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Event-Based Haptics and Acceleration Matching: Portraying and Assessing the Realism of Contact

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Event-Based Haptics and Acceleration Matching: Portraying and Assessing the Realism of Contact

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Abstract

Contact in a typical haptic environment resembles the experience of tapping on soft foam, rather than on a hard object. Event-based, high-frequency transient forces must be superimposed with traditional proportional feedback to provide realistic haptic cues at impact. We have developed a new method for matching the accelerations experienced during real contact, inverting a dynamic model of the device to compute appropriate force feedback transients. We evaluated this haptic rendering paradigm by conducting a study in which users blindly rated the realism of tapping on a variety of virtually rendered surfaces as well as on three real objects. Event-based feedback significantly increased the realism of the virtual surfaces, and the acceleration matching strategy was rated similarly to a sample of real wood on a foam substrate. This work provides a new avenue for achieving realism of contact in haptic interactions.

1. Introduction

The field of haptics aims to recreate the experience of real manipulation by stimulating the user's complex sense of touch. Using a pen-like interface attached to a robotic arm, the user's motions are mapped into a virtual world, and appropriate reaction forces are displayed. Ideally, interacting with virtual objects would be as simple and vivid as using a pen to probe items on your desk. Consider the task of tapping on a piece of wood, as shown in Figure 1(a). Each tapping event is described by a sudden change in velocity with associated acceleration and force spikes, followed by a continuous force to balance the user's pressure. The user determines his or her hand impedance and velocity, but it is the mass, density, compliance, and damping of the objects that shape the details of the impact. As such, each tapping response is observed by the user but not actively controlled.

Most haptic algorithms attempt to re-create the experience of hard contact by measuring the user's penetration into a virtual object and producing quasi-static restoring forces. This strategy is illustrated in Figure 1(b) as a virtual spring attached to the interface. Finite position resolution and present computational speeds limit virtual spring stiffnesses to about 1,000 N/m, but providing realistic high-frequency feedback with this closed-loop approach would require gains up to 1,000,000 N/m. Thus, the classic penetration-based approach to haptics is doomed to render soft, dull contacts devoid of the high-frequency transients encountered during real manipulation.

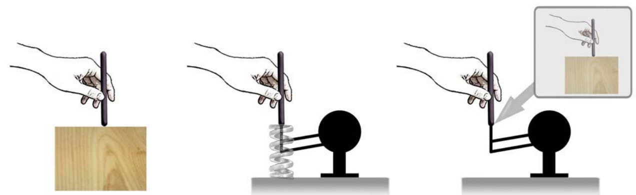

Figure 1. Real and virtual contact.

We propose the alternative paradigm of event-based haptics to increase the realism of virtual interactions, as described in Section 2. Impact transients are vital to the user's experience and are entirely pre-specified by the initial conditions of contact, providing a unique signature for every event. We propose to pre-compute the transients and display them open-loop when each event is triggered. This strategy can be executed with a lower servo rate and significantly lower sensor resolution than would be required for closed-loop generation of identical transients. Figure 1(c) depicts this rendering approach, in which the event signature is displayed to the user at impact. Section 3 presents our method for computing force feedback profiles that produce accelerations matched to the experience of real contact.

To validate the concept of event-based haptics and the method of acceleration matching, we studied user perception of realism during contact with real and virtual wood, as detailed in Section 4. Asking users to tap on a range of samples, we assess several rendering techniques and show that event-based haptics with acceleration matching can portray hard contact with significantly more realism than traditional methods. The results of this study are discussed in Section 5, followed by conclusions in Section 6.

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2. Event-Based Haptics

Stylus-based haptic devices promise users the ability to interact with and feel virtual objects as though the tip of the pen-like handle were directly touching an equivalent real object. Honoring the user's sensitivity to and reliance upon high-frequency interaction transients, event-based haptics defines an alternative display strategy for improved realism. Rather than trying to generate force transients using closed-loop position feedback, this method uses discrete event triggers to begin playback of pre-computed force histories.

