.

The measurement of peak force is relatively easy since it involves the use of a sufficiently accurate load cell and interposing it between the active end and a stiff reference, thus under isometric conditions.

4.6 Inertia and Damping

Inertia specifications are important [20]. It is an important issue because inertia is not easily reduced by feedback. In the event it is, for the reasons outlined in the next subsection, it should be specified specifically for the ground device (GDI). Here, the same difficulties in terms of invariance arise, and the same technique should apply. Instead of specifying one or several inertia tensors, it is convenient and accurate to specify it in terms of perceived mass at the various device-body interfaces. Similarly, the specification may be simplified by reporting only the best and worst case figures over the various areas of contacts and regions of the operating volume.

If the device is indeed designed to achieve inertia reduction by control, via force or acceleration feedback for example, other dependencies are introduced. One way to solve the problem is as follows. Presumably, the device will be instrumented with adequate sensors and the placement of these sensors will determine the structure of the feedback including the non-linear coordinate transformations needed to close the loop. To decouple the ability of a device (including its sensors and control system) from the merit of a particular control method, the improvement of this figure of merit should be specified using a feedback which does not depend on frequency (i.e. fixed gains, no filters) and indicating the improvement for a specified stability margin, the most convenient being a phase margin, say 45^o in isometric conditions (end clamped) (FBI).

It is clear however that direct measurement is not easy. One measurement method would consist of connecting the active end to a shaker vibrating at a known amplitude and low frequency. The same load cell as above would report the effective inertia. To handle angular motions, two motions of equal amplitude and opposite phase could be applied to specified places of the active end. The distance in between could be agreed to be 5 cm for hand held devices, a reasonable figure for most grip positions.

Damping measurements are also important and should be measured under the same conditions.

4.7 Peak Acceleration

Experience has taught us that a crucial figure of merit of a haptic device is its acceleration capability (peak acceleration, PACC). This has been reported in [8] [9] where it was mentioned that it was consistent with physiological observations. In these papers, peak acceleration was used as design guideline not only to increase its the average value but also to minimise the difference between its extrema over a target workspace. The reasoning is simple: Contacts and shocks are characterised by rapid changes in velocity, hence the need for high and uniform acceleration. The importance of peak acceleration was further confirmed in [24].

If we combine peak force with inertia, we get peak acceleration. Peak acceleration cannot be improved by feedback since it depends solely on the actuator capabilities (STPFK) combined with the inertial properties. It is therefore a fundamental figure of merit.

The measurement of peak acceleration is relatively simple given the recent availability of light weight and low cost solid-state accelerometers.

4.8 Energy Flux – Power Density

Given a device, or rather a device-body interface of given inertia and given peak acceleration, we can define its power since we can calculate its increase (or decrease) of energy by unit of time, assuming neither a change in potential energy nor dissipation. Since a device-body interface is meant to operate inside a given volume, combining all these figures we can specify its power density (per unit of distance, area, or volume whichever the case may be, PWRD). This can also be viewed as a measure of the energy flux a device is capable of. This forms a single concise figure over all the device-body interfaces. A further possibility is to include a frequency dependency leading to spectral power density.

4.9 Broad Device Classification and Examples

4.9.1 *Low DOF Devices*

A *low DOF* (degree of freedom) device does not attempt to address the literal emulation of tasks which would occur during actual performance. It has been found for example that 2 or 3 controlled mechanical freedoms could provide an operator with a task metaphor sufficiently suggestive to lead to a high level of usefulness.

An excellent example of this idea is the Phantom device which can exert forces at one point in three dimensions but is not meant to exert any torque [17]. The operator either grasps a cylindrical handle and forces are applied at the end of that handle, or one finger of the operator is braced in a single hoop gimballed to the active end. The metaphor is these cases is either to “probe” a [virtual] object or touch it with an intervening brace. Another example is the Pantograph which has only two degrees of freedom in a plane [21]. The operator uses one or several fingers to interact with a knob. In this case the metaphor is exploration of a planar world using a small hand-held object. As a further example, D. K. Pai at UBC is developing an extension to the Pantograph device with an additional rotational degree of freedom, while the task remains planar. The metaphor, in this case, is the manipulation of a small object constrained to move in a plane. Other examples could include Adelstein’s spherical device [1], as well as Hannaford’s miniature haptic device [4].

It has been recently been realized that the level of “usefulness” of low DOF devices is actually higher than intuition would predict, with the benefit of a great deal of construction simplification compared to a high DOF device. The combined use of several low DOF devices can lead to a richer set of metaphors as discussed in [13].

