A Tactile Glove Design and Authoring System for Immersive Multimedia

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This article describes a tactile system designed to provide viewers with passive, on-skin sensations synchronized with audiovisual media.

Viewer expectations for rich, immersive interaction with multimedia are driving new technologies—such as high-definition 3D displays and multichannel audio systems—to greater levels of sophistication. While researchers continue to study ways to develop new capabilities for visual and audio sensory channels, improvements in haptic channels could lead to even more immersive experiences. One early example of this line of thinking was the Percepto system, which was used in the 1950s to present cinema audiences with simple tactile feedback to simulate movie events such as earthquakes. This trend to use channels other than audio and video in media presentation continues today and can be seen in amusement park rides that combine 3D projection with physical stimuli, such as jets of air to simulate bullets and mists of water to mimic cool temperatures. The fundamental motivation underlying the development of these physical cues is that haptic information is a key mechanism for increasing immersion. Simply put, audiences are drawn into media experiences that they can feel physically.

Regardless of modality, it's a truism to suggest that creating complex multimedia content requires skill and time. There are countless sophisticated tools to help author audiovisual material and seamlessly merge and synchronize independent channels. For example, when filming on location, it's common practice for sound to be recorded separately in a studio and manually overlaid on the video to provide directorial flexibility and to ensure the audio is high quality