The Influence of Different Haptic Environments on Time Delay Discrimination in Force Feedback

Markus Rank[1], Zhuanghua Shi[2], Hermann J. Müller[2], and Sandra Hirche[1]

[1] Institute of Automatic Control Engineering, Technische Universität München,
Munich, Germany {`m.rank,hirche`}`@tum.de`,
[2] Institute of Experimental Psychology, Ludwig-Maximilians-Universität München,
Munich, Germany {`shi,hmueller`}`@psy.lmu.de`

Abstract. Time delay in haptic telepresence arising from compression or communication alters the phase characteristics of the environment impedance. This paper describes how well a human operator can discriminate these changes in haptic environments. Three different environments are rendered on a haptic interface and manually excited by a human operator using sinusoidal movements. We find that time delay in haptic feedback can be discriminated starting from 15 ms in a pure damper environment, 36 ms in a spring system, and 72 ms when moving a damped inertia. We conclude that the discrimination thresholds increase with the absolute phase between velocity and force signals resulting from the remote environment characteristics. These results may benefit the human-centered design of high-fidelity haptic communication protocols and haptic filters.

Key words: Time delay, telepresence, psychophysics.

1 Introduction

High-fidelity teleoperation requires sensory feedback from the remote environment with sufficient resolution and low latency [1]. While perceptual discrimination limits for different types of sensory information, e.g., force and position [2–4], and detection thresholds for latency in the visual and auditive modality [5–9] have been studied extensively, the perception of time delay in continuous haptic feedback has been largely neglected. However, time delay is an inherent artifact in long-distance telepresence [10] and in some compression techniques for haptic data [11], though there are haptic data reduction schemes without time delay [12, 13]. In the few available studies on perception of time-delayed force feedback [5, 14–16], detection and discrimination thresholds vary substantially, ranging from dozens to one hundred milliseconds, depending on the specific task and environment. To reveal potential common perceptual fundamentals capable of guiding engineers in dimensioning communication protocols, we embarked on a series of studies designed to systematically explore perceptual effects of haptic feedback latency. In a first study, we examined the impact of various manual excitation amplitudes and frequencies as well as different spring constants in a spring environment during performance of a sinusoidal movement [15]. It is found that increasing manual movement amplitude, and frequency, result in lower detection thresholds for time delays. By contrast, varying stiffness within a certain range does not influence the delay perception [15]. To our knowledge, however, the influence of different environment characteristics on delay perception is still an open issue.

The contribution of the present study lies in the analysis of human delay discrimination capabilities when interacting with a remote spring, damper, and, respectively, inertia environment. We find that discrimination thresholds for time delay increase with the absolute phase between velocity and force signals.

The remainder of this paper is organized as follows: In Section 2, we describe the experiment on delay discrimination; thresholds and just noticeable differences (JNDs) for phase shifts in the haptic feedback are presented in Section 2.2. The results and preliminary implications for data transmission and filter design for haptic signals are discussed in Section 3.

2 Delay Discrimination Experiment

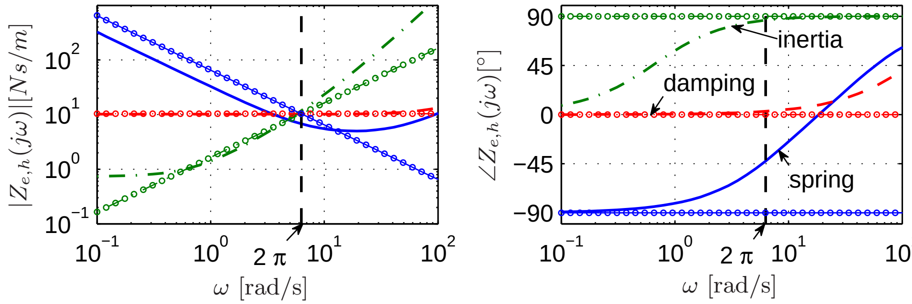
The dynamic haptic environments examined in this study are a linear spring, a damper, and a damped inertia, described by the equations

$$f_e(t) = \begin{cases} -k \int_0^t v(\tau - T_d) d\tau, \\ -d_1 v(t - T_d), \\ -d_2 v(t - T_d) - m\dot{v}(t - T_d), \end{cases} \tag{1}$$

