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Haptics

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hap·tic ('hap-tik)

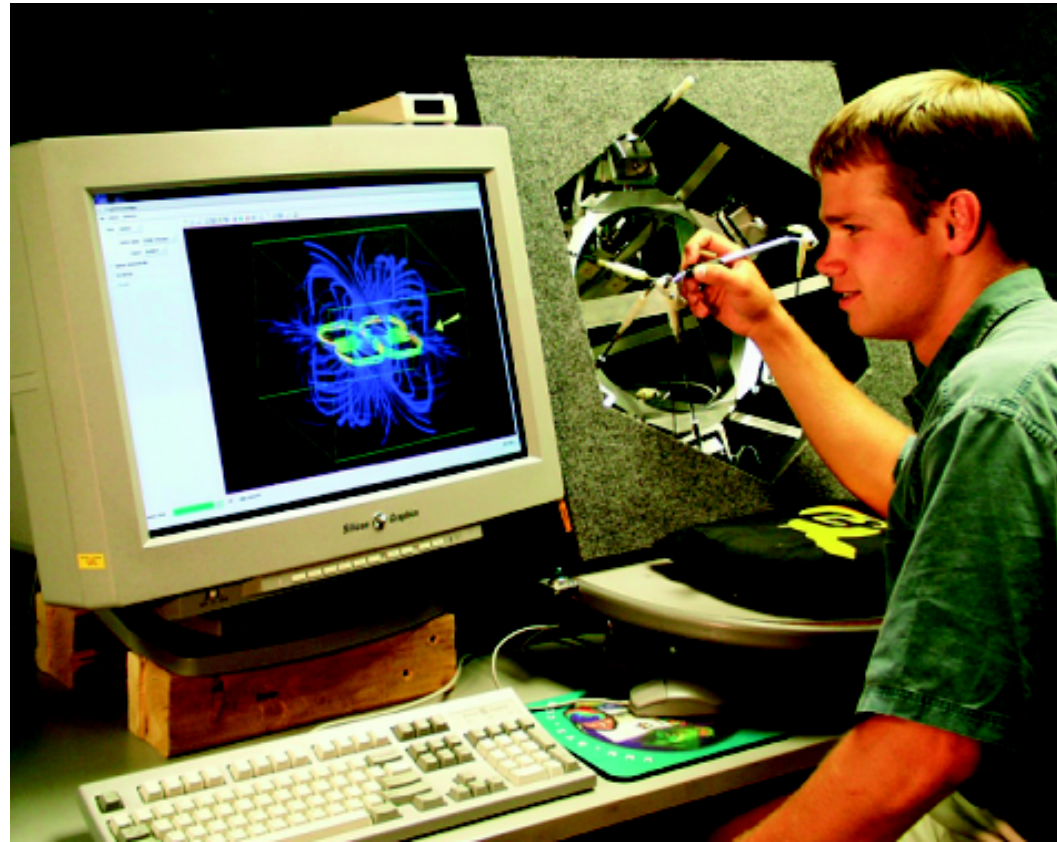
adj.

Of or relating to the sense of touch; tactile.

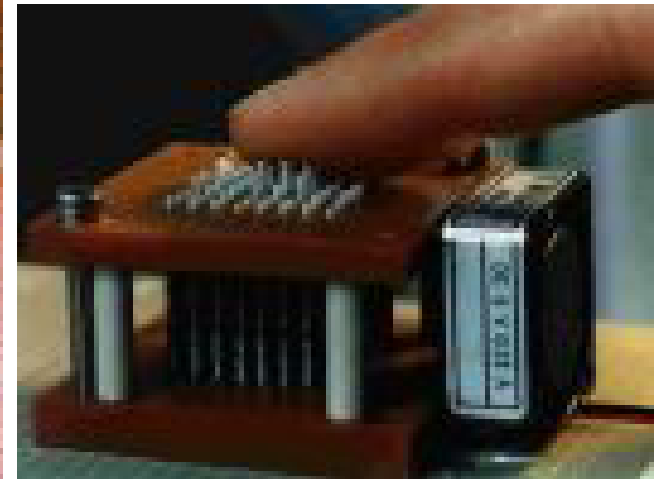
Greek *haptikos*, from *haptesthai*,

grasp, touch. (1890)

