Improving Contact Realism through Event-Based Haptic Feedback

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Abstract—Tapping on surfaces in a typical virtual environment feels like contact with soft foam rather than a hard object. The realism of such interactions can be dramatically improved by superimposing event-based, high-frequency transient forces over traditional position-based feedback. When scaled by impact velocity, hand-tuned pulses and decaying sinusoids produce haptic cues that resemble those experienced during real impacts. Our new method for generating appropriate transients inverts a dynamic model of the haptic device to determine the motor forces required to create prerecorded acceleration profiles at the user's fingertips. After development, the event-based haptic paradigm and the method of acceleration matching were evaluated in a carefully controlled user study. Sixteen individuals blindly tapped on nine virtual and three real samples, rating the degree to which each felt like real wood. Event-based feedback achieved significantly higher realism ratings than the traditional rendering method. The display of transient signals made virtual objects feel similar to a real sample of wood on a foam substrate, while position feedback alone received ratings similar to those of foam. This work provides an important new avenue for increasing the realism of contact in haptic interactions.

Index Terms—Haptics, force feedback, contact transient, event-based.

1 Introduction

Human manipulation is inherently asymmetric, using low-frequency hand motions to elicit high-frequency responses from the environment [1]. For example, consider the act of tapping on a wooden table with a stylus, as illustrated in Fig. 1a. Though the person initiates the motion, it is the physical properties of the table and pen that shape the transient details of contact. Each tapping event creates sudden accelerations with frequency content up to several hundred Hertz, strongly stimulating the Pacinian corpuscles in the hand and fingertips [2]. These tool-mediated contact vibrations provide the person with far richer information about the table's material properties than could be obtained by merely pressing the stylus into it [3]. Together with low-frequency forces sensed in the muscles and tendons, high-frequency accelerations provide important haptic cues that allow humans to interact easily with their physical surroundings.

Haptic simulations aim to recreate the feel of real manipulations for virtual reality. This technology is desirable for tasks such as surgical training, computer-aided design, and exploration of three-dimensional models. Commonly using a pen-like interface attached to a robotic arm, such systems map the user's motions into a virtual world and display appropriate reaction forces during contact with virtual objects. Ideally, these interactions would be as simple and vivid as using a pen to probe items on your desk, but present rendering methods cannot deliver haptic feedback that feels fully authentic [4], [5], [6].

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Most haptic algorithms observe the user's penetration into a virtual object and produce quasi-static restoring forces. This strategy is illustrated in Fig. 1b as a virtual spring attached to the interface. Such an approach captures steady-state interaction forces, but its stiffness is limited due to closed-loop stability considerations [7]. As reviewed in Section 2, position-based haptic feedback is doomed to render soft, dull contacts devoid of the information-laden high-frequency transients encountered during real manipulation.

We propose the alternative paradigm of event-based haptics to increase the realism of virtual interactions, as illustrated in Fig. 1c and described in Section 3. Standard position feedback is augmented by precomputing impact transients and displaying them open-loop when a contact event is triggered. This approach was implemented on the standard haptic interface described in Section 4. Section 5 details the generation of an event's transient force signature and introduces an analytic method for matching the accelerations experienced during 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 6. Asking users to tap on a range of samples, we assess the efficacy of several rendering techniques and show that event-based haptics can portray hard contact with significantly more realism than traditional methods. The results of this study are presented and discussed in Sections 7 and 8, followed by concluding remarks in Section 9.

2 Background

Haptic feedback was originally motivated by telerobotics, where users wanted to feel interactions with remote objects [8]. The combination of force feedback and visual information

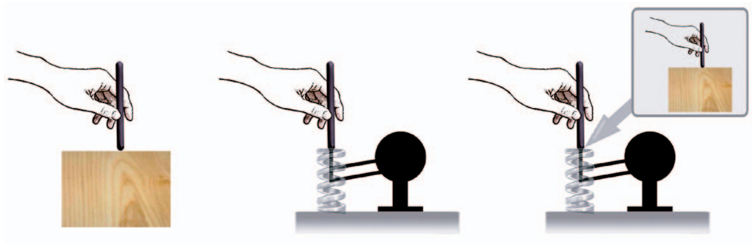

Fig. 1. Contacting real and virtual wooden surfaces. (a) Real wood, (b) position-based virtual wood, and (c) event-based virtual wood.

reduces task completion time, error incidence, and excessive force application in a variety of situations, making interactions feel more natural and easing the cognitive burden on the operator [9], [10], [11]. Over the last 15 years, similar ideas have matured in the context of virtual reality [12], [13], where users want to feel interactions with virtual objects in tasks such as surgical training [14], [15], [16].

The addition of haptic feedback is particularly crucial when simulating interactions with rigid objects. While visual feedback can convey sufficient information for the exploration of soft environments, surface deformations of hard objects are too small and abrupt to be seen. The same argument applies to the exploration of edges, small surface features, and other discontinuities; in all such cases, visual cues are of limited value, and the sense of touch becomes the dominant source of information [17].

To meet this need, robotic mechanisms have been adjusted to serve as haptic interfaces, providing lightweight, low-friction, backdrivable devices capable of displaying forces. Yet, the corresponding control strategies have fallen short of the objective to portray realistic hard contacts and impacts. This discrepancy may be traced to the robotic heritage of using position-based closed-loop feedback to regulate all output forces.

2.1 Rendering Algorithm

The classic haptic rendering algorithm for rigid objects [18] applies a force F proportional and opposite to the user's penetration x into the virtual object,

$$F = \begin{cases} -kx & \text{if } x > 0 \\ 0 & \text{if } x \leq 0, \end{cases} \tag{1}$$

where k represents the virtual object stiffness. The penetration depth is the difference between the user's position and the closest point on the surface of the virtual object, which is tracked by a proxy [19]. This algorithm has been augmented to simulate texture and friction, perturbing the force vector to depict more realistic interactions [20], [21], [22]. The quasistatic feedback law (1) has also been modified to include velocity and, possibly, acceleration feedback from a dynamic proxy [23].