Haptic feedback is particularly crucial when simulating interactions with rigid virtual objects. While visual feedback conveys sufficient information for exploring soft environments, surface deformations of hard objects are too small and abrupt to be seen. The dynamics of rigid contact predict two distinct, superimposed forces: a characteristic high-frequency transient that appears for a short period after impact, and a quasi-static, low-frequency force that opposes penetration over long durations. The shape of the transient is determined by material properties and initial user conditions, including grasp configuration and incoming velocity. Impact transients generally take the form of exponentially decaying sinusoids [6, 8], though multiple resonant modes and intermittent contact may lead to a more complex response. It is these signals, lasting tens of milliseconds, that allow the user to infer material properties.

Fingertip mechanoreceptors detect signals up to 1 kHz, with peak sensitivity near 300 Hz [1]. In contrast, humans cannot move or position their fingertips above 10 Hz. The asymmetry of human sensory and manipulation bandwidths leads to a strategy of identifying signature force patterns and treating them as discrete cognitive events. The human body takes at least 100 ms to react to tactile stimuli, and higher-level cognition takes even longer. Consequently, Daniel and McAree separate haptic feedback into distinct power and information bands, below and above 30 Hz respectively [2]. Kontarinis and Howe used vibrotactile displays to improve perception of remote accelerations during teleoperation [4], and Okamura et al. improved material discrimination by displaying virtual vibrations in the form of exponentially decaying sinusoids that were empirically tuned to observed signals [6]. Rigid virtual environments devoid of such high-frequency feedback will never feel truly realistic.

Built upon the realization that high-frequency transients are both vital and uncontrolled, event-based haptics superimposes proportional and transient force outputs, as depicted in Fig. 2. Equivalent to classic haptic rendering algorithms [9], a force proportional to the user's penetration into the virtual object is applied, creating a linear virtual spring. This feedback channel provides a quasi-static restoring force but cannot generate high-frequency transients.

In the event-based paradigm, proportional feedback is augmented by the playback of open-loop, high-frequency force signals at contact. An event is triggered when the user reaches the surface of a virtual object, and a pre-computed transient is displayed. Because the shape of the transient depends on material properties as well as impact velocity and user impedance, a library of transient signals may be utilized. Such a library may be built from physical measurements or based on multi-modal vibration models and analysis. To achieve true realism, we believe the accelerations experienced by the user should match real impact acceleration profiles, as described below in Section 3. Regardless of the method used to pre-determine the transient, its output remains deterministic for the duration of the user's reaction time and hence does not require continual sensor feedback or additional computation.

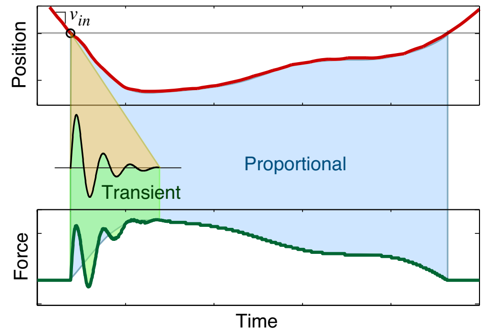

Figure 2. Open-loop forces superimpose on traditional penetration-based feedback.

Beyond providing realistic high-frequency signals, event-based forces can quickly reduce the user's momentum into the virtual object. Because momentum scales with velocity, the transient signal should also scale with the measured incoming velocity of the user. High-magnitude, short-duration pulses have been shown to stop the user's motion, reduce maximum penetration distance, and increase the perceived stiffness of a virtual environment [3, 7]. These benefits are retained by transient signals containing sharp force spikes, typical of all impacts. Thermal constraints prevent the motors used in standard haptic devices from being driven with high current for long durations, but transient signals may exceed the steady-state maximum for short periods of time, enabling far more forceful momentum cancellation than can be achieved with proportional feedback alone.