respectively. Here, $f_e(t)$ is the momentary force feedback from the remote environment, $v(t)$ is the velocity at time t, and T_d is the controlled variable – the time delay. The environment-specific parameter k denotes the spring constant, d_1, d_2 the damping factors, and m the inertia. The frequency characteristics of the spring, damping, and inertia (without time delay, $T_d = 0$) are characterized by their mechanical impedance $Z_e(j\omega) = \frac{F_e(j\omega)}{V(j\omega)}$ as depicted as in Fig. 1. Besides differences in the amplitude characteristics, the phase relation between velocity input and force feedback differs by 90° between inertia and damping, and spring and damping environment, respectively. Introducing time delay into the force feedback, i.e., $T_d > 0$ does not alter the environments' amplitude characteristics but the phase changes. This is observable from the force feedback response $F(j\omega)$ to an excitation with a specific trajectory of $v(t)$ with frequency response $V(j\omega)$

$$F_e(j\omega) = Z_e(j\omega)\mathrm{e}^{-j\omega T_d} \cdot V(j\omega) = |Z_e(j\omega)| \cdot |V(j\omega)|\mathrm{e}^{j(\angle Z_e(j\omega) - \omega T_d)}. \tag{2}$$

The larger the time delay for a given frequency, the larger is the phase difference between the velocity and force signal. Hence, the question as to the time delay discrimination threshold can equivalently be posed as a question as to the phase discrimination thresholds depending on the environment-induced phase between



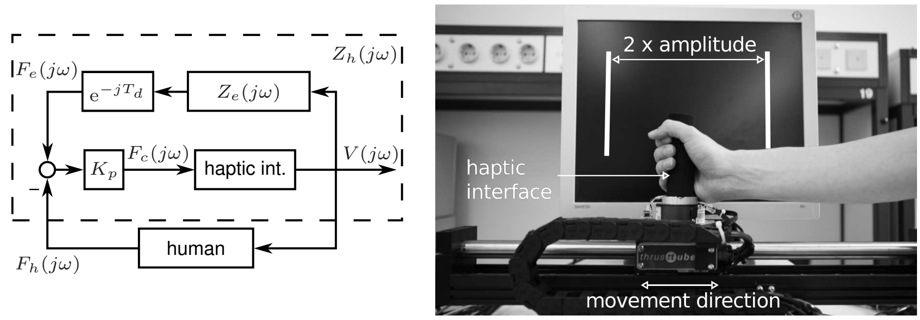
(a) (b)

Fig. 1. Amplitude (a) and phase characteristics (b) of the ideal environment impedance $Z_e(j\omega)$ (light, circle markers) for inertia (dash-dotted), damper (dashed), and spring (solid), and the actually rendered $Z_h(j\omega)$ (bold).

the velocity and force signal. To address this question, participants were required to make sinusoidal arm movements $x(t) = \int_0^t v(\tau)d\tau = A\sin(\omega t)$ of fixed amplitude $A = 15$ cm and frequency $\omega = 2\pi$ rad/s. To ensure good comparability between the conditions, the environment-specific constants were chosen to result in force feedback of equal amplitude: $k = 65\frac{\text{N}}{\text{m}}$, $d_1 = 65/(2\pi)\frac{\text{Ns}}{\text{m}}$, $d_2 = 43/(2\pi)\frac{\text{Ns}}{\text{m}}$, and $m = 22/(2\pi)^2\frac{\text{Ns}^2}{\text{m}} \approx 560\text{g}$.

2.1 Stimuli and procedure

Ten university students (7 male; age range 20-27 years; 9 right-handed) participated in the experiment; they were paid at a rate of 10 Euros per hour. None of them reported any history of somatosensory disorders. Informed consent was obtained from all participants prior to the experiment. The haptic stimuli were rendered using a ServoTube linear motor module (Copley Controls Corp.), equipped with an optical encoder of 1μm resolution. A rubber-coated handle was used for user interaction with the device. Force and torque information was measured with a 6DoF force-torque sensor (JR3 Inc.). The device was controlled by a PC, running Gentoo Linux and equipped with a Sensoray 626 DAQ Card. The haptic environment including the delay was realized using a force control scheme, depicted in Figure 2(a) and rendered in real-time with a sample rate of 1kHz by means of the RealTime Application Interface (RTAI). Visual information was displayed on a 22" LCD Monitor with a refresh rate of 60 Hz. To mask the noise produced by the haptic device, pink background noise was delivered to both ears of participants during the experiment via KOSS QZ99 Headphones. Participants sat in an upright position centered towards the middle of the linear actuator, and the forcefield was rendered in the users' transverse plane within a comfortable manual reaching range. Participants' responses were collected using a joystick. The setup is depicted in Figure 2(b). For an evaluation of the actually presented impedances $Z_h(j\omega) = \frac{F_h(j\omega)}{V(j\omega)}$ including the haptic interface dynamics,