A low DOF device is labelled LDOF#, where # stands for the number.

4.9.2 *High DOF Devices*

A *high DOF* device attempts to recreate a task in its integral form. Under this category, we find all devices which are designed around a hand held manipuladum applying arbitrary forces and torques. Thus they must have at least six DOF’s although the case of a 5 DOF device could arguably fall under this category too. In this case, the haptic display no longer relies on a metaphor but instead is quite literal in the attempt to recreate a task that would occur if the handle was actually used to perform a task. In this category we find many many devices developed for teleoperation such as JPL’s FRHC [19] and CEA’s MA23 [25]. More recently, a six (extendible to seven) DOF device is being developed at McGill for specific application to virtual environments [8]. A six DOF device has also been developed by Iwata [14]. Other examples include Salcudean and Hollis magnetic levitation devices [12] [22]. Of course there are many tasks and application which require full DOF display. An interesting case is the device developed by SRI [11] for telesurgical application which has only four degrees of freedom, but is quite literal in its use, and therefore must be classified has a high DOF device.

A high DOF device is labelled HDOF# where # stands for the number.

4.9.3 *Very High DOF Devices*

A *very high DOF* device also attempts to re-create a task in its literal form but also involves combinations of body motions: complete arm, shoulder, torso, legs, etc. In other terms, it includes more than one body-device interface and this means that, almost certainly, it must be worn, that is braced around the operator's body.

In this category we find the Sarcos exoskeleton master, Kazerooni's extenders [15], the dextrous master of Burdea *et al.* [3], and the exoskeleton system of Bergamasco *et al.* [2].

A high DOF device is labelled VHDOF# where # stands for the number.

5 Detailed Features

The questions of backdriveability, resolution, precision and repeatability consolidate many of the injurious properties associated with mechanical systems; these include in combinations, friction, backlash, and elasticity. What is more, these measures can be universally applied to the various actuator-transmission or sensory systems in terms of various defects such as hysteresis, ripple, cogging, and drift.

A haptic device being nothing but a bi-directional mechanical transducer, enables us to apply the methods used to specify more general transducers such as motors. It is possible to consolidate all these factors in terms of noise specifications.

As with any transducers, the noise on each signal will depend on the load. Consequently, isometric or isotonic measurement conditions are not strictly speaking correct, since under normal operation, the device will be in contact with fleshy tissues which have varying but finite viscoelastic properties. It is proposed that in the absence of a definition of maximum and minimum values of the viscoelastic properties of tissues, isometric (same motion) and isotonic (same force) conditions be used for now, and to be replaced later with more meaningful figures.

Similarly, measurements should not always be taken under static conditions. The mechanical noise generated by a transmission, an actuator, or sensor noise will depend dynamically on the signal. This is the case of friction, for example, seen as noise on the mechanical signal. At the very least, velocity should not identically be zero when the transmission performance is measured. The same is true for cogging (cogging causes spurious forces to appear because of cyclical mechanical or magnetic energy storage). On the other hand, ripple (periodic change of actuator gain) and digital reconstruction noise can be captured by static precision measurements.

Under specified conditions we will perform resolution and precision measurement for force, displacement and velocity signals. The repeatability figures can be found using the same measurements obtained in the precision experiments.

5.1 Resolution

It has been observed many times that resolution is the most critical detailed feature of haptic devices, while precision matters less.

The resolution is considered from the output point, rather than at the individual joints, if any. The resolution of the system represents the smallest deviation from system equilibrium which can be detected by the sensors under study. When the haptic device is under computer control the resolution may be limited by the analog to digital converter; in any case, the complete system must be considered.

To measure the position resolution of the position sensor, the device-body interface must be connected a very rigid reference to create isometric conditions. One way to achieve this is to use the bed of a milling machine which permits both static and low velocity conditions. The complete set-up should include a load-cell of appropriate characteristics interposed between the bed and and the device-body interface under study.

The measurements obtained from this are: the smallest displacement detectable in static conditions and in low velocity conditions, say $\pm.01$ m/s. Under the same isometric conditions, force readings should be taken in a wide frequency range while the device is controlled not to exert any force. The spread will provide hysteresis figures, while noise can be reported in terms of RMS form specific frequency bands, so in Newtons per root Hz. The specific bands of interest here are, low range: 1-100 Hz, and high range 100-1,000 Hz,[4] or perhaps a more finely sampled

[4]Based roughly on the response range of various skin receptors: see Reynier, F., Hayward, V. 1993. Summary of the kinesthetic and tactile function of the human upper extremity". McGill Ctr. for Int. Machines, TR CIM-93-4.

frequency scale such as 1-10-100-1000 Hz. These measurements will give a precise picture of what is commonly called “backdriveability”.