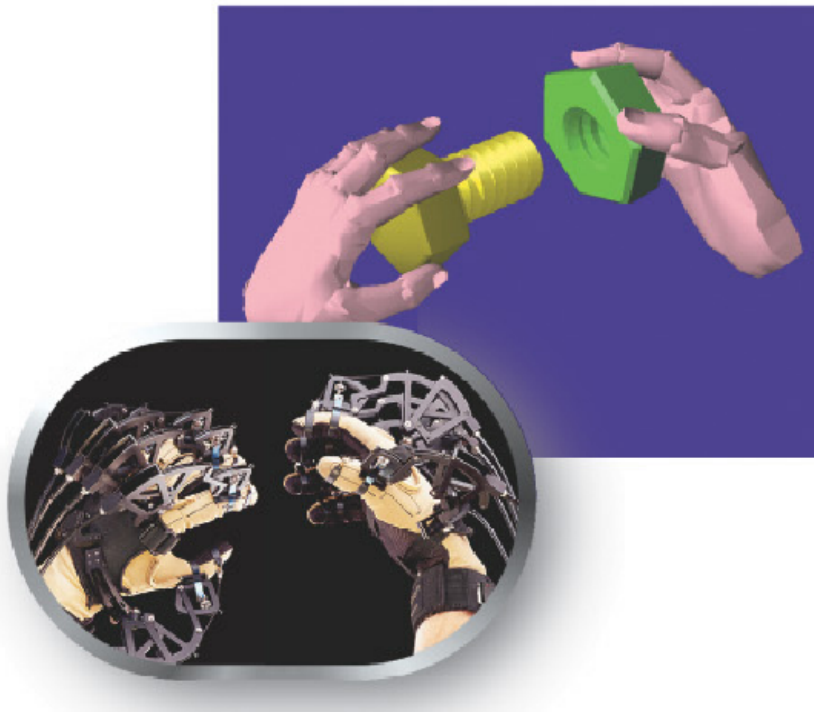
Introduction - Devices



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Introduction



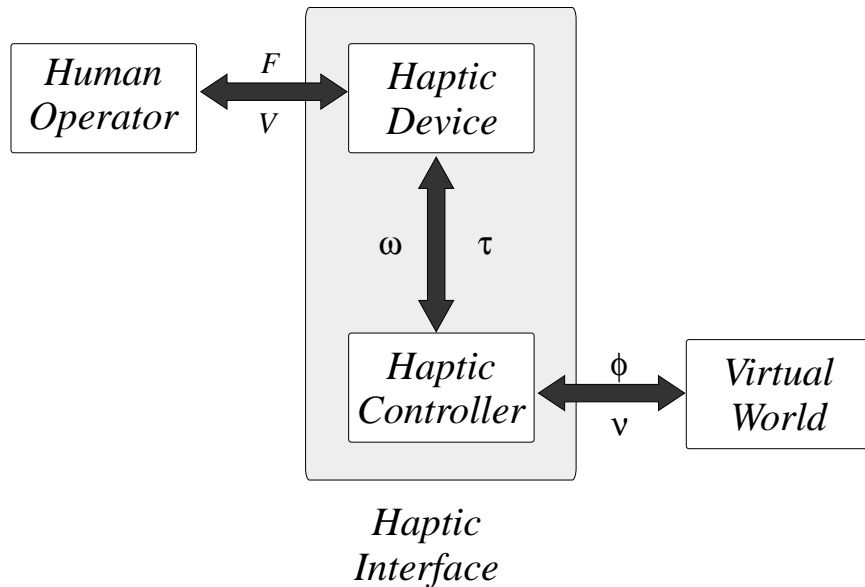
- The word “haptic” does not have a rigorous definition and it means something related with the kinesthetic and tactile human perception with the use of the hand.
- Haptic devices have to be in contact with the human operator giving him sensations as similar as possible to those he could perceive from the interaction, due to handling or grasping, with an object.
- Sometimes, a visual or acoustic feedback, through appropriate displays, is added to the device to give a more complete and detailed perception to the user.

Introduction

- “*Haptics*” generically means the human perception of *tactile* and *kineto-static* information
- Haptic interfaces are robotic devices able to give to a human operator the feeling of a *kineto-static* interaction with a (virtual¹) environment.
- In particular, we have:
 - *Impedance devices*: the operator imposes the velocity (position) and perceives the “interaction” force
 - *Admittance devices*: the operator imposes the force on the environment, which in turns determines the velocity (position)

¹ *virtual environment*: a model of a physical environment simulated on a computer

Overview on haptic interaction



- Simple HMI (e.g. joysticks) are used only to perform position control
- Haptic systems are characterized by the presence of a force/velocity feedback related to the interaction with a virtual world

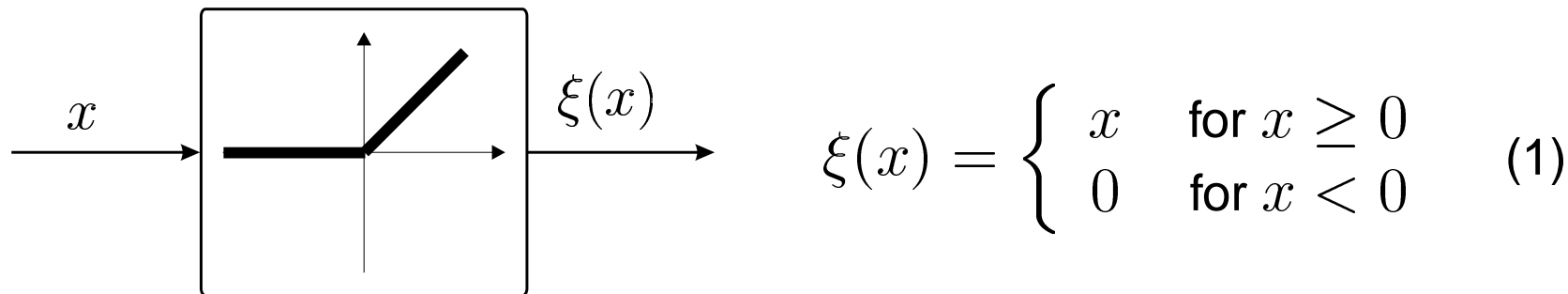
- The design of control law for haptic devices has to preserve the stability of the overall apparatus
- Control law should guarantee stability independently on the virtual world

Desired behavior of haptic systems

- Beside stability, the interaction perceived by the human operator should be as realistic as possible
- This means that the dynamics of the haptic device should be negligible
- Generally speaking, *transparency* of a haptic display depends on:
 - mechanical structure of the device
 - control algorithms
 - simulated virtual environment

Stability Issues

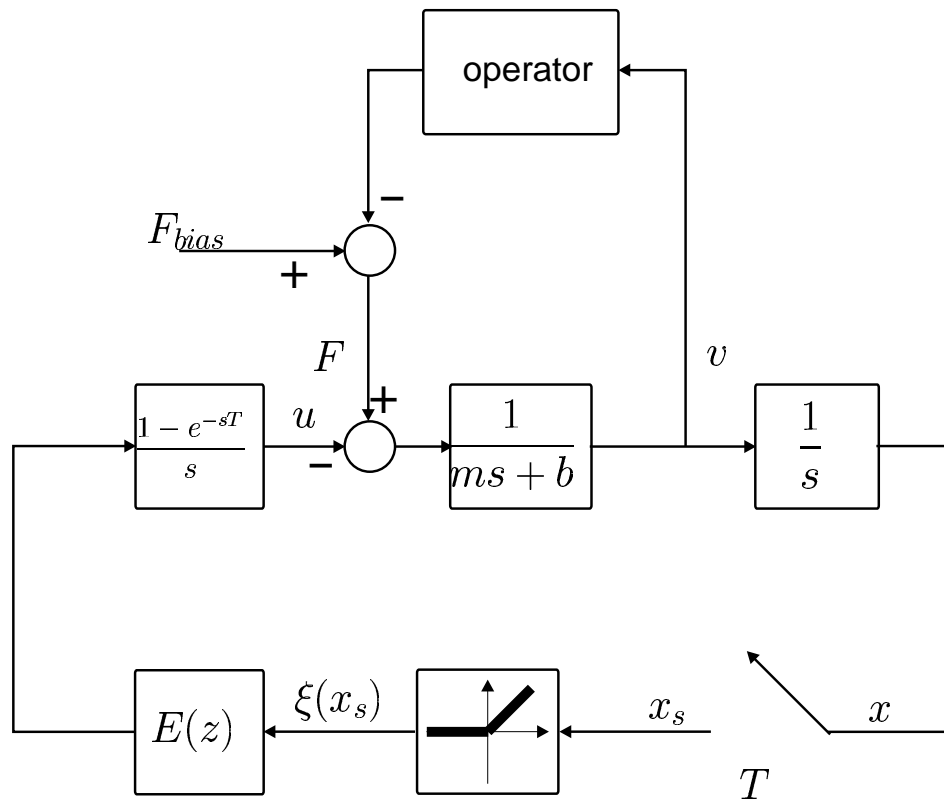
- Factors affecting the stability of the apparatus can be summarized as:
 - presence of force/velocity feedback
 - interconnection of a **time-continuous system** (device+human operator) with a **dicrete time algorithm** (control law+virtual world)
- As an example, consider the virtual world to be a wall (*unilateral nonlinearity*):



Stability with unilateral nonlinearity

- Since real physical walls are *passive*, they cannot inject energy to the human operator and therefore physical contact cannot lead to instability or limit cycles.
- However, a *virtual wall* is implemented as a discrete time system:
 - it is impossible to exactly know the moment at which the virtual surface is touched or released.
 - In the latter case, the interaction force is not zero (as it should be), for "some time".
 - Therefore, the virtual wall becomes a source of energy that could lead the system to instability (oscillations).
 - The frequency of oscillations is outside the range of human voluntary movement and involuntary tremor \implies They are caused by the interface itself, which turns out to be **active**, not passive.
- A criterion for the absence of unstable oscillations has to be found.

Stability with unilateral nonlinearity



- Haptic device is modelled as a mass m with viscous friction b
- $E(z)$ is a stable, linear, shift-invariant transfer function representing the behavior of the virtual wall
- F_{bias} is the (constant) force required to the operator to stay in contact with the virtual wall

- If the haptic display is passive, the human operator cannot extract energy from it:

$$\int_0^t F(\tau)v(\tau)d\tau > 0 \quad \forall t > 0 \quad (2)$$

Stability with unilateral nonlinearity

Theorem (Colgate, 95) A sufficient condition for passivity of the haptic display is:

$$b > \frac{T}{2} \frac{1}{1 - \cos \omega T} \Re \{ (1 - e^{-j\omega T}) E(e^{j\omega T}) \} \quad 0 \leq \omega \leq \frac{\pi}{T} = \omega_N \quad (3)$$

This condition is also necessary when the human operator is modelled with a passive arbitrary impedance $Z_0(s)$ and the unilateral nonlinearity is removed.

Stability with unilateral nonlinearity

Proof. Suppose that the mass is initially at rest, therefore its kinetic energy cannot be as great as the total provided energy:

$$\frac{1}{2}mv^2(t) < \int_0^t F(\tau)v(\tau)d\tau \quad \forall t > 0 \quad (4)$$

that is equivalent to the definition of passivity. The total power balance leads to:

$$\frac{1}{2}mv^2(t) = \int_0^t [F(\tau) - u(\tau) - bv(\tau)]v(\tau)d\tau \quad \implies \quad \int_0^t [u(\tau) + bv(\tau)]v(\tau)d\tau > 0$$

By considering the truncated version of velocities and their Fourier transforms, by means of Parseval's the passivity condition can be rewritten as:

$$\int_{-\infty}^{+\infty} U(j\omega)V^*(j\omega)d\omega + \int_{-\infty}^{+\infty} bV(j\omega)V^*(j\omega)d\omega > 0 \quad (5)$$

Stability with unilateral nonlinearity

Proof (*continued*) From the figure U can be written as:

$$U(j\omega) = \frac{\bar{E}(\omega)}{-j\omega} \sum_{n=-\infty}^{+\infty} \frac{V(j\omega + jn\omega_s)}{j\omega + jn\omega_s} \quad \bar{E}(\omega) \doteq -\frac{1 - e^{-j\omega T}}{T} E(e^{j\omega T}) \quad (6)$$

that leads to:

$$\int_{-\infty}^{+\infty} \bar{E}(\omega) \sum_{n=-\infty}^{+\infty} \frac{V(j\omega + jn\omega_s)}{j\omega + jn\omega_s} \left[\frac{V(j\omega)}{j\omega} \right]^* d\omega + \int_{-\infty}^{+\infty} bV(j\omega)V^*(j\omega)d\omega > 0 \quad (7)$$

and it is possible to find the lower bound:

$$\int_{-\infty}^{+\infty} \left[b + \Re\{\bar{E}(\omega)\} \sum_{n=-\infty}^{+\infty} \frac{1}{(\omega + n\omega_s)^2} \right] V(j\omega)V^*(j\omega)d\omega > 0 \quad (8)$$

Therefore passivity is achieved if the expression in brackets is positive at every frequency.

The following equality holds:

$$\frac{1 - e^{-j\omega T}}{T} \sum_{n=-\infty}^{+\infty} \frac{1}{(j\omega + jn\omega_s)^2} = \frac{T}{2} \frac{e^{-j\omega T} - 1}{1 - \cos \omega T}$$

Stability with unilateral nonlinearity

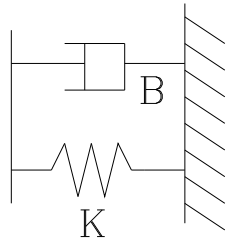
Proof (*continued*) Finally it is possible state the sufficient condition for passivity when the unilateral constraint is absent:

$$b + \Re \{ \bar{E}(\omega) \} \frac{T^2}{2} \frac{1}{1 - \cos \omega T} > 0 \quad \forall \omega \quad (9)$$

Since viscous friction b is present, the haptic interface will dissipate energy while moving during each sample period. In addition, the device is passive (without the feedback loop), so that $u(t)$ can be zero during any sample period without affecting the sufficiency result. Therefore, the unilateral constraint does not affect the condition obtained only for a given linear controller $E(z)$.

Example

- A virtual wall is usually implemented by means of a virtual spring and a virtual damper connected in parallel:



$$E(s) = K + Bs \quad \Longrightarrow \quad E(z) = K + B \frac{z-1}{Tz} \quad (10)$$

K is the (virtual) stiffness, while B is the (virtual) damping coefficient.

- The passivity condition becomes:

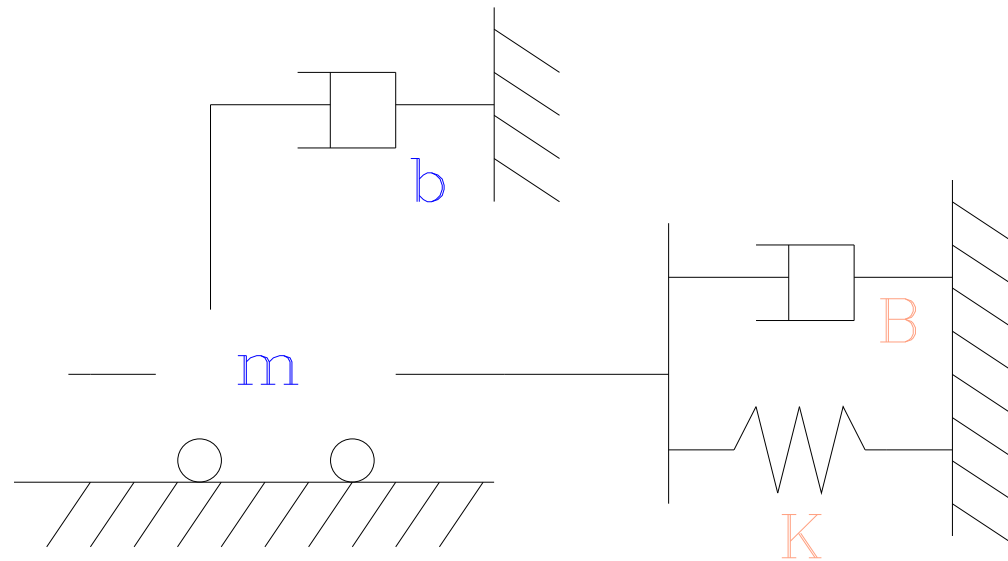
$$b > \frac{T}{2} \frac{1}{1 - \cos \omega T} \Re \left\{ (1 - e^{-j\omega T}) \left(K + B \frac{e^{j\omega T} - 1}{T e^{j\omega T}} \right) \right\} \quad 0 \leq \omega \leq \omega_N \quad (11)$$

- This relation can be rewritten as:

$$b > \frac{KT}{2} - B \cos \omega T \quad \Longrightarrow \quad b > \frac{KT}{2} + B$$

Example

- The haptic device is modelled as a mass m with viscous friction b ; the virtual wall as a spring K and a damper B :



- Condition for stability:

$$b > \frac{KT}{2} - B \cos \omega T \quad \Longrightarrow \quad b > \frac{KT}{2} + B \quad (12)$$

- It gives a condition on the maximum stiffness K and compliance B of the virtual wall given the sampling time T

Problems

Some problems:

- Modelling/Simulation of soft “tissues”
- Extension to the full geometric case (3D - wrenches/torques)
- Impedance estimation/rendering to the operator
- ...