Yet, fundamentally, this penalty-based method represents a linear control system. The frequency content of the force output is governed by the input signal (i.e., the user's motion) and the system's resonant frequency, $\omega = \sqrt{k/m}$, with m denoting the combined mass of the haptic device and the user's hand. Assuming a typical gain of $k = 1{,}000$ N/m, limited by sensor resolution and computational update rates, this resonance falls no higher than 15 Hz. In contrast, interactions with real materials such as metal and glass commonly exhibit force transients above 1,000 Hz [24]. Closed-loop generation of such signals would require feedback gains up to 1,000,000 N/m, roughly a 1,000-fold increase over the performance of existing systems; such stiffnesses would necessitate significant improvements in both position resolution and servo rate, as analyzed in [7]. Considerable effort has been expended to understand and overcome these limitations [25], [26], but closed-loop feedback is inherently restricted to smooth, low-frequency forces.

2.2 Human Perception and High-Frequency Transients

When interacting with real specimens via a stylus, humans can gauge stiffness more accurately by tapping, which elicits high-frequency contact transients, than by pressing continuously [3]. Indeed, the mechanoreceptors in our fingertips detect signals up to 1 kHz, with the highest sensitivity around 300 Hz [27]. In contrast, we cannot move or position our fingertips above 10 Hz [1]. The asymmetry of our sensory and manipulation bandwidths leads to a strategy of identifying signature transients and treating them as discrete cognitive events. Other researchers have also distinguished between the user's skill at perceiving high-frequency force information and his or her inability to control and regulate these forces [28]. We therefore believe that, while a low-bandwidth closed-loop controller may sufficiently capture user motion, the display of faster transients is vital to stimulating the user's perception.

Interestingly, the perceived rigidity of a virtual object is not necessarily associated with static object stiffness, but rather with the dynamics of the interaction. Rate hardness, which is defined as the initial rate of change of force over the penetration velocity, has been shown to be a much better predictor of perceptual hardness than stiffness [29]. Adding impulsive braking forces at contact improves rate hardness, creating sharp force changes and reducing virtual object penetration [30], [31], [32].

Examining impact transients, the force response of a stylus tapped on a rigid surface can be approximated as an exponentially decaying sinusoid with a frequency that depends on material composition [33]. Human-subject testing demonstrated that the addition of such transients improved the perception of virtual stiffness during tapping. This work was subsequently extended to a teleoperational testbed where users showed improved performance at a variety of tasks under vibrotactile feedback [34]. Okamura et al. also recognized the importance of high-frequency

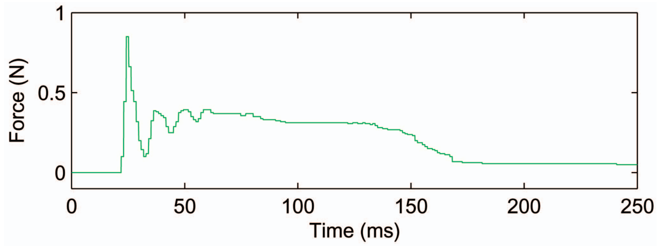

Fig. 2. Tapping on a hard wooden surface yields a high-frequency transient force superimposed on a low-frequency response.

transients and measured the accelerations felt during tapping, exploring surface texture, and puncturing a membrane [24], [35]. Empirical models were fit to this data, tuned via user testing, and used to provide vibrotactile feedback during virtual interactions, improving both task execution and surface discrimination. This paper develops a new method for generating contact transients and compares its performance with previously explored approaches and with the feel of real objects.

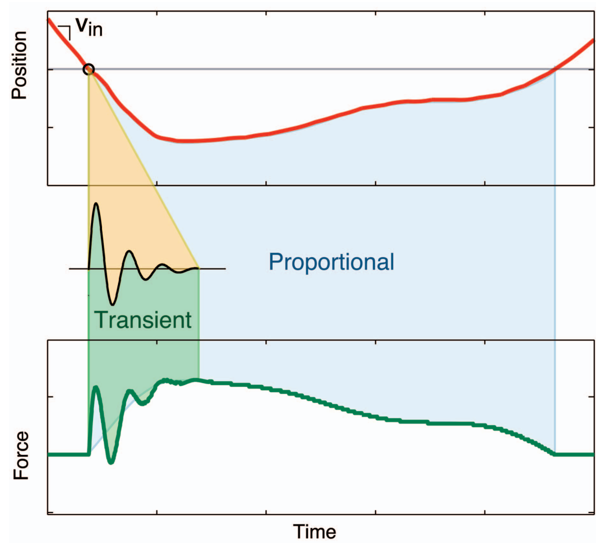

Fig. 3. Event-triggered open-loop force signals superimpose on traditional penetration-based feedback forces.

3 Event-Based Haptics

Honoring the user's sensitivity to and reliance on high-frequency interaction transients, the paradigm of event-based haptics defines an alternative display strategy for improved realism. Rather than trying to generate adequate force transients using closed-loop position feedback, this method uses discrete event triggers to begin playback of precomputed force histories. To achieve true realism, we believe the accelerations experienced by the user at contact should match real impact acceleration profiles. Building on previous efforts in transient playback, we seek to explore the event-based paradigm and understand its potential for improving the realism of haptic interactions.

The dynamics of contact with rigid objects produce two distinct, superimposed forces: an initial high-frequency transient and a slower extended response. Fig. 2 shows a force signal recorded from tapping on a hard wooden surface with a stylus. Over long durations, the object opposes penetration, yielding a quasistatic, low-frequency reaction force. The shape of the short-duration transient at impact is determined by material properties and initial user conditions, including grasp configuration and incoming velocity. Impact transients generally take the form of decaying sinusoids, though multiple resonant modes and intermittent contact may lead to a more complex response. It is these signals, lasting tens of milliseconds, that create high-frequency accelerations and allow the user to infer material properties of the object. Virtual environments devoid of these high-frequency cues will never feel truly realistic.