The other resolution measurements will be obtained by getting the device to produce specific level of forces and repeating the same procedure as above for, say, 1 percent, 10 percent and all of its maximum force capacity (already defined). A complete test suite should include figure reports both in static and low velocity conditions. High velocity conditions (say above .1 m/s) for resolution are not necessarily important for the performance of a haptic device.

As far as isotonic conditions are concerned, they are more difficult to set-up because a pure source of force (except the null source) is not as easy to provide as a pure position source is. Similarly, instrumentation is more difficult since it will require position and velocity sensors that will not disturb measurements and that will work over significant ranges. In the event that such a test bench is available, the measurement will take place in an analogous fashion as above: forces (static and slowly ramping) are applied and the corresponding displacements measured. Fortunately, since most devices are meant to display forces and read displacements, isotonic condition are not as important as isometric ones.

Of course, as already mentioned, best and worst case figures should be provided.

5.2 Precision

The precision of the device can be described as the difference between the target coordinate and the centre of the distribution curve of the actual coordinates of the arm end point.

Here again, isometric conditions are the most useful and the milling machine will come handy again. The device-body interface is forced at various known positions of its motion range and readings of the device are noted. Conversely, the device is programmed to exert a scale of forces and readings are taken.

Repeatability will be found (independent of control) from the width of the distribution curve.

5.3 Bandwidth

This figure is particularly difficult to define because unlike noise figures, isotonic nor isometric conditions are appropriate to convey a precise meaning. In bandwidth specifications, one sometimes speaks of “small signal” and this begs the question of what signal (displacement or force) and how small. In fact, it is unclear what subjects are sensitive to; there is evidence that subjects are sensitive to all of these signals. In some cases, pressure on the skin (force per unit area) is the relevant quantity, in others the skin indentation. To compound this problem, the response of a device may depend critically on the load, or in other terms is highly sensitive to its nature [10].

There does not seem a way to escape the necessity to specify a meaningful load which would be representative of actual operating conditions. It is proposed to specify the load as a piece of defined and widely available material of normalised dimensions (say specific silicon gel), designed to approximate a typical fleshy tissue.

The frequency response and the bandwidth can then be measured with the device-body interface loaded by the sample in terms of its microdisplacements at, say 1, 10 and maximum peak force. The method for measurement must involve a small displacement transducer of appropriate characteristics. This cannot be discussed here but of number of possibilities exist in the area of optical measurement methods.

A fall back measurement is the force isometric response.

5.4 Structural Response

Similar to loudspeakers, a haptic device will ‘color’ the signal due to its imperfect structural properties. In fact, an experienced operator will probably, from a blind folded experiment, recognize the make of a device. So it is reasonable to also specify this in some way. The structural response measured in some specified conditions is probably the best way to do this. As before, there are two basic ways to achieve this, isometric and isotonic conditions. A large number of excitation methods are available to achieve this: impulses, sine sweep, white noise, pink noise, etc. Since presumably any device includes a number of non-linearities, these different methods will produce different results. It is suggested that the method most appropriate for application to haptic devices is the impulse excitation method. In isotonic conditions (free end), an impulse of maximum amplitude is applied at the actuators, and acceleration is measured. The spectral response is reported. In isometric conditions, the force is measured and the spectral response reported.

5.5 Dynamic Precision

5.5.1 *Cross Talk*

There is evidence that humans are capable of discriminating between the spatial properties of vibratory motions quite high in the frequency domain. One way to look at a haptic device is to consider it as multichannel transducer with one channel per DOF. Thus is is possible to specify dynamic precision in terms of 'cross talk' between these channels. Cross couplings, most probably from mechanical origin, will cause signals in one channel to spill over another one.

The way to measure this around an operating point is to constrain the device in isotonic condition along or around one dimension, (to a slide or ball bearing) causing it to apply periodic forces along or around that direction and measuring the reaction forces along or around other directions.

5.5.2 *Distortion*

Another aspect of dynamic precision is in terms of non-linear signal distortion. The device is programmed to apply a signal in some specified condition, say a force in isometric condition, and the signal distortion is reported in percent energy (RMS) for a periodic signal as it is customary in electroacoustic equipment specification. More refined distortion measurement accounting for certain types of nonlinear distortions measures the device ability to not distort transients. A high amplitude low frequency square wave is superimposed on a higher frequency sine wave. The distortion of the sine wave as the result of the square wave is reported.