3. Acceleration Matching

Event-based haptics applies high-frequency force feedback to the user's hand at the start of contact with a virtual object. These open-loop signals are played by the device's actuators, traveling through its structure to create high-frequency accelerations at the endpoint. Ideally, these accel-

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erations would match the transients experienced when tapping on the real object that is being emulated by the virtual environment. In the past, researchers have used decaying sinusoids [6] and short-duration pulses [3] for the transient signal. These methods provide the user with high-frequency accelerations at contact, but their parameters must be hand-tuned for each device and target object. We have developed an analytical method for determining the force feedback required to produce a specified acceleration profile.

The acceleration matching strategy requires hardware capable of measuring high-frequency accelerations and producing high-frequency forces. It centers on characterizing and inverting the system's transfer function from force to acceleration. The inverse model can then be used to transform desired acceleration profiles, which may be difficult to parametrize, into force feedback commands. By recording accelerations for contact with the same object at a range of incoming velocities, a force transient library can be assembled for playback to the user during event-based haptic interactions. The steps required to provide acceleration-matched feedback are detailed in the following sections, showing results for our experimental testbed.

3.1. Hardware Selection

Systems that can transmit grounded, high-frequency force signals to the user are most suitable for event-based haptics. We chose an early Phantom, produced by SensAble Technologies, Inc., to provide an interface for tapping on both real and virtual objects. The Maxon motors, smooth cable drive, and stiff linkage elements allow transmission of high frequency signals, and the motor-shaft-mounted optical encoders enable high-fidelity position measurement. The Phantom's distal link was reversed to point upward, and a pen-based stylus was rigidly attached to its endpoint. Contact forces were rendered with the motor on the shoulder joint. The stylus was kept vertical by proportional control on the elbow, and the base was centered by mechanical stops.

Our setup uses linear current amplifiers from an Immersion Impulse Engine 2000 rather than the lower-bandwidth pulse-width modulation amplifiers commonly used with Phantoms. The linear amplifiers provide excellent high-frequency response, producing full-scale sinusoidal current at up to 1 kHz with no attenuation or phase lag. One drawback of these amplifiers, however, is their 1.4 A maximum current; the Phantom's motors can sustain much higher current levels for short durations, which would allow for even stronger event-based cues.

To record endpoint accelerations, we selected an Analog Devices ADXL150 chip with a bandwidth of 1 kHz and a range of ±50 g. Its small package was attached to the Phantom's distal link using double-stick tape, and its wires were routed along the arm. The voltage output of the accelerometer was measured using a National Instruments PCI-1200 card. A desktop computer running RTAI Linux sampled the accelerometer signal and the Phantom's encoders at 10 kHz, commanding feedback forces to the current amplifier at the same rate. This high servo frequency was chosen to allow the system to measure and produce accelerations at many hundreds of Hertz. Once the system was calibrated, software gravity compensation was added to allow the Phantom to hold any position during an interaction.

3.2. System Identification

After choosing the hardware, we sought to estimate the transfer function from commanded force to measured acceleration while the stylus was held by a user. The fidelity of this model is most important at the high-frequencies we seek to display, far above the region of intentional human motion. The multi-element transmission from motor to endpoint makes it well-suited to non-parametric identification techniques, which treat the system as a black box. An empirical transfer function estimate (ETFE) can be obtained by applying a swept sinusoid force signal to the motor and recording the resulting endpoint acceleration. The frequency content of these two signals is then compared by taking the ratio of their discrete Fourier transforms (DFTs) and examining the resulting magnitude and phase. We have found this method to be effective at characterizing haptic devices [5], because it elucidates intervening dynamics without assuming a model structure.