Event-based haptics aims to replicate the feel of real interactions by adding high-frequency force transients at the start of contact. An impact event is triggered when the stylus moves through the surface of a virtual object. The entire transient signal is computed and then overlaid with traditional proportional feedback for its short duration, as depicted in Fig. 3. With tapping, the contact state is latched during transient output, preventing multiple event detections. Because the shape of real transients depends on material properties as well as impact velocity and user impedance, a library of transient signals may be utilized. Such a library can be built from physical measurements or based on multimodal vibration models and analysis. In this sense, the haptic experience should closely match the audio behavior of objects, possibly combining multiple resonant frequencies [36]. Regardless of the method used to predetermine the transient, its output remains deterministic up to the user's reaction time of approximately 150 ms [27] and, hence, does not require continual sensor feedback or additional online computation.

In addition to providing important high-frequency cues, event-based forces can quickly decrease the user's momentum and reduce penetration into the virtual object. Bringing the hand to a stop requires the force transient to be carefully matched to the user's incoming momentum. Under the assumption of constant mass, momentum varies linearly with incoming velocity v_{in}. The transient signal magnitude should thus be scaled by this measurable quantity. Care must be taken to maintain force levels that do not overwhelm the user's incoming momentum to keep the surface feeling passive and natural. Additionally, the apparent impedance of a hand-held stylus can vary significantly with hand configuration and grip force [37], foreshadowing the possible importance of a hand impedance indicator in future work. Present investigations have found it sufficient to scale transient signals by incoming velocity, provided the user maintains a consistent grip on the stylus.

Using standard haptic hardware, event-based rendering can also take advantage of higher force levels than those permissible with proportional feedback alone. Thermal constraints prevent the motors from being driven with high current for long periods of time; however, high-frequency transient signals may exceed the steady-state maximum for short durations, enabling faster, more forceful momentum cancellation. These high current levels are available in most haptic systems but are not leveraged by traditional feedback algorithms.

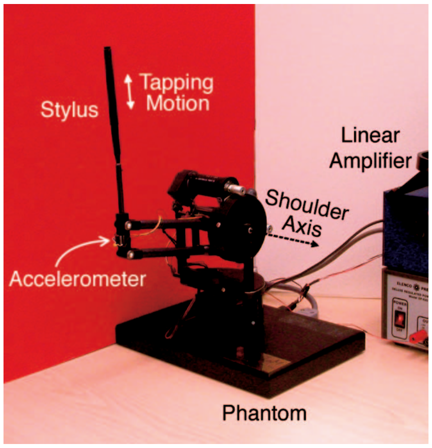

Fig. 4. Experimental setup for tapping on real and virtual objects.

4 HAPTIC INTERFACE

The event-based haptic paradigm was explored and analyzed via implementation on a standard haptic device. For this initial investigation, we selected the target interaction of tapping on a horizontal object, considering only the forces along the axis of the stylus. In the past, some researchers have used the motors of the haptic device to provide vibratory cues [24], [35], and others have placed a separate actuator near the user's fingertips, specifically for teleoperation [34]. We prefer to use the device's main, grounded actuators, keeping the system simple and allowing event-based transients to cancel the incoming momentum of the user's hand.

A high-bandwidth haptic system is necessary to provide the user with the transient cues essential to the event-based approach. As illustrated in Fig. 4, we chose an early Phantom, produced by SensAble Technologies: Its Maxon motors, smooth cable drive, and stiff linkage elements allow transmission of high-frequency signals, and its motor-shaft-mounted optical encoders enable high-fidelity position measurements. The orientation of the Phantom's distal link was reversed to point upward and was rigidly extended with a pen-based stylus. During interactions, motion along the axis of the stylus was isolated using a proportional controller to keep the distal link vertical. The motor on the shoulder joint was used to render all interaction forces, and mechanical stops were added to the base joint to keep it centered. Software gravity compensation allowed the stylus to maintain a constant position when the user was not holding it.

The amplifiers, which produce the current that drives the system's motors, must be able to output signals in the frequency range of interest. 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; although the Phantom's motors can sustain only 1.26 A continuously, they can tolerate much higher currents for short durations, which would allow for even stronger event-based cues.

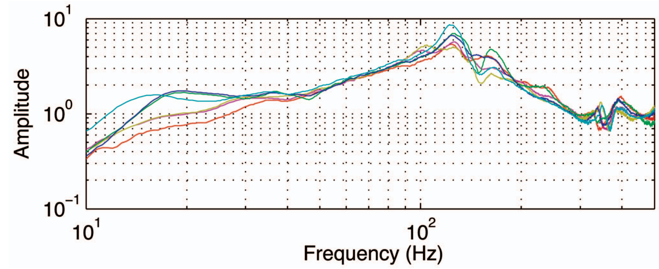

Fig. 5. The chosen system shows good high-frequency transmission from motor force (Newtons) to stylus acceleration (g's) for a variety of users and input amplitudes.

In order to measure accelerations at the endpoint, we selected an Analog Devices ADXL150 with a bandwidth of 1 kHz and a range of ± 50 g. The small package of this accelerometer was easily attached to the Phantom's distal link using double-sided 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, as well as the Phantom's encoders, at 10 kHz, commanding output from the current amplifier at the same rate. This high servo frequency was chosen to allow the system to measure accelerations and output forces at many hundreds of Hertz.

Once the hardware platform was chosen, we characterized the ability of its actuator to create high-frequency accelerations at the endpoint. The multielement transmission from motor to stylus makes it well-suited to nonparametric frequency-domain techniques, which treat the system as a black box. A 2.5-second-long swept sinusoid force signal from 10 to 500 Hz was applied to the system as a user passively held the stylus with a moderate grip force, and the resulting acceleration was recorded. Four tests were performed at three force magnitudes for two users, and results were averaged across tests. The frequency content of input and output signals was compared by taking the ratio of their discrete Fourier transforms (DFTs) in the complex domain; the resulting magnitude profiles are shown in Fig. 5, matching well between users and across force amplitudes, especially at high frequency. The system exhibits good transmission from 20 to 250 Hz with peak response at 125 Hz, highlighting the important role that device dynamics play in shaping transient behavior. High device bandwidth enables the exploration of a range of transient signals for use in event-based haptic feedback.