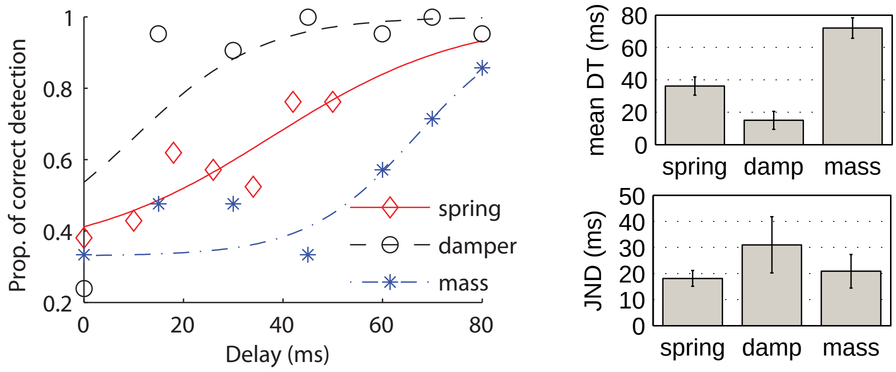


(a) (b)

Fig. 2. (a) The force control scheme to render the impedance $Z_h(j\omega) = \frac{F_h(j\omega)}{V(j\omega)}$. **(b)** The experimental apparatus consisting of a linear actuator device with a rubber-coated handle and a TFT screen used for visual stimulus presentation.

control and $Z_e(j\omega)$ as illustrated in Figure 2(a), we identified the haptic interface dynamics in the frequency domain. The uncontrolled linear actuator dynamics were found to be sufficiently well captured by a linear second-order system with the commanded force $f_c(t)$ as input and the endeffector position $x(t)$ as output. To determine the specific parameters, a standard least-squares system identification procedure was applied. By employing the implemented controller K_p used in the experimental procedure and the environmental dynamic equations in (1) as they were used in the actual experimental procedure, the respective frequency responses for $Z_h(j\omega)$ were calculated – see Fig. 1.

As shown in the Bode diagram, inertia and damper were rendered quite accurately around the instructed movement frequency in terms of amplitude and phase characteristic. The influence of the actuator's mass and friction, however, changed the phase characteristic of the spring to approximately -45° at the movement frequency of 2π rad/s, instead of an ideal phase of -90°. All of the following results are based on the really rendered impedance $Z_h(j\omega)$, rather than the ideal environment impedance $Z_e(j\omega)$. The movement amplitude on a given trial was indicated by two vertical bars on the monitor, as can be seen in Fig. 2(b). The movement frequency was cued audibly by a rhythmic beep train, with each beep indicating the turning point in the direction of movement. An additional guidance dot moving in the desired sinusoidal way was shown on the monitor in the training session. After the participant had become familiar with the movement shape, the visual cue was removed to reduce potential distraction from the discrimination task to be performed in the formal experiment. To obtain an accurate estimate of the perceptual thresholds, the method of odd-one-out 3-alternative forced-choice (3AFC) was used in the experiment. Each trial was subdivided into three intervals of 3 seconds; one randomly chosen interval contained the target stimulus with a specific level of time delay introduced into the force feedback. In the remaining two intervals, the system responded with



(a) (b)

Fig. 3. **(a)** Estimated psychometric curves for the three environments for one typical participant. **(b)** Mean thresholds (± standard error, $n = 7$) for the different environments.

a non-delayed force feedback. In order to remove any abrupt-onset cues due to switching delay conditions, a transition phase of 1.5 seconds was added between delayed and non-delayed force feedback intervals. No feedback about the correctness of the answer was provided. Seven levels of time delay T_d, segmented equally between 0 ms and 50 ms, were tested for the spring environment, and seven delays between 0 ms and 80 ms for the mass and damping environments. These levels were determined in a pilot study and respected stability conditions for the experimental setup. Each delay level was tested 21 times, yielding a total of 441 trials. The experiment was conducted over three sessions, where each session contained 7 repetitions of all conditions in a random order.