A 2.5 second long swept sinusoid from 10 to 500 Hz was applied to the system as a user passively held the stylus. Four tests were performed at three force magnitudes for two users, and results were averaged in the complex domain across tests. Fig. 3 presents the six resulting ETFEs, which match well between users and across force magnitudes, especially at high frequency. Small variations are observed between users at low frequency, most likely due to differences in hand impedance. The device exhibits a resonance near 130 Hz and diminishing response thereafter.

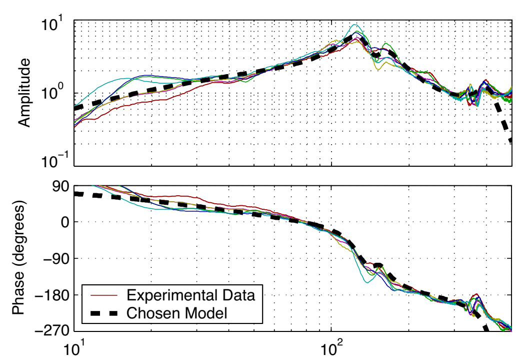

Figure 3. ETFE from force to acceleration.

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A linear seventh-order, relative degree four model with a 0.25 ms time delay was hand-fit to these ETFEs, and its Bode plot is shown in Fig. 3. Though interpreting its physical significance is difficult, this empirical model aptly captures the system's frequency response under a range of conditions. It was validated in the time domain by playing a variety of event-based transients as a user tapped on a virtual object. The model's response matches the measured values closely, especially at high frequency, leading us to conclude that a simple, user-invariant dynamic model is useful in describing this system's response during haptic interactions.

3.3. Model Inversion

Inverting the system model enables us to determine the force transient that must be applied to create a specified acceleration profile at the device's endpoint. We record acceleration for 100 ms following impact between the Phantom and the target substance. This signal is smoothed to remove high-frequency electrical noise without altering phase and then applied to the inverse of the system model, producing a raw version of the required force. Low-pass filtering and smoothing, combined with high-pass filtering, eliminates noise and drift while preserving the force signals in our frequency range of interest, from 10 to 500 Hz, which constitute the sensory signature of the impact. The magnitude of the force transient is then tapered to zero at the start and end to ensure smooth superposition. The model inversion process is verified by applying the computed force transient to the forward model and comparing the model's predicted response with the targeted acceleration. Further verification was obtained by testing the transients on the actual hardware, supporting the viability of model inversion for matching virtual feedback to real accelerations.

3.4. Feedback Algorithm

The model inversion process can be used to build a library of transients for portraying contact with a specific object. Each signal is characteristic of the real situation that produced it, including incoming velocity, hand impedance, and object contact location. The strongest observed effect occurs with incoming velocity, v_{in}, as magnitude increases and frequencies shift. A velocity-scaled library can be generated by recording a series of varied contacts with the target sample. Contact events are identified as crossing of a position threshold, and the subsequent acceleration signals are isolated, conditioned, and applied to the inverse model as described above. After ensuring even distribution of contact velocities, we assemble the remaining transients into an event-based haptic library.

We constructed a transient library for contact with wood on a foam substrate, as shown in Fig. 4. Note the significant

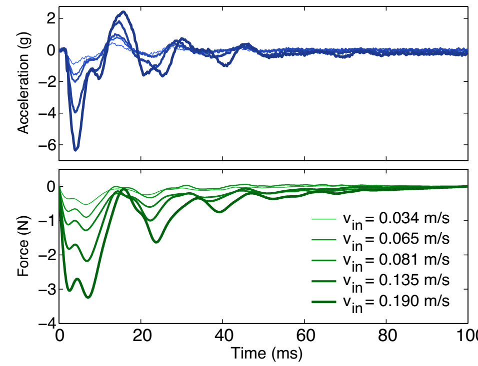

Figure 4. Recorded accelerations and force transient library for wood on foam.

differences between acceleration and force signals, which highlight the usefulness of a model-based approach. The real-time controller loads the library and selects appropriate transients when contact events occur. The user's incoming velocity is compared to those of the library transients, and a linear combination of the closest signals is selected. This method of acceleration-matching succeeds at creating contact accelerations that closely resemble those experienced when tapping on the real sample, but its performance is best evaluated by comparing its feel to that of tapping on the target sample. When transients were superimposed with strong proportional forces, some users reported that the surface felt slightly active. Attenuating the library by a factor of 0.8 eliminated these complaints; future algorithms will account for superposition during transient generation and will also consider hand impedance at contact.

4. Assessing Contact Realism

Realism of virtual contact is inherently difficult to quantify and can only be accurately assessed by perceptual tests. A comparative user study was conducted to analyze the effectiveness of event-based haptics and the performance of the force feedback transients produced via acceleration matching. Subjects rated the realism of tapping on three real and eight virtual objects. The real objects included samples of dense balsa wood, soft foam, and dense balsa on a foam substrate, as shown in Fig. 5. Approximate stiffnesses for these three real objects are given in Table 1, which contains the parameters used for all test samples. The eight virtual objects were chosen to represent a variety of rendering algorithms, differentiating between steady-state and transient effects. The first two controllers provide proportional feedback alone; the higher gain was tuned to avoid buzzing from encoder discretization, and the lower gain was set to half this level. The remaining six virtual samples combine velocity-scaled transients with either the firm or soft proportional controller, following the event-based paradigm.

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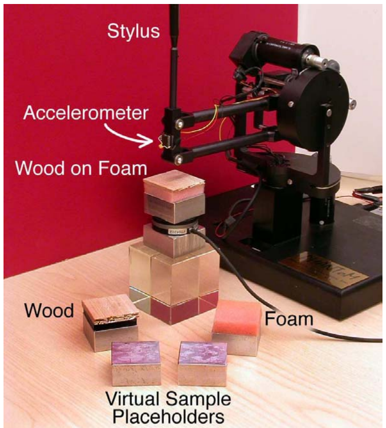

Figure 5. Users blindly tapped on three real and eight virtual samples using the Phantom.

Wood	K = 70,000 N/m
Wood on Foam	K = 350 N/m
Foam	K = 220 N/m
Firm Proportional	K = 680 N/m
Soft Proportional	K = 340 N/m
Fixed-Duration Pulse	A = 5.7 Ns/m, d = 0.020 s
Decaying Sinusoid*	A = 15.9 Ns/m, d = 0.055 s, f = 36.2 Hz

Table 1. Sample Parameters

The three chosen contact signals were a pulse, a decaying sinusoid, and a library of acceleration-matched transients developed according to the methods presented in Section 3. All three were tuned to emulate the experience of tapping on the combined wood/foam sample because the response of wood alone contains higher frequencies that require actuation power presently beyond the capability of our amplifiers. Even at low magnitudes, the chosen transients produced virtual contacts that felt more realistic than those matched to wood, perhaps because the impact dynamics were more consistent with the low stiffness of the underlying proportional controller.

While previous work investigated fixed-magnitude, varying-duration pulses [3], we chose to use a pulse of fixed duration and varying magnitude. The duration of the pulse was tuned to approximately match the first half-period of the measured acceleration transient, and its nominal magnitude was tuned by hand. The frequency of the decaying sinusoid was chosen to be 66 Hz, but unfortunately an error in the testing routine reduced its frequency to 36.2 Hz and was not discovered until the completion of user testing. This parameter change produced a sinusoid that was poorly matched to the target sample, and pertinent results are marked with an asterisk (*) to remind the reader of this mistake.

User testing was performed on the hardware described in Section 3.1. A rigid stand was positioned beneath the stylus for placement of the real samples, as shown in Fig. 5. We began each experiment by explaining its three phases to the subject: familiarization with the wood sample, demonstration of the eleven test samples, and repeated rating of sample realism. Users were told that they would be presented with a number of different renderings of the hard, wooden surface and would be asked to rate, on a scale from one to seven, how well each sample represented the experience of tapping on the real piece of wood. Each subject was asked to repeat the definition of this realism metric before starting the experiment to ensure comprehension.

To isolate the user's sense of touch, extraneous stimuli were removed from the experimental setting. Sitting at a computer terminal, the user passed his or her right arm through an opening in a tall barrier to prevent observation of the device and samples. The user rested his or her elbow on a padded armrest to prevent muscle fatigue. The user was instructed to hold the stylus with a consistent grasp and to avoid touching the table in order to prevent inadvertent transmission of contact vibrations. The user wore headphones playing white noise at a high volume to mask the sounds caused by tapping on the different samples. Simple text commands were presented on the computer monitor to guide the user through the three phases of the experiment. The operator sat behind the barrier at another computer, monitoring the progress of the experiment and placing samples beneath the stylus.

During the first phase of the experiment, the user had an opportunity to tap repeatedly on the real wooden sample to become familiar with its response. When the user was done interacting with the wooden sample, the system transitioned into a demonstration phase, in which each of the eleven samples, both real and virtual, were presented to the user once in random order. This phase was included to allow the user to learn the experimental procedure, which was replicated in the following testing phase, and to explore the range of samples before beginning to rate their realism. Before each tap, the system would move the stylus to a home position above the sample, giving the operator space to place the next object. Two virtual placeholder blocks were used so that the operator removed and placed an item on the stand every trial, regardless of whether the sample was real or virtual. When the sample was ready, the user was instructed to tap, both by a visual command on the monitor and by a recorded voice in the headphones.

The user would then move the stylus down to tap on the surface of the object, which was always at the same height. From the time of first impact, they were given five seconds in which to tap repeatedly on the surface. If they exceeded the device's current limit when tapping on a virtual sample, a low tone sounded in the headphones and the test was returned to the sample pool to be randomly drawn again. After five seconds, the device returned to the home position, and the user was instructed to rate the realism of the sam-

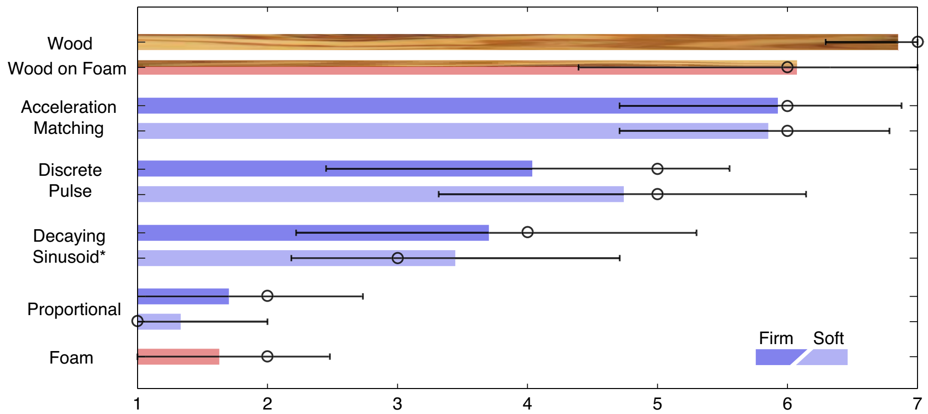

Figure 6. Realism ratings of the eleven test samples: bars and circles indicate the mean and median across subjects and tests, and error bars extend one standard deviation from the median.

ple on a scale from one to seven using the keyboard.

Following completion of the demonstration phase, the user proceeded to the testing phase, wherein each sample was presented three times in random order, for a total of 33 trials, plus any repeats for saturations. The testing procedure was identical to that of the demonstration phase, and the entire experiment lasted between ten and fifteen minutes. A short debriefing session followed the completion of the testing, wherein subjects were asked to specify the criteria they had used to evaluate sample realism.

5. Results and Discussion

The user study included nine subjects, ranging in age from 24 to 31, including three females and six males. Their level of experience with haptic systems ranged from novice to near-expert. For each trial, the system recorded the sample type, testing phase, saturation, the set of incoming tap velocities, and the user's realism rating.

Each sample's average realism rating for valid tests, pooled across users, is shown in Fig. 6. Each sample was rated three times by each of the nine subjects, with higher values indicating higher perceived realism. The average incoming velocity, pooled across subjects and valid test-phase taps, was 0.11 m/s, with a standard deviation of 0.033 m/s. Users saturated virtual samples an average of five times during the testing phase, with a range from zero to eleven. Saturations occurred most frequently for the decaying sinusoids and the acceleration-matched library, which both contain large initial force spikes.

Statistically significant differences were found among the realism ratings given to the eleven samples. The most highly rated sample was wood, followed by wood on foam and the acceleration-matched virtual surfaces. The foam and the two proportional controllers were rated most poorly, while the pulse and poorly-tuned decaying sinusoid transients fell in the center of the distribution. To evaluate these variations, paired t-tests were conducted on user average ratings for each sample combination, the results of which are shown graphically in Fig. 7. The p-value gives the probability that two rating sets stem from indistinguishable populations; therefore lower p-values indicate more significant differences between the ratings, and higher p-values show that user ratings on the pair of samples were similar.

While the majority of sample rating pairs showed little correlation, there were three noticeable exceptions. The firm and soft acceleration-matched libraries cluster with the wood on foam sample ($p_{firm} = 0.72$, $p_{soft} = 0.56$); the library was constructed from transients recorded while tapping on the wood/foam sample, and subjects rated its realism at a level very similar to that of the target sample. This finding supports the efficacy of the acceleration-matching technique for mimicking real contact transients using event-based haptics. Additionally, the strength of the underlying proportional controller did not significantly affect the realism of the two acceleration-matched samples ($p = 0.56$).

Also note that ratings given to the firm proportional con-

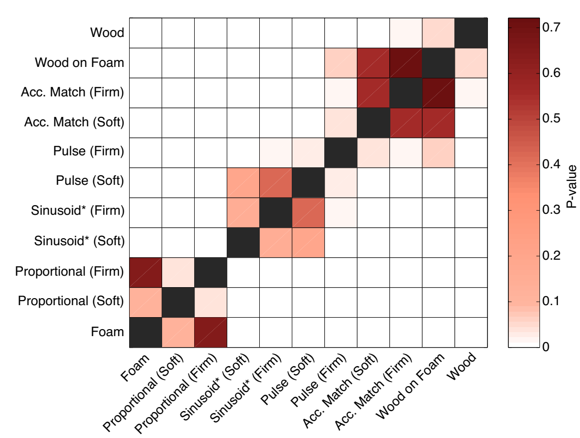

Figure 7. Paired t-tests on the user average realism ratings show three clusters.

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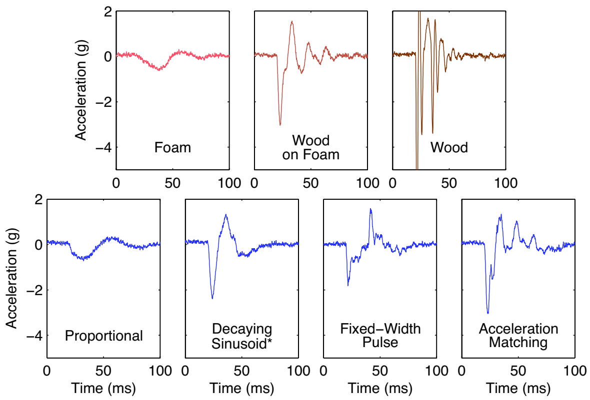

Figure 8. Accelerations for contact with samples at an incoming velocity of 0.11 m/s.

troller were similar to those assigned to foam (p= 0.65). This appraisal of standard haptic rendering methods is consistent with our experience. It is also important to remember that the frequency of the decaying sinusoids was poorly matched to the target sample due to an implementation error; we expect that the intended transient would have been rated more highly and plan to investigate its relative performance in future work.

When asked to name their rating criteria, users listed several salient metrics. First among these was whether the stylus came to a sudden stop after contact; we hypothesize that the foam and the proportional controllers were rated most poorly because they cannot quickly cancel the user's incoming momentum. The second commonly mentioned criterion was the presence of high frequency vibrations at contact. We can examine the accelerations produced by tapping on the real and virtual surfaces, as shown in Fig. 8. The three event-based virtual samples produce high-frequency accelerations that are similar to those seen for the wood on foam and wood objects. Of these three, the acceleration-matched transient most closely resembles the real signals, which we hypothesize contributes to its high realism ratings. Third, users disliked samples that felt bouncy or active. We conjecture that some of these comments were due to the poorly tuned decaying sinusoid, and others stem from variations in hand inertia and grasp. These user comments and the above findings support the case for event-based haptics and provide guidance for its future development.

6. Conclusions

Encouraged by the results of this work, we believe the paradigm of event-based haptics has the potential to significantly improve the rendering of hard contact. Its asymmetric structure naturally compliments user capabilities, generating high-frequency transients by observing low-frequency user motions. The basic algorithm is user-independent and does not require changes to device hardware. Meanwhile, open-loop output precludes the need for high-gain closed-loop feedback, potentially relaxing requirements for computation rate and sensor resolution.

User evaluations validated the realism of transient overlays; in particular, ratings of a force display based on dynamic inversion and acceleration matching were rated similarly to contact with wood on a softer substrate. We believe increasing the current available to drive the mechanism will allow us to reproduce the sensation of contact with even stiffer materials such as metal. Users also judged classic haptic feedback to be equivalent to real foam, reiterating the softness of traditional haptic display. Future work will investigate the role of hand impedance in contact dynamics, adding the variables of inertia and grasp strength to the transient generation algorithm. Extrapolating to three-dimensional surfaces and additional dynamic effects, we hope event-based haptics will instill authenticity into virtual-reality simulations.

References

[1] K. R. Boff and J. E. Lincoln. *Engineering Data Compendium: Human Perception and Performance*. Armstrong Aerospace Research Laboratory, Wright-Patterson AFB, 1988.

[2] R. W. Daniel and P. R. McAree. Fundamental limits of performance for force reflecting teleoperation. *Int. J. Robotics Research*, 17(8):811–830, Aug. 1998.

[3] J. D. Hwang, M. D. Williams, and G. Niemeyer. Toward event-based haptics: Rendering contact using open-loop force pulses. In *Proc. Symp. Haptic Interfaces*, Mar. 2004.

[4] D. A. Kontarinis and R. D. Howe. Tactile display of vibratory information in teleoperation and virtual environments. *Presence*, 4(4):387–402, 1995.

[5] K. J. Kuchenbecker and G. Niemeyer. Cancelling induced master motion in force-reflecting teleoperation. In *Proc. ASME IMECE*, Nov. 2004.

[6] A. M. Okamura, M. R. Cutkosky, and J. T. Dennerlein. Reality-based model for vibration feedback in virtual environments. *IEEE/ASME Trans. Mechatronics*, 6(3):245–252, Sept. 2001.

[7] S. E. Salcudean and T. Vlaar. On the emulation of stiff walls and static friction with a magnetically levitated input-output device. *ASME J. Dynamics, Measurement and Control*, 119:127–132, 1997.

[8] P. Wellman and R. D. Howe. Towards Realistic Display in Virtual Environments. In *Proc. ASME DSCD*, volume 57, pages 713–718, 1995.

[9] C. Zilles and J. Salisbury. A constraint based god-object method for haptic display. In *Proc. Int. Conf. Intelligent Robots and Systems*, 1995.

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