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Interaction Power Flow Based Control of a 1-DOF Hybrid Haptic Interface

Carlos Rossa*, José Lozada, Alain Micaelli

CEA, LIST, Sensorial and Ambient Interfaces Laboratory 91191
Gif-sur-Yvette, France

Abstract. A control method based on instantaneous interaction energy is used to control a hybrid haptic actuator, comprising magnetorheological brake and a DC motor, linked in parallel. We have combined this method with a quantitative analysis of interaction forces to develop two control variants, which can determine an optimal sharing of efforts between the active and dissipative actuators and make the system more reactive. The proposed control laws have been validated in a rotary 1-DOF force-feedback device.

Key words: force feedback, haptic devices, hybrid actuator.

1 Introduction

Haptic interfaces use electric motors (active actuators) or brakes (passive actuators) to generate controllable interaction forces and sensors for measuring the position. The use of electric motors is an effective way to display high fidelity haptic renderings [1], however, it poses a potential danger to the user if the interface becomes unstable. Based on the Nyquist stability theorem, Colgate et al. [2] developed a stability criterion for active interfaces and demonstrated that there is a compromise between the interface's stiffness and stability via the control loop gains. Their results suggest that, to achieve stability, some physical energy dissipation is necessary. Nevertheless, physical damping can damage the fidelity and the transparency of the haptic feedback [3]. Using the same analysis, An et al [4] conclude that a passive brake-based haptic device is intrinsically stable, but in this case, it is impossible to restore any energy to the operator and the system remains too conservative. The combination of both kinds of actuators is a promising solution to increase performance and to achieve global stability [5] [6] [7].

We have developed a 1-DOF rotary force feedback interface combining a magnetoheological brake and a DC motor. To control the system, an interaction energy flow based method is employed. Using this technique, it is possible to determine an optimal sharing of efforts between active and dissipative elements, using the brake to dissipate energy, whereas the DC motor should only be used to produce active efforts. Since brakes cannot create energy, it is difficult to

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* Corresponding author. Current address: Department of Electrical and Computer Engineering, University of Alberta, Edmonton, AB, Canada T6G2V4.

determine the behavior of the system when the velocity is zero. A quantitative analysis of interaction torque has been combined to this method to manage the transition brake/motor in this case. It has been implemented and validated in the mentioned haptic device.

2 Interaction power flow based control

Fig. 1 presents a block diagram of a 1-DOF rotary force-feedback device. The haptic interface comprises a mechanical device, composed of a mass that has an inertia J with some viscous friction b, a controllable brake and a DC motor in direct interaction with a human operator modeled as impedance $Z_0(s)$. The system is controlled by a microcontroller according to a sampling period T. The conversion of the discrete/continuous domain is modeled by a zero-order-hold function ($ZOH(s)$). Only the position θ is measured and this value is used by $H(z)$, a function, linear or not, which represents the virtual environment and determines the desired interactions torque M_h^*.

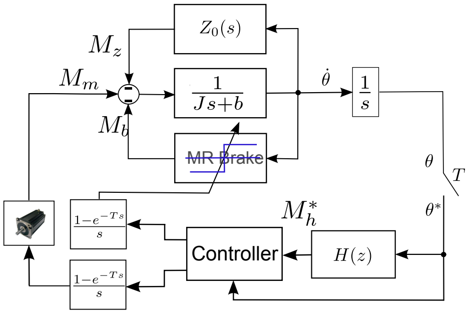


Fig. 1: Hybrid haptic device: The interaction torque M_h^* is calculated by $H(z)$ and applied in the interface by means of the brake (M_b) or the motor (M_m). The torque induced by the user is noted M_z and $\dot{\theta}$ represents the rotational speed. The symbols marked with a star correspond to discrete variables.

The force calculated in the virtual environment must be divided into two different values to activate the brake and/or the motor. In terms of energy, the brake is activated to dissipate energy and the motor should be activated only to create an active behavior. The analysis of the power can be used to determine the control laws. By definition, the haptic device dissipates energy if the power is positive: the force applied by the interface on the user is opposed to the velocity. In other words, the power flows from the user to the interface. The condition for a dissipative behavior is given by:

$$\dot{\theta}(s)\left[-M_m(s) - M_b(s)\right] \geq 0 \tag{1}$$

The desired torque M_h^* is calculated by the transfer function $H(z)$ and is applied in the device using the brake and/or the motor ($M_h(z) = H(z)\theta(z)$). If we consider that $M_h(z) = M_m(s) + M_b(s)$, the power can be calculated as:

$$P(z) = (-M_h^*)\dot{\theta}^* \tag{2}$$

Equation (2) defines the power flowing in the interface. If $P(z)$ is positive, the applied torque by the interface is opposed to the velocity: the interface dissipates energy. If the power is negative, the applied torque induces a velocity in the same direction: the haptic device creates energy. This suggests that the virtual power $P(z) = (-M_h^*)\dot{\theta}^*$ can be used to control the haptic device (torque calculated by $H(z)$ and measured velocity). If the power is positive, the brake must be activated; if the power is negative, only the active actuator should be enabled. The control law is given by:

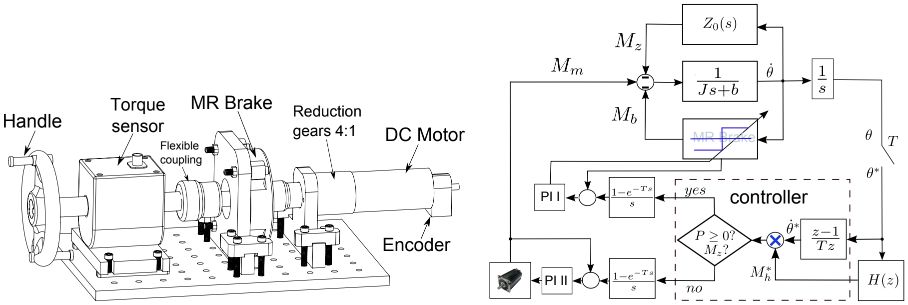
$$\begin{bmatrix} M_m \\ M_b \end{bmatrix} = \begin{cases} ZOH(s)\begin{bmatrix} 0 \\ M_z sgn(\dot{\theta}) \end{bmatrix} & (-M_h^*)\dot{\theta}^* \geq 0 \\ ZOH(s)\begin{bmatrix} M_z \\ 0 \end{bmatrix} & (-M_h^*)\dot{\theta}^* < 0 \end{cases} \tag{3}$$

Where:

$$ZOH(s) = \frac{1 - e^{-sT}}{s} \tag{4}$$

Consider an example when $H(z)$ simulates an angular spring. The user moves the handle ($\dot{\theta} > 0$) at $\theta > 0$, it induces a resistive torque $M_h^* \neq 0$. If the user releases the handle ($M_z = 0$) or if he imposes an effort inferior to the virtual spring's reactive torque ($M_z < H(z)\theta(z)$), the speed should be inverted and the handle should turn back. Using a passive interface, this active behavior is not displayable. Nevertheless, in an hybrid interface controlled by the interaction power flow method, the brake is used to simulate the compression phase of the spring whereas the motor is used to simulate its decompression phase. The transition brake/motor has to be supervised using a measure of the torque imposed by the user. In this case, the controller is informed that one of these cases occur, to activate the motor in consequence. Note that these two conditions appear around $\dot{\theta} = 0$. Based on this analysis, we propose two control methods using interaction torque measurement combined with power flow based control. First, a quantitative torque measure is used to compare the applied torque by the actuators with the imposed torque by the user. The second method, a torque detection, informs the controller if a torque is imposed at the handle ($M_z = 0$ or $M_z \neq 0$).

Fig. 2a shows the 1-DOF interface used as a test bench to validate the control . The active behavior is provided by a DC motor (maxon RE40, nominal torque 54 mNm) while the dissipative torque is supplied by a controllable magnetorheological brake (Lord RD2087, 400 mNm). A torque transducer (Sensor Developments 01324) is placed between the handle and the brake to measure torque interactions. All these elements are linked together in parallel through a flexible coupling. Fig. 2b shows its respective control scheme. The actuator's force is controlled by two analog proportional-integral controllers (PI). An incremental encoder (4096 ppr) is utilized to measure the position. The global system is controlled by a microcontroller $8051F120$ operating at 99,3 MHz.



(a) 1-DOF mechanical device (b) control loop

Fig. 2: 1-DOF hybrid force feedback device and its respective control loop

We have implemented a simulation of an angular spring in the virtual environment ($H(z) = K$, where K is the spring's stiffness). Since passive actuators cannot produce energy, it represents the most critical simulation case using an hybrid interface.

3 Torque measurement based control

This method uses a quantitative torque measure to define the behavior of the system when the velocity is zero, comparing the imposed torque by the user with the applied torque by the interface. We include in the developed control laws a measure of torque. Two conditions are henceforth required to maintain a dissipative effort. The control laws could be implemented as:

$$\begin{bmatrix} M_m \\ M_b \end{bmatrix} = \begin{cases} ZOH(s) \begin{bmatrix} 0 \\ M_z^* sgn(\dot{\theta}) \end{bmatrix} & \begin{matrix} (-M_h^*)\dot{\theta}^* \geq 0 \\ and \\ M_z \geq M_h \end{matrix} \\ ZOH(s) \begin{bmatrix} M_z^* \\ 0 \end{bmatrix} & otherwise \end{cases} \tag{5}$$

This control method is designed to notify the controller when the torque imposed by the user is inferior to the reactive torque calculated by $H(z)$. In this case the motor must be activated and the torque will induce a speed in the same direction. From this point, the power becomes negative. Note that, if motors and brakes do not have the same torque capacity, the measured torque must be compared to the maximum torque of the motor to avoid undesirable vibration at the transition brake/motor.