2.2 Results

Three participants failed to follow the movement instructions accurately enough, so their data had to be excluded from further analysis. With the remaining data sets, an adjusted logistic function [17]

$$P(x) = \gamma + (1 - \gamma) \cdot \frac{1}{1 + e^{\frac{\alpha - x}{\beta}}} \qquad (3)$$

is used for estimating the psychometric function, where the guessing rate γ is set to 1/3 according to the 3AFC paradigm. Fig. 3(a) shows typical correct responses, produced by one participant, for the three different environments. Using equation (3), the discrimination threshold DT and the just noticeable difference JND at response level 67% can be easily obtained as DT$= \alpha$ and JND$= \beta \log 3$. In Fig. 3(b), the mean DTs and JNDs for spring, damper and inertia are presented. The results indicate that the discrimination threshold is the largest for the inertia, with a mean of 72 ms, corresponding to a phase shift of 25° as deriveable from equation (2). The threshold associated with the damper is the lowest, with a mean of 15 ms, equivalent to a phase shift of 5°. In the spring condition, time delay can be discriminated from a non-delayed spring starting at a threshold of 36 ms, corresponding to 13° phase lag. A repeated-measures ANOVA reveals the discrimination thresholds to be sensitive to the different environments, $F(2, 12) = 14.17, p < 0.01$. Follow-on comparison tests show the discrimination thresholds to differ reliably from each other ($p < 0.05$). This indicates that the different environments do indeed influence the subjective judgment of haptic feedback time delay. A further repeated-measures ANOVA for the JNDs of discrimination fails to reveal a significant effect of the environment, $F(2, 12) = 1.03, p > 0.1$. Further studies using more than three environmental conditions need to be performed in order to derive an analytic relationship between the environment induced phase $\angle Z_h(j\omega)$ and the time delay discrimination threshold DT. In general, it is observed that discrimination thresholds increase with the absolute value of the phase difference between an arbitrary $\angle Z_h(j\omega)$ and the phase of a damper environment.

3 Discussion

The present study shows that discrimination thresholds of delayed force feedback from spring, damper, and, respectively, inertia are different. This supports our conclusion put forward in [15] that in a continuous haptic environment, the time delay detection mechanism is not based on a temporal correlation or an internal clock mechanism, e.g., as proposed in [18]. Considering equation (2), time delay shifts the phase characteristics independently of the environment type. Thus, there is a strong indication that the undelayed dynamical system properties play a role in discriminating the difference in phase. There are several effects potentially contributing to this observed perceptual performance. One of them is that JND of force discrimination is lowest when the limb is not moving [19, 20]. Evidently, the force feedback from the various environments around the movement turning points, where $v(t) \approx 0$, differs significantly in terms of magnitude and slope: Inertia and spring with phases of $+90°$ and approximately $-45°$, respectively, have non-zero force feedback around these instances. High force levels are known to result in large discrimination thresholds [2]. Damping, by contrast, does not only combine low velocities with low force feedback, but additionally reverses force direction at the turning point of the movement. It is possible that this feature provides additional help for discriminating between delayed and undelayed force feedback. Further investigations may be considered to shed additional light on the mechanism responsible for the discrimination performance observed here.

Nevertheless, the present results have direct implications for the assessment and design of haptic communication protocols: If a time delay is introduced that shifts the phase by more than 5°, perception of damping is compromised, while spring and mass can still be perceived unaffectedly. Schedulers, data compression techniques or filters – i.e. all potential measures inducing phase-lag – need to be dimensioned based on the environmental conditions: If it is known that no damping force, such as friction, is present in the remote environment, larger latencies are tolerable with respect to perceptual fidelity. Our results suggest that in order to achieve the best filter effect on force magnitude without compromising phase perception, an adaptive filter based on an online-estimation of the environmental properties may be considered, using techniques such as described in [21, 22]. However, guided by our initial findings, more experiments exploring a broader frequency range should be carried out to refine and validate the suggested specifications for communication protocol and filter design.

4 Conclusion

We present an experiment investigating human time delay discrimination thresholds in continuous haptic environments, which, in our setup, is equivalent to the discrimination threshold of changes in the phase characteristic of the mechanical impedance. Discrimination thresholds are found to increase with the absolute value of the phase between velocity input and force of the environment. Based on these findings, we suggest that communication protocols and filters for haptic signals should take into account the environment's phase characteristic, e.g., by adapting the filter gains in accordance with the type of remote environment. Future research should test a greater range of frequencies and environments, composed of the elementary environment components spring, damper, and inertia, to contribute to the emerging picture on phase discrimination.

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