5 TRANSIENT GENERATION

Event-based haptics seeks to create high-frequency accelerations at impact, mimicking those experienced when tapping on the real object emulated by the virtual environment. In the past, researchers have successfully used short-duration pulses and decaying sinusoids as contact transients, two approaches that we find promising. Signal parameters such as duration, frequency, and nominal magnitude must be hand-tuned for each device and target object, a process that is more art than science. Extensive psychophysical testing can be used to identify preferred

TABLE 1
Sample Parameters

Wood	K ≈ 70,000 N/m
Wood on Foam	K ≈ 350 N/m
Foam	K ≈ 220 N/m
Very Firm Proportional	K = 1020 N/m
Firm Proportional	K = 680 N/m
Soft Proportional	K = 340 N/m
Fixed-Width Pulse	A = 4.55 Ns/m, d = 0.020 s
Decaying Sinusoid	A = 15.9 Ns/m, d = 0.055 s, f = 55 Hz

values, but there has not before been a deterministic method for generating transients that feel realistic. Working from a desire to recreate the accelerations caused by real contact, we have developed a new analytical method for determining the force profile required to produce a specified acceleration signal, a strategy we call acceleration matching.

Transient generation strategies for velocity-scaled pulses, decaying sinusoids, and acceleration-matched signals are discussed below. Tapping on wood was chosen as the target interaction, a familiar material whose characteristic transients fall within the bandwidth of our device. The high-frequency signals caused by contact with stiffer substances, such as metal, require actuation power that is beyond the capabilities of our current amplifier. The steady-state stiffness of wood is still approximately seventy times greater than the highest proportional gain achievable on our haptic device (see Table 1), so a moderately firm position gain was chosen to underlie the event-based feedback. To create contact accelerations that are consistent with this lower underlying stiffness, all of the transients were tuned to duplicate the feel of wood on a foam substrate rather than solid wood. We have found that this new tuning technique produces virtual feedback that feels significantly more real than transients matched to the response of solid wood.

5.1 Fixed-Width Pulse

The first investigated transient is the pulse, a simple signal that requires little computation during generation. While our previous work investigated fixed-magnitude, varying-duration pulses [31], we chose to use a pulse of fixed duration d and varying magnitude, scaling the nominal amplitude A by incoming velocity:

$$F_{pulse} = A|v_{in}| \text{ for } 0 < t \leq d. \qquad (2)$$

This strategy keeps the frequency content of the transient approximately constant over all incoming velocities, as is observed during contact with real objects. The pulse's width and nominal magnitude were tuned by hand while tapping repeatedly on the sample of wood on foam and the virtual surface. The amplitude was further adjusted after some subjects in a preliminary study reported that the pulses felt too active [38]. These and all other chosen transient parameters are given in Table 1.

5.2 Decaying Sinusoid

The use of decaying sinusoids was also investigated, following the observation that transient accelerations often resemble exponentially decaying sine waves. The nominal magnitude A of this transient is also scaled by incoming velocity:

$$F_{sine} = A|v_{in}|e^{\ln(0.01)t/d}\sin(2\pi ft) \text{ for } 0 < t \leq d. \qquad (3)$$

We selected the frequency f and duration d to match accelerations recorded from tapping on the wood-on-foam sample, picking duration to be an even multiple of the sinusoid's half period for smooth overlay. The nominal magnitude was tuned by hand via comparisons with the specimen of wood on foam.

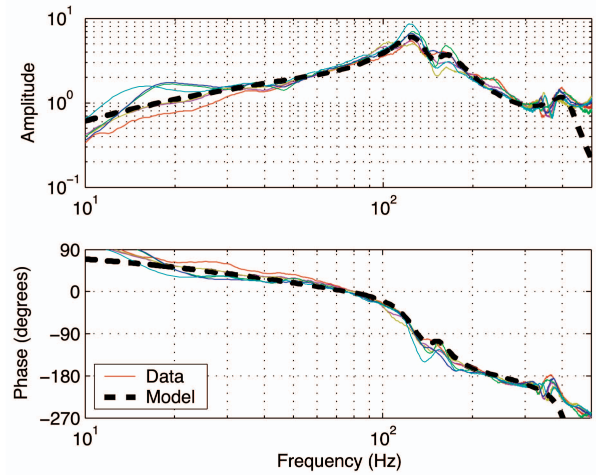

Fig. 6. System transfer function from force feedback to acceleration output.

5.3 Acceleration Matching

The complex dynamic relationship between motor forces and stylus accelerations prompted us to develop the new method of acceleration matching. This strategy centers on characterizing the haptic system's transfer function from force to acceleration and inverting this dynamic relationship. The inverse model can then be used to transform desired acceleration profiles, which may be intricate and difficult to parametrize, into transient force commands. By recording accelerations for contact with the same object under a variety of conditions, a force transient library can be assembled without extensive parameter tuning. Each signal is characteristic of the real situation that produced it, including incoming velocity, hand impedance, and object contact location; for this work, we focused on the dominant effect of incoming velocity, v_{in}, which increases the magnitude and smoothly changes the shape of the transient.

To understand the dynamic behavior of our testbed, we return to the identification performed in Section 4. The magnitude and phase of the frequency-domain analyses can be viewed together as an experimental Bode plot and are often called an empirical transfer function estimate (ETFE). A linear, seventh-order, relative-degree-four transfer function with a 0.25 ms time delay was matched to the ETFEs, and its Bode plot is shown as the model in Fig. 6. Though interpreting its physical significance is difficult, this empirical model aptly captures the system's frequency response under a range of conditions. We have found such methods to be effective at characterizing the intervening

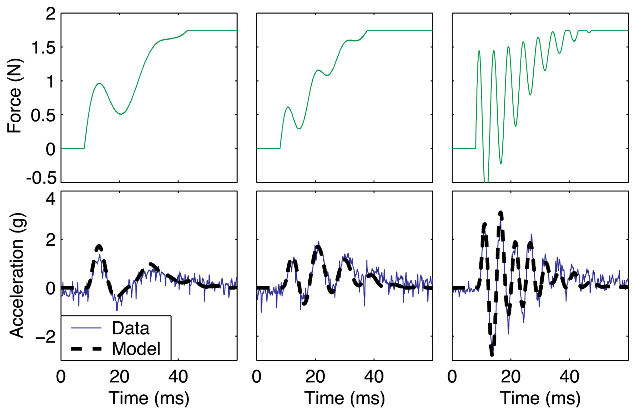

Fig. 7. Time-domain model validation.

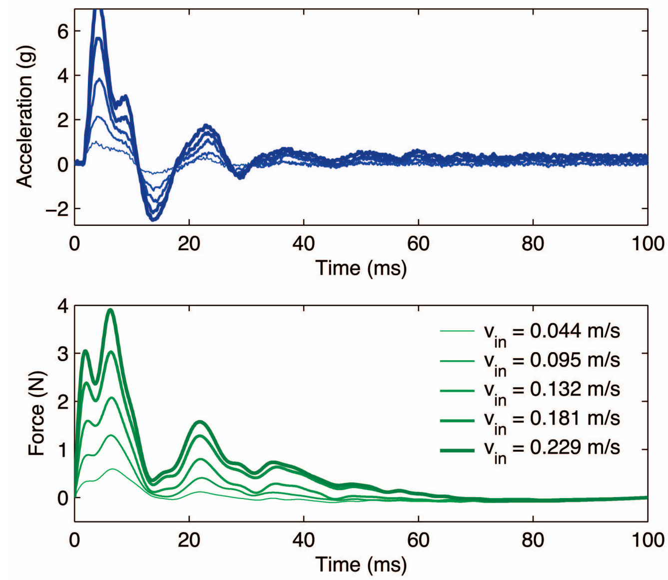

Fig. 8. Recorded accelerations and force transient library for tapping on wood with a foam substrate.

dynamics of a variety of other haptic devices, including a one-degree-of-freedom testbed [37] and an Impulse Engine 2000 joystick [39], [40].

The system model was validated in the time domain by playing a variety of transients as users held the stylus with a moderate grip force and tapped on a virtual object. Three sample force and acceleration traces are shown in Fig. 7, and we see that the model's response matches the measured values very closely, especially for the short durations characteristic of force transients. We conclude that a simple, user-invariant dynamic model is useful in describing the response of our system during haptic interactions, provided the user maintains a consistent grip on the stylus. The influence of grip force on system dynamics will be characterized in future work.

Inverting the identified system model enabled us to determine the force transient that must be applied to create a specified acceleration profile at the device's endpoint. We began by recording acceleration at 10 kHz for 100 ms following tapping contact between the Phantom and the target substance at five different velocities. These signals were each prepadded with zeros and smoothed to remove high-frequency electrical noise without altering phase. The smooth acceleration transients were 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, eliminated noise and drift while preserving the force signals in our frequency range of interest, from 10 to 500 Hz. The force transients were then extracted from the longer zero-padded signals, forcing zero magnitude at the beginning and tapering the end to ensure smooth superposition. The model inversion process was verified by applying the computed force transient to the forward model and by testing the transients on the actual hardware. Close correspondence was achieved with the above methodology, supporting the viability of model inversion for matching virtual feedback to real accelerations.

We constructed a transient library for contact with wood on a foam substrate, as shown in Fig. 8. Note the nonlinear variation of both acceleration and force with velocity, which highlights the ability of a model-based approach to produce realistic, nonparametric accelerations at impact. 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. After the acceleration-matched library was constructed, its feel was compared to that of tapping on the target sample. When such transients are superimposed with strong proportional feedback, force levels and contact accelerations increase, and some users report that the surface feels slightly active. Multiplying the library transients by a gain of 0.8 restored appropriate force magnitudes and eliminated these complaints. Future work will account for proportional feedback during transient generation to avoid these issues. We found that this technique of event-based, acceleration-matched feedback creates contact accelerations that closely resemble those experienced when tapping on the real sample.

6 Assessing Contact Realism

Encouraged by the feel of our three transient signals, we sought to evaluate the performance of the event-based paradigm more thoroughly, especially as compared with traditional position-based feedback. Realism of virtual contact is inherently difficult to quantify and can only be accurately assessed by perceptual user tests; consequently, we conducted a human-subject experiment to analyze the effectiveness of event-based haptics and the performance of the pulse, decaying sinusoid, and acceleration-matched transients. Subjects rated the realism of tapping on three real and nine virtual objects. The real objects included samples of wood, soft foam, and wood on a foam substrate, as shown in Fig. 9. The approximate linear stiffness of each of these samples was measured using the Phantom and the force sensor, as listed in Table 1.

The first three virtual samples were designed to represent traditional position-based feedback; the highest proportional gain (very firm) was chosen near the limit of the device's capabilities, at which point encoder discretization causes significant buzzing. The mid-level gain (firm)

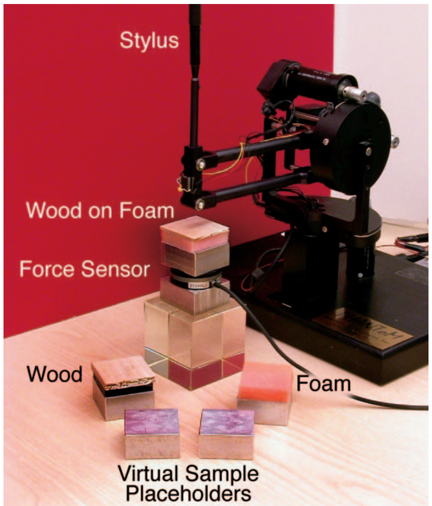

Fig. 9. Users blindly tapped on three real and nine virtual samples using the Phantom. Real interactions were monitored with the force sensor, and virtual samples were rendered via motor forces.

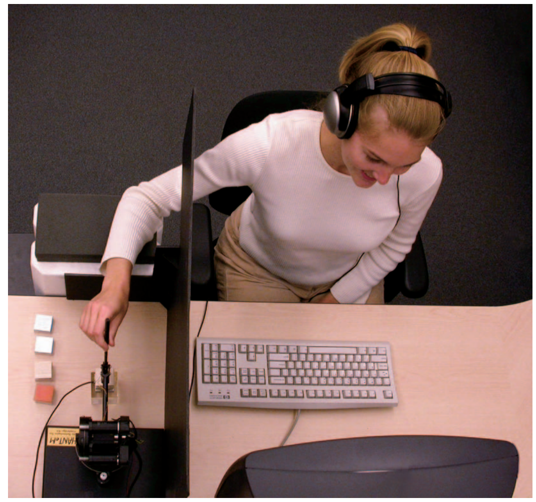

Fig. 10. Test subjects rated each sample's ability to approximate the haptic sensation of tapping on real wood.

was tuned to provide strong feedback without encoder buzzing, and the lower gain (soft) was set to half this level. The remaining six virtual samples represent the event-based rendering approach, combining a contact transient with either the firm or soft proportional controller. Overlaying transients on the very firm proportional feedback requires short-duration force output presently beyond our system's capabilities and was thus not included in user testing.

User testing was performed on the hardware described in Section 4 with motion of the stylus constrained to one degree of freedom to isolate tapping motions. The real samples and virtual sample placeholders were positioned on a rigid stand beneath the center of the stylus, as shown in Fig. 9. An ATI Mini-40 force sensor allowed the system to measure contact forces at 1 kHz during interactions with real samples.

At the beginning of each experiment, we collected information on the subject's age, gender, handedness, and prior experience with haptic devices. We then outlined the three phases of the study: familiarization with the wood sample, demonstration of the 12 test samples, and repeated rating of sample realism. Users were told that they would be presented with a number of different renderings of a hard, wooden surface. They were asked to rate, on an scale from one to seven, how well each sample represented the experience of tapping on the real piece of wood. Subjects were 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, as illustrated in Fig. 10. Sitting at a computer terminal, the user passed his or her right arm through an opening in a tall barrier to prevent visual observation of the device and samples. The user rested his or her elbow on a padded armrest to counteract muscle fatigue. The user was instructed to hold the stylus with a consistent grasp and to avoid touching the table with his or her left hand 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 was able to tap repeatedly on the real wooden sample to become familiar with its response. The interaction was monitored with the force sensor, and forces known to exceed the amplifier's current limit (had the controller been in use) were detected and indicated to the user by auditory feedback. During virtual tests, the same low tone was provided whenever the commanded force actually exceeded the amplifier's current limit. Throughout the experiment, all trials that evoked this auditory cue were repeated to prevent the system's force limit from biasing the data.

When the user was done interacting with the wooden sample, the system transitioned into the demonstration phase, in which each of the 12 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 text 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 to tap repeatedly on the surface. After five seconds, the device moved the user's hand back to the home position, and the user was instructed to rate the realism of the sample on a scale from one to seven using the keyboard. The test

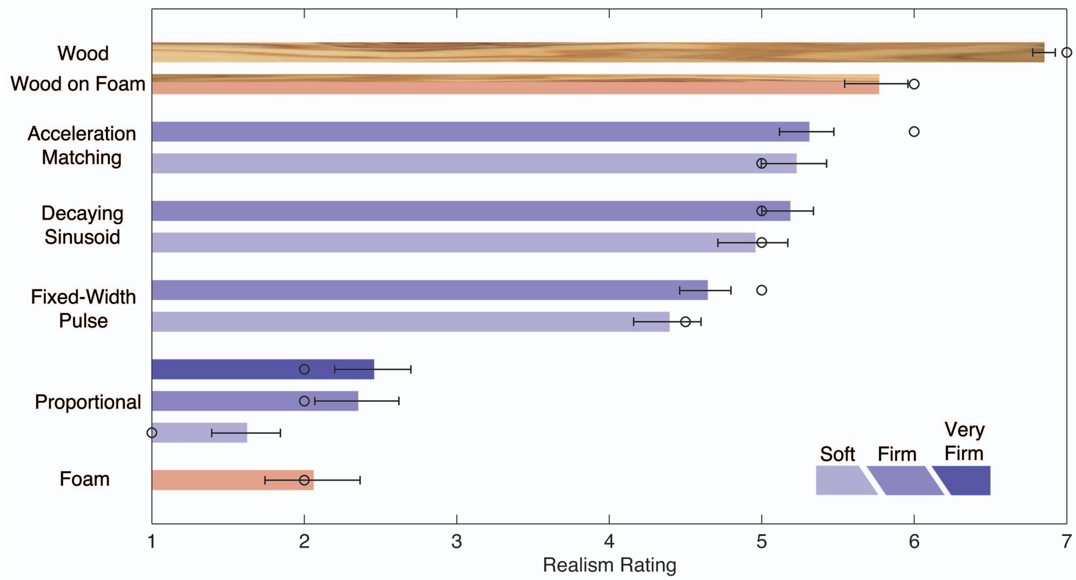

Fig. 11. Realism ratings of the twelve test samples: bars and circles indicate the mean and median across all tests, and capped lines show the standard error of our sixteen-subject sample.

was repeated if the contact force exceeded the device's capabilities at any time during the tapping, or if the user overpowered the homing force and tapped on the object after the five seconds had expired. Finally, the user could reject a trial by typing an "x" instead of a digit, indicating that a mistake had occurred such as letting go of the stylus.

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 36 trials, plus any repeats for excessive force or rejection. The testing procedure was identical to that of the demonstration phase, and the entire experiment lasted about 10 minutes. A short debriefing session followed the completion of the testing, wherein subjects were asked to state the criteria they had used to evaluate sample realism and comment on the experimental procedure.

7 Results

The user study included 16 subjects, none of whom had participated in the preliminary version of this study described in [38]. Individuals ranged in age from 19 to 33 and included four females and twelve males. Three of the subjects were left-handed, though all completed the experiment with the right hand. Seven of the subjects had never used a haptic device before. Seven had used such systems a few times, and two reported using haptic interfaces on a regular basis. During the familiarization phase, subjects tapped on the real sample between four and twenty-two times. For each subsequent trial, the system recorded the sample, saturation, rejection, and the set of incoming tap velocities and penetration depths.

The system also stored the user's rating for each trial, indicating the degree to which the user believed the sample felt like real wood. Each of the 12 samples was rated three times by each of the sixteen subjects. Each sample's average realism rating for valid tests, pooled across users, is shown in Fig. 11, with higher values indicating higher perceived realism.

Users exceeded the system's force capability an average of six times during the testing phase, with a standard deviation of 8.5. Saturations occurred most frequently for the real wood and the event-based virtual samples. As described above, all such tests were returned to the sample pool to be randomly drawn again and thus are not included in the presented results. The average incoming velocity, pooled across subjects and nonsaturated test-phase taps, was 0.10 m/s, with a standard deviation of 0.042 m/s. Within each sample, no significant correlation was found between incoming velocity and realism rating.

8 Discussion

8.1 Realism Ratings

Statistically significant differences were found among the ratings given to the twelve samples shown in Fig. 11, indicating that some samples felt very similar to wood and others were poor imitations. Not surprisingly, the most highly rated sample was real wood, followed interestingly by the wood on foam and the six transient-overlaid virtual surfaces. The ratings given to the three proportional controllers were comparable to those assigned to foam, significantly lower than those given to the event-based samples.

To evaluate the significance of these ratings, paired t-tests were conducted on average user ratings for each sample combination. These tests were performed for the entire user group as well as for the subset of nonnovice users, the results of which are shown graphically in Fig. 12. The experienced user subgroup was chosen to isolate the effects of first-time users, whose ratings varied substantially between trials, as will be discussed below.

While the majority of sample rating pairs showed little correlation for either group, there were some noticeable exceptions. For the event-based samples, we see that the

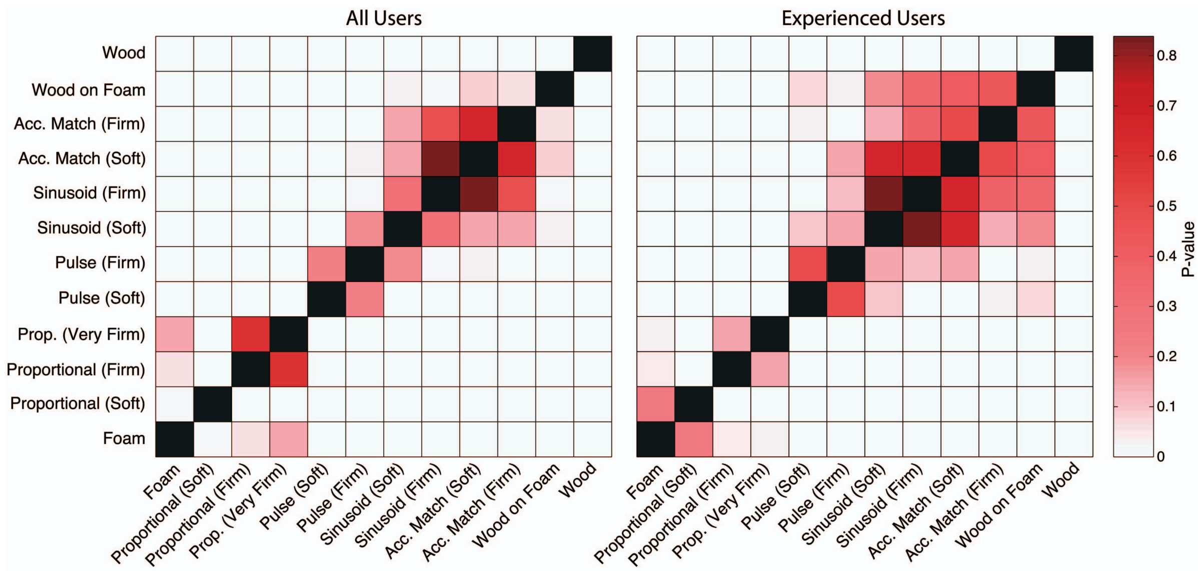

Fig. 12. P-values from t-tests on the average realism rating given by each subject for all sample pairs. The shade of each square shows the probability that the ratings given to the two intersecting samples stem from indistinguishable populations; therefore, dark squares indicate pairs of samples that were rated similarly. All users and experienced users show distinct clustering of the samples.

strength of the underlying proportional controller did not significantly affect realism ratings, with p-values ranging from 0.21 to 0.82. This trend can be seen by the clustered elements near the diagonal in both charts of Fig. 12. Such a finding highlights the important role of high-frequency transients in haptic perception of contacts.

In comparing the results of the entire group with the subset of experienced users, we see that the experienced group ratings for the event-based samples and the wood-on-foam sample are statistically very similar (p-values ranging from 0.20 for the soft sinusoid to 0.47 for the firm acceleration matching). These results echo closely those found in our preliminary study, which included a higher percentage of expert users [38]. This finding is particularly interesting because all of the event-based virtual samples were constructed to match the experience of tapping on the wood-on-foam sample (see Section 5), demonstrating the efficacy of the event-based paradigm for mimicking real contact transients.

While many factors likely contributed to the different ratings provided by the experienced group and the novice users, we hypothesize that the testing experience was somewhat overwhelming to the novices. Many first-time users appeared to have difficulty identifying the subtleties of the various samples, and a few admitted that their ratings were arbitrary at times. In contrast, those with some level of experience seemed to be more capable of identifying the differences and gave qualitative feedback that was much more consistent. Alternative hypotheses include speculation that naïve users are more attuned to the characteristics of real interactions, as well as a conjecture that experienced users might be more accepting of virtual rendering methods due to their familiarity.

8.2 Rating Criteria

When asked to name their rating criteria, subjects listed several salient metrics. First among these was whether the stylus came to a sudden stop after contact. In our preliminary study [38], we hypothesized that the foam and the simple proportional controllers were rated most poorly because they cannot quickly cancel the user's incoming momentum. For this study, we tracked penetration depth during every tapping event to test this hypothesis. Fig. 13 shows the mean penetration depth for each sample, plotted against the sample's average realism rating. While the wood and wood-on-foam sample penetration depths were less than 0.25 mm, the foam and soft proportional controller allowed penetrations of over 2 mm. Interestingly, we discovered that the average penetration depth for the firm and very firm proportional samples were actually less than many of the event-based samples, but their ratings were consistently much lower. This finding alone demonstrates that there is clearly more to impacts than can be represented with a simple position-based controller.

The second most commonly mentioned criterion was the presence of a high-frequency transient at the moment of contact. Reexamining the results shown in Fig. 13, we see

Fig. 13. Mean penetration depth versus realism rating for each sample. Error bars indicate one standard deviation from the mean.

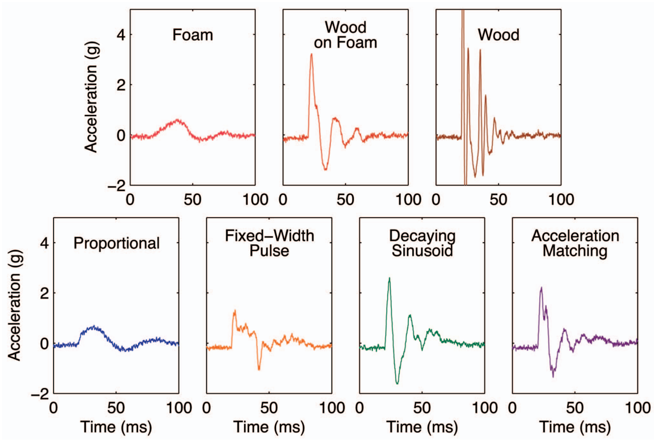

Fig. 14. Sample accelerations for contact with samples with an incoming velocity of 0.11 m/s.

that all of the event-based samples were rated more highly than the proportional samples, a result also seen clearly in Fig. 11. Directly comparing the penetration depths for the event-based samples and their underlying proportional controllers, we see that the inclusion of the transient roughly decreases the penetration depth by a factor of two. The transient cancels a significant portion of the user's incoming momentum, decreasing penetration and improving the realism of the virtual surface.

We can also examine the accelerations produced by tapping on the real and virtual surfaces, as shown in Fig. 14. Firm and soft underlying proportional control produce nearly identical acceleration histories, so only the firm samples are illustrated. 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 decaying sinusoid and acceleration-matched transients most closely resemble the real signals, which we hypothesize contribute to their high realism ratings.

As additional criteria, users commented that they gave lower ratings to samples that felt unnatural. Two subjects noticed a high-frequency buzzing that detracted from sample realism. We believe this sensation stems from encoder discretization in the proportional controller that holds the stylus vertical during all tests, but it may also be a result of encoder discretization in the firm and very firm virtual objects. Also, a few users reported feeling an occasional double impact, which can occur when the stylus is held very loosely. We believe that measuring and compensating for changing hand impedance could further improve the realism of event-based transient display, avoiding excessive force application and double event triggering.

9 Conclusions

Encouraged by the results of this work, we firmly believe the paradigm of event-based haptics has the potential to significantly improve haptic display. This approach particularly improves the rendering of hard contact, which is an important challenge in haptic simulation. Just as finite element methods and extensive offline computation have improved the haptic fidelity of deformable objects, event-based haptics enables accurate rendering of the dynamics that characterize rigid contact.

The event-based approach defines an asymmetric algorithm, responding to position changes at a low rate and providing sharp, high-frequency accelerations at the start of contact. This paradigm naturally complements the user's capabilities and matches the characteristics of real interactions. Relying on open-loop display also limits the need for high-gain closed-loop feedback, potentially relaxing requirements for computation rate and sensor resolution. Simultaneously, brief transients can take advantage of high peak currents without violating the device's thermal restrictions. Our present algorithm is user-independent and does not require changes to device hardware.

Human subject evaluations confirm that high-frequency transients are vital to achieving realism, proving substantially more important than penetration distance or object stiffness. Outputting either manually tuned decaying sinusoids or analytically computed force signals provides the highest level of realism; we hypothesize that these methods succeed because they create high-frequency stylus accelerations that closely match those experienced during real contact. Experienced haptic users cannot distinguish such virtual event-based renditions from a piece of wood mounted on a similarly soft substrate. Users also judge classic proportional feedback to be equivalent to real foam, reiterating the softness of traditional haptic displays.

As mentioned in Section 6, the low current limit of the system's amplifier prevented us from overlaying event-based transients with the very firm proportional controller. Higher peak current capacity will enable us to implement the event-based approach with stronger underlying proportional control, bringing the realism of event-based interactions even closer to actual tapping. Additionally, increasing available force magnitudes will allow us to simulate materials with higher-frequency transients, such as metal.

Our future work will also extend these one-degree-of-freedom results to other mechanisms, three-dimensional surfaces, and a variety of materials. We intend to expand the range of events and transient signatures to simulate fine surface features and textures. Adjusting the transient signal for variations in hand impedance will further improve the algorithm. The success of our present efforts at providing realistic acceleration signals to the user will also enable much-needed investigation into the underlying psychological mechanisms of this perceptual channel. Built on the belief that transient accelerations are vital to realism, event-based haptics provides a pathway for instilling authenticity into current and future virtual-reality simulations.

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