5.6 Closed Loop Performance

A crude approximation of a haptic device may be a pure inertia. If position and velocity signals are fed back to the actuator, the system becomes a second order "mass-spring-damper" system. If the pure inertia approximation truly is valid, any positive values of the feedback gains, corresponding to damping and elasticity, will lead to a (possibly marginally) stable system. In practice, clearly, such is not the case. Often the device is driven by a digital system which introduces at least sampling and discretization. Thus, for some gains, the closed loop system either enters limit cycles or becomes unstable [5]. The closer the ground device is from an ideally instrumented pure inertia, the higher these gains will be.

For example, it is relatively easy to find the stability conditions for a pure inertia being driven by an ideal actuator and having ideal sensors but with the feedback closed by a sampled data control having a zero-order hold and one time delay of one sampling period.

In practice, these are only approximations and instability occurs before theoretical values are reached because of other sources of error; nevertheless, the form of these conditions remains valid. It is proposed to quantify the closed loop performance of a device including its digital control system by specifying α and β such that the system remains stable if $B < \beta\frac{M}{T}$ and $K < \alpha\frac{B}{T}$. Of course, the floor value of B is the intrinsic damping of the system.

This discussion does not consider the interaction between the haptic device and the operator although is it important [16]. The interaction will greatly influence closed loop performance and introduce many control tradeoffs the discussion of which fall outside the scope of this paper.

6 Environmental Factors

Environmental factors are extremely pertinent in haptic devices because of the direct human-machine interaction which takes place. Some of the issues associated with environmental factors can not be specified in the form of a single number; yet, as haptic devices enter the commercial market place, these environmental factors will be of equal importance to some of the measurable indices we have already described.

Environmental factors which can be measured are: weight, acoustic noise and volume. These three factors can generally exclude some designs from certain applications before the performance indices have even been considered. Non measurable, but important factors are visual intrusion and service requirements.

The human link in the haptic equation requires that safety be a critical issue. What is the maximum speed and maximum force which the device could exert on the user? In the case of electrical or mechanical failure, is the system safe? (For example, a computer crashing.) Haptic designers are now forced to address these issues more than has ever been necessary before.

7 Conclusion

This paper has set out to define a set of performance measures which are applicable to haptic devices. It has been stated that a haptic device is bi-directional, i.e. is capable of both reading and writing to the user. This bi-directionality and direct human interaction with the device, makes the emphasis of performance measures for haptic devices different to that of traditional robotics. Also many of the performance measures used to to date for haptic devices have blurred the comparison to other devices due to ambiguity in measures and different measuring conditions. By moving toward a standard, it is hoped that comparison, improvement, specification and analysis of haptic devices will become possible.

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A Measures found in the specifications of a number of devices

In this appendix we list the performance measure which we uncovered in the literature. For each category, we list in bold the performance index which we propose, followed by similar indices (if any) found in the literature.

Mechanical degrees of freedom. (P) passive or (A) active. and unilateral (U), bracing (B) or held (H): None found

Motion Range (MR): Reach, Range of Motion, Work Volume, Position, Workspace, Work Envelope, Range of Travel, (Roll, Pitch, Yaw), Volume of Operation, Angular Operation, Cubic Workspace, Angular Range, Working Areas.

Peak Force (PKF): Force, Long term peak force (LTPKF), short transient peak force (STPKF) and persistent transient peak force (PTPKF): Max force/torque, Maximum Exertable Force, Max Force Output, Long Duration Force Output, Maximum Force.

Ground Device Inertia (GDI): Imposed Inertia, Inertia (apparent mass at tip), Calculated Reflected Inertia of Motor@Hand-grip, Inertia.

Peak Acceleration (PACC): Acceleration, Maximum Acceleration, No Load Accelerations.

Energy Flux - Power Density: None found.

Broad Device Classification: LDOF, HDOF, VHDOF: Implied but never classified.

Resolution at 10, 100, and 1000Hz: Nominal Position Resolution, Positional Resolution, Backlash. Friction Breakaway, (No dependency on frequency given.)

Precision: Not found.

Structural Response Isometric and Isotonic: Not found.

Bandwidth: Mechanical Bandwidth.

Dynamic Precision: Not found.

Closed Loop Performance: Not found.

Environmental Factors: Storage Volume, Overall Mass, Weight, weight of various subassemblies, Weight: Joystick, Weight: Power and Computer Unit, Limit Stops, Power Requirements.