Method for Estimating the Stability Boundary of Impedance Haptic Systems

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ABSTRACT The stability of impedance haptic systems is dependent upon several parameters such as sampling rate, time delay, virtual viscous damping, the flexibility of the mechanical interface, and in particular the dynamics of the human arm. Thus far, estimating the range of stable impedances for a specific device is an arduous task that requires many experiments. In this paper, a reliable and fast method for estimating the stability boundary of an impedance haptic system is presented. It extends traditional stability analyses to multiple degrees of freedom and workspace positions. Experiments are carried out on a PHANToM 1.0 haptic interface to validate the methodology.

NEW FREQUENCY-RESPONSE METHOD
This method is a based on a pre-existing procedure, but it has the advantage of not needing to find the theoretical model of the system to estimate its stability boundary. It is designed to be easily applied to multiple positions of the workspace and to compute the critical impedances over several directions. The methodology works as follows:

1) Hold the device at a desired workspace position.
2) Command the actuators to generate at the end-effector of the device decoupled white-noise force signals in each Cartesian axis.
3) Record the output position for each Cartesian axis.
4) Repeat the experiment, steps 1) to 3), for different workspace positions.
5) For each position and Cartesian axis, compute the experimental frequency response of the system using Welch’s averaged periodogram method.
6) For each position and Cartesian axis, and using the experimental frequency response, compute the critical stiffness of the system. In this step, increasing virtual damping coefficients can be tested.

EXPERIMENTAL RESULTS
The new method is used to explore the stability boundary of the PHANToM 1.0 haptic interface at different points of its workspace. The user holds the stylus like a pencil, with his elbow resting on the table (Fig. 1). With regard to grip force, the only instruction given to the user is to grasp the stylus in a comfortable manner and to try to maintain the position once the motors are commanding the white-noise signal. The system is tested at positions regularly separated along y and z-axis within the squared subregion (Fig. 2).

Critical Impedances in (K,B)-Planes
Our first approach is to depict the critical impedances of the system at different points of the workspace along the same row. Within the same row, the critical impedances can be computed along the directions (y-axis and z-axis). Interestingly, the critical impedances along the y-axis are smaller for the lower rows, while the critical impedances along the z-axis are smaller for the upper rows. Fig. 5 shows the stable impedances for another user and the same direction and positions as in Fig. 4; it is clear that the shape and size of the stability regions are different. Nevertheless, the general behavior of the system is quite similar for both users.

Critical Stiffness without Virtual Damping in (y,z)-Planes
An alternative way to depict the experimental results consists of ignoring the effect of the virtual damping and focusing on the critical stiffness without additional damping. Colored maps (isolines in N/m) are selected to depict the critical stiffness value associated to each point of the workspace. This type is preferred to a 3D surface plot. Isolines with the same critical stiffness coefficient are also included.

MATLAB CODE FOR STEPS 5) AND 6)
% load experiment data on
% f_y force input (N) in y-axis
% f_y output position (m) in y-axis
[T_y,F_y]=estimate([f_y,0,0,0],[1,1,1,1,1000]);
Sy = frd(T_y,F_y,0.01,’FrequencyUnit’,’Hz’);
p = bodeoptions;
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