Experimental Stability Analysis of a Haptic System[*]

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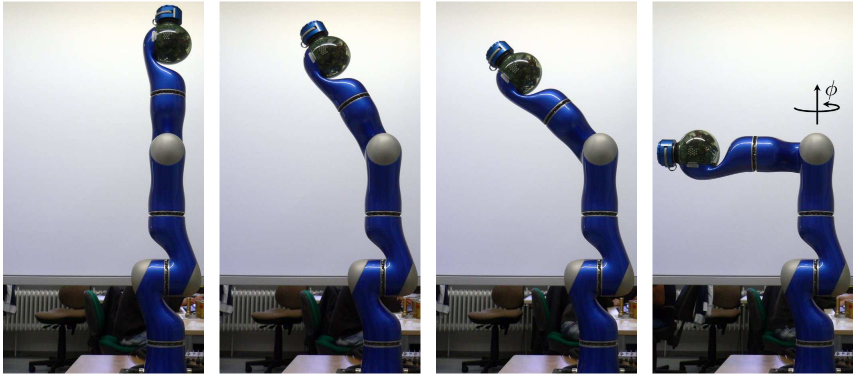
An elementary prerequisite for haptic applications is to preserve stability. Numerous studies have been presented in the past dealing with ensuring stability for haptic interfaces. The passivity condition of Colgate et al. (1994; 1997) represents one of the most cited theoretical studies towards a common stability condition. Although ensuring passivity of haptic devices is a general approach, it has the disadvantages of being conservative in terms of stability.

The exact stability boundary for undelayed 1DoF haptic devices colliding with a virtual wall was derived by Gil et al. (2004). They also showed that the human operator tends to stabilize an impedance controlled system. Therefore, the worst-case in terms of stability is a system where the operator is omitted.

Hulin et al. (2006a) enhanced this approach specifying the time delay as parameter. Different control rules were compared inside the stable regions for undelayed and one sample step delayed force. In further studies (Hulin et al., 2006b), the influence of the physical damping was also included. The stability boundaries depending on the parameters of the impedance control were numerically computed. They normalized the parameters involved in the control loop in order to obtain dimensionless stability boundaries.



(a) (b) (c) (d)

Fig. 1 Four different configurations of the DLR light-weight robot for the experiments: joint angle = [0°, 30°, 45°, 90°].

This publication evaluates the dimensionless stability boundaries by experiments using the DLR light-weight robot (see Fig. 1). Two different phases of experiments are performed concerning the dependency of (A) the mass (inertia) and (B) the time-delay on the stability boundary. In all experiments only one robot joint is active at the same time. For the first-phase of experiments the inertia is modified by changing the configuration of the robot as shown in Fig. 1. The effect of different time-delay is analyzed by adding a delay inside the control-loop in the second set of experiments.

Experimental results

A bilateral virtual wall consisting of a virtual spring and damper is implemented in the third axis of the robot (rotation angle ϕ in Fig. 1). Limit stable parameter values are obtained when sustained oscillations are observed increasing the stiffness. The environment is implemented in a computer connected via Ethernet to the robot. The sampling rate is 1 kHz and the overall

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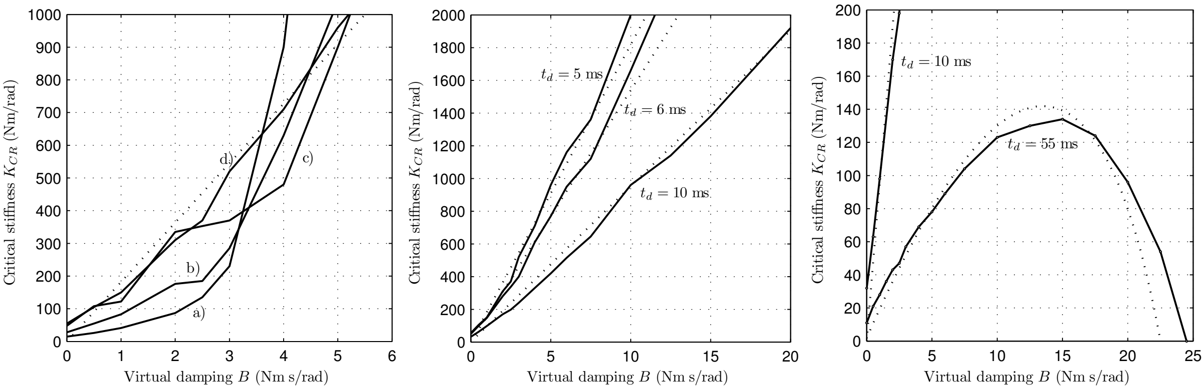
loop contains a delay of 5 ms. No user is involved in the experiments. Fig. 2 a) – c) shows the experimental results introducing several fixed values for the virtual damping. The theoretical behavior is depicted with dotted lines.

The results for the experiments with four different robot configurations are shown in Fig 2 a). The best correspondence between the theory and the experiments is achieved for the configuration with maximum inertia (Fig. 1 d). The second set of experiments is performed with this configuration for different values of the time-delay. Fig 2 b) shows the stability boundary for different delays (5 ms, 6 ms and 10 ms). A very large delay has also been introduced in the system in order to receive a curved stability boundary. Fig. 2 c) shows the experimental stability boundary for an overall delay of 55 ms. The beginning of the stability boundary for a delay of 10 ms is also shown. The theoretical stability curve in Fig 2 c) has been computed using the inertia of the device in the configuration selected for the second set of experiments: 0.8 kg m^2.



(a) (b) (c)

Fig. 2 Experimental stability boundaries compared to the theoretical ones (dotted lines).

Conclusions

The set of experiments performed with the DLR light-weight robot shows that the theoretically determined normalized stability conditions hold for real haptic devices. If the delay is small, the stability boundaries can be assumed to be linear. Therefore, larger virtual stiffness can be implemented when adding virtual damping. However, for large values of stiffness the hardware limitations are rapidly reached.

In the theoretical conditions, the inertia does not play any role in the linear part of the stability boundary. In practice, when the inertia is reduced, the experimental stability boundary does slightly change.

References

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