Stability

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In the interaction between humans and real mechanical world, there is usually no stability problem. Conversely when electro-mechanical machines mediate such interaction, the physical real bilateral interaction is transformed into electro-mechanical input/outputs signal processes. This transformation introduces causality between the variables exchanged between the two interacting bodies (for example between forces and positions), whereas such causality does not exist in the real mechanical interaction. This may lead to introduce a specific question identified as the question of stability. In particular, in the case of digital processes, the effect of this causality is directly related to the temporal sampling of the signals, the temporal sample rate being a quantitative expression of the causality.

Consequently, when haptic interactions between a user and a physical object is mediated by haptic devices, or when manipulating a virtual object by means of an haptic device, an essential prerequisite is to preserve the stability of the whole haptic system. Indeed, unstable behaviours of the system can damage the user and the system itself.

From a theoretical point of view, stability is the ability of a system to maintain equilibrium under the influence of external factors. More precisely, there are two ways to mathematically assume that a system is stable:

1. The output signal is bounded for every bounded input to the system.

2. The response – i.e. the output signal - to an impulse input signal tends to zero along time.

Condition 1 considers that a system with limit-cycles in the output (sustained oscillations) is stable; while condition 2 does not. From control theory point of view, as developed in Automation Sciences, a system is stable if all the poles of the Laplace transfer function of the system are placed in the left-half of the S-plane. For condition 1, the poles of the system can be placed on the imaginary axis of the S-plane.

Numerous studies [Minsky et al, 1990] [Gillespie, 1996] [Salcudean et Vlaar, 1997] [Gil et al, 2004] [Hulin et al, 2006] [Gil et al, 2007] dealing with ensuring stability for haptic interfaces have been presented so far. Some interesting conclusions of all these studies are reported in the following.

Stability imposes a limit to the stiffness of the virtual objects that can be manipulated by the human through haptic devices. For this reason, the typical benchmark to check stability is to interact with a very hard wall. A possible way to rank haptic devices is to evaluate the maximum value possible for the stiffness of the virtual objects. If one implements a stiffness larger than this maximum stable value, users would be bounced from the wall with undamped oscillations.

In the same way, stability imposes a limit to the viscosity of the virtual objects. More precisely, for low values of viscosity, the effect of viscosity has the natural effect of damping the system. On the contrary, for very high values, increasing the viscosity tend to make the system become more unstable.

The sampling rate of the haptic loop is very important to ensure stability. Forces must be rendered as fast as possible (much faster than the graphical refresh rate). The faster the frequency rate is, the larger the value of the simulated stiffness can be. Usual frequency rates are 1 or 2 kHz, but some high quality force feedback systems, such as the ACROE ERGOS technology systems or the Mc Gill Pantograph system, are built to run with higher frequency rates, possibly more than 10 KHz.

Both physical and virtual damping can also contribute to maintain stability. Increasing the damping of the physical haptic device enlarges the upper limit of the virtual stiffness and of the virtual damping values that can be simulated.

The shorter the delay in the haptic loop – i.e. the time between the inputs and the outputs of the haptic device – is, the larger the simulated stiffness value can be. The delay of the haptic loop directly depends on the sampling rate of the haptic loop. This is a challenging issue in haptic systems, because it imposes that all the computations are made within a short time, typically no more than one sample at the sampling rate. Computations include typically collision detection algorithms, the simulation of physical contacts, and the simulation of the physical manipulated object. Computing all these in such a short time (typically less than 1 ms) is really difficult. This becomes very critical when computation involves several interconnected computers, which introduces supplementary delays and relaxed synchronisations, particularly when using standard networking communication protocols.

Finally, the inertia of the haptic device is usually considered to play no significant role in the stability of the system. Low inertia is only desired for good transparency [→ Transparency_3].

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