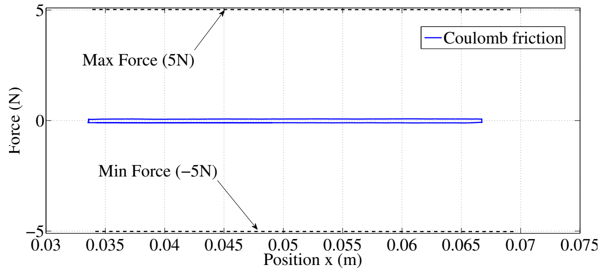

Fig. 9. Force evolution resulting from Coulomb friction.

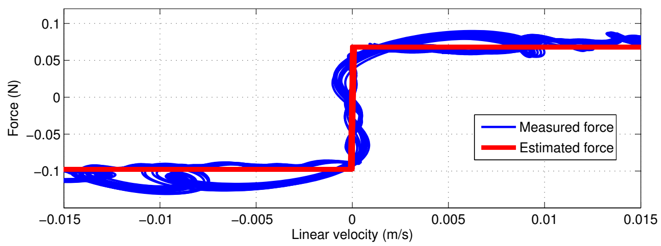

Fig. 10. Coulomb friction identification.

conservative conditions for stability, Diolaiti et al. [12] define local stability for such a system. It results in a larger stiffness range for which the haptic interface remains stable:

$$\frac{2F_v}{T_e} \leq K \leq \frac{2(F_s + F_v \dot{x}_{max})}{\Delta + \dot{x}_{max} T_e} \tag{25}$$

where F_v is the viscous friction coefficient, F_s is the Coulomb friction coefficient, K is the desired stiffnes to render, T_e the sampling period, Δ the elementary translation corresponding to the encoder resolution and $\dot{x}_{max}$ the maximum velocity of the interface before instability. Applying those formulae to our system gives a theoretical stiffness capability of 2500 N/m with $T_e = 0.33$ ms, $\Delta = 5.46\ 10^{-5}$ m and $\dot{x}_{max} = 0.04$ m/s. Nevertheless, experimental results are better and the interface is able to render a stiffness of 15000 N/m before instability occurs. Thus can be explained by the conservative hypothesis expressed in equation (25).

IV. Conclusion

In this paper the use of approximate straight line mechanisms has been proposed to design linear force feedback displays. They have (a 4-bar) parallel architecture which is suitable to improve rigidity, as generally admitted in haptics. At the expense of a relative complexity, these systems do not make use of cables nor linear bearings, thus limiting the drawbacks of these components: friction and flexibilities. These systems, particularly the Hoeken's one, can potentially be used in haptic applications without gears, which may help to obtain interesting displays, both for the purpose of education or research. For instance, we used it at the moment as a master interface in teleoperation experimental testbed to validate the results presented in [13].

A prototype has been built, and both the methods and the results of its characterization have been presented. They demonstrate that the Coulomb friction is not negligible. It is mostly due to the use of a brushed DC motor, which was preferred to prevent from the effects of torque cogging of DC brushless motors. The apparent mass of the system proves to remain below 50 grams, which is certainly enough for such a simple mechanism, and could be reduced by the use of carbon links. It is important to notice that the system can easily be modified to meet other characteristics (translation length and maximum rendering force). Further research is mainly related to the identification of the dynamical model, that could be improved to obtain an even finer description of the system.

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References

[1] Richard, C., Okamura, A., Cutkosky, M.: Getting a feel for dynamics: Using haptic interface kits for teaching dynamics and controls. In: ASME IMECE 6th Annual Symposium on Haptic Interfaces, Dallas, USA (1997) 15–21

[2] Grow, D., Verner, L., Okamura, A.: Educational haptics. In: AAAI 2007 Spring Symposia - Robots and Robot Venues: Resources for AI Education. (2007)

[3] Rosenberg, L.: Virtual fixtures: Perceptual tools for telerobotic manipulation. In: IEEE Virtual Reality International Symposium. (1993) 76–82

[4] Boldea, I., Nasar, S.: Linear electric actuators and generators. IEEE Transactions on Energy Conversion **14**(3) (1999) 712–717

[5] Etel: Etel – linear motors (2008) `http://www.etel.ch/linear_motors`.

[6] Hayward, V., Astley, O.: Performance measures for haptic interfaces. In: International Symposium in Robotics Research, Springer Verlag (1996) 195–207

[7] Adams, R., Moreyra, M., Hannaford, B.: Excalibur, a three-axis force display. In: ASME Winter Annual Meeting, Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. (1999)

[8] Weir, D.W., Peshkin, M.A., Colgate, J.E., Buttolo, P.: Design and performance of a high fidelity, low mass, linear haptic display. In: IEEE Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Pisa, Italy (2005) 177–182

[9] Barbé, L., Bayle, B., Piccin, O., Gangloff, J., de Mathelin, M.: Design and evaluation of a linear haptic device. In: IEEE International Conference on Robotics and Automation, Roma, Italy (2007) 485–490

[10] Artobolevski, I.: Mechanisms in Modern Engineering Design. Mir Publisher (1975)

[11] Colgate, J., Schenkel, G.: Passivity of a class of sampled-data systems: Application to haptic interfaces. Journal of robotic systems **14**(1) (1997) 37–47

[12] Diolaiti, N., Niemeyer, G., Barbagli, F., Salisbury, J.: Stability of haptic rendering: Discretization, quantization, time delay, and coulomb effects. IEEE Transactions on Robotics **22**(2) (april 2006) 256 –268

[13] Joinié-Maurin, M., Bayle, B., Barbé, L., Gangloff, J.: Force feedback teleoperation with physiological motion compensation. In: 9th International IFAC Symposium on Robot Control, Gifu, Japan (2009)