Haptic Rendering and Human Stabilization in Presence of Structural Flexibility

Csaba Budai1, László L. Kovács1 and József Kövecses3

Abstract

Unstable behaviour is a significant problem in many haptic applications. The nonlinear nature and time delays induce complex dynamic behaviours in such systems. Structural flexibility may further reduce the stable domain of operation. This is illustrated via the systematic modeling and analysis of an impedance type haptic device with typical design elements such as check dam mechanisms and cable-cable drives. The role of the operator in the dynamics of these systems is also demonstrated. The present work provides stability analysis, experimental validation and design conditions for the range of parameters in which the operator can significantly contribute to the destabilization of the system.

Representative Haptic Models

Impedance type kinesthetic haptic devices are usually multi-DoF mechanisms, that transfer forces to the human user to create the sense of physical interaction with a virtual environment. Usually, the haptic system consists of three main parts: the haptic device, the virtual environment, and the human operator (see Fig. 1).

Generally, the linearized dynamical model of a haptic system can be written in the form

\[ M \ddot{q} = f_e + f_v + f_d + f_h \]

where \( f_e \) represents the force applied by the human operator, \( f_v \) and \( f_d \) come from the dissipation and the structural flexibility. The force generated by the virtual environment is denoted by \( f_v \).

Man orthogonal decomposition can be used to obtain

\[ \mathbf{J} \mathbf{q} = \mathbf{f}_v \]

The contact force generation in the rendered direction can parametrically be investigated by the structural model presented in Fig. 3.

Stability Analysis and Dynamics Characterization

The stability of different models were investigated by considering backward difference approximation for the velocity term in Eq. (3). In each case, discrete maps were derived to characterize the controlled dynamics of the given sampled data systems. The different stable domains are summarized in Fig. 5. Here the shaded area in a measure of the impedance range of the analyzed haptic device. This measure can be approximated by the closed form expression (4) obtained with the 1 DoF flexible model without damping.

\[ \omega_n = \sqrt{\frac{m_1 k}{M}} \]

The analysis confirmed that the stable domain can be divided into two parts. For low impedances the system loses its stability with high frequency vibrations, while for higher impedance values the loss of stability occurs at higher frequencies. The calculated stability boundaries were verified with experiments. The observed sudden change in the vibration frequencies is explained by the frequency plots (e.g., \( f/\omega_n = \Delta \)) along the stability limits.