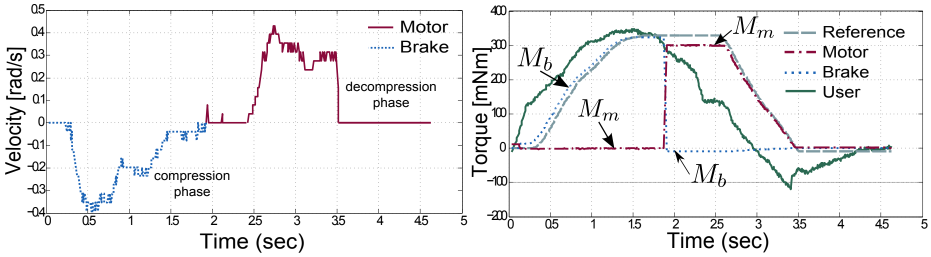


Fig. 3: Experimental results using interaction power and torque based control

Fig. 3 shows the experimental results. Between $t = 0$ and $t = 1.8s$ the user compresses the spring ($|M_z| > |M_h^*|$), the velocity is opposed to the reaction torque, thus, the power is positive and the rendering is assured by the brake. At $t = 1.8s$ the user begins to release the handle (the torque decreases gradually) and the speed becomes zero when$|M_z| = |M_h^*|$. When the imposed torque by the user is inferior to the applied torque ($|M_z| < |M_h^*|$) ($t = 1.9s$), the desired torque is transferred to the motor and the velocity inverted. Thus, the interface simulates the decompression phase of the spring using the motor (power becomes negative). The difference between the desired and applied torque is due to uncompensated viscous friction.

4 Torque detection based control

In this section, the torque measurement is replaced by a torque detection. Different to the previous method, this procedure informs the controller if the user imposes a torque or not, without quantifying it. In this case, the control law of the interface becomes:

$$\begin{bmatrix} M_m \\ M_b \end{bmatrix} = \begin{cases} ZOH(s)\begin{bmatrix} 0 \\ M_h^* sgn(\dot{\theta}) \end{bmatrix} & \begin{matrix} (-M_h^*)\dot{\theta}^* \geq 0 \\ and \\ M_z \neq 0 \end{matrix} \\ ZOH(s)\begin{bmatrix} M_h^* \\ 0 \end{bmatrix} & otherwise \end{cases} \tag{6}$$

The experimental results are presented in the following figure. In this case, we note that a torque detection method imposes an inherent delay in the transition brake/motor. The user presses the spring until $t = 2.8s$ ($|M_z| > |M_h^*|$). At this point the reactive force is equal to the imposed force ($|M_z| = |M_h^*|$) and $\dot{\theta} = 0$. The user gradually releases the handle and the measured torque decreases, while the brake remains activated and in consequence $\dot{\theta} = 0$. Only when the torque becomes zero ($M_z = 0$) at $t = 4.0s$, the brake is turned off and the motor is activated. Thus, the handle can turn freely until its initial position ($M_z = 0$).

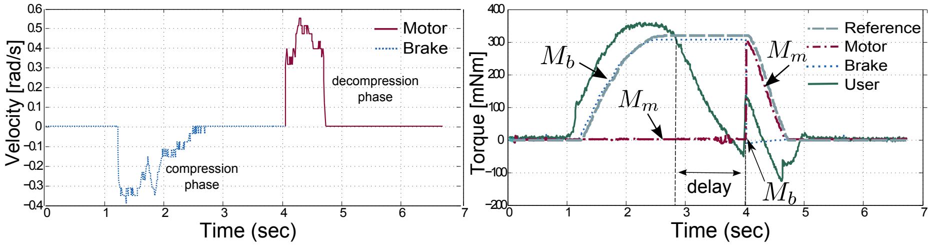


Fig. 4: Experimental results using energy flow and torque detection based control

5 Discussion and future works

In terms of energy, the interaction power flow based control determines an optimal share between the actuators of an hybrid device: the brake is activated to dissipate energy and the motor is used only to create an active behavior. In addition, this method makes the system control independent of the application: a desired torque is converted into two signals to control each actuator. The controller does not know what is simulated in the virtual environment. Combined with torque measurement, it is possible to determine precisely the behavior of the system, even when the velocity is zero. This method uses a torque transducer which increases the system complexity. Using torque detection only, it introduces an inherent delay that may be acceptable for some applications. Moreover, using the hybrid control method, it is also perceptible that the motor is rarely used to dissipate energy, and it is possible to combine a powerful brake with a small DC motor. These configuration minimize the energy necessary to display a haptic rendering. Furthermore, for a same volume, a MR brake can provide 50 times more torque than a conventional DC motor. The conclusions drawn from the current work, enable us to create a new hybrid actuator approach based on unidirectional magnetorheological brakes, which is under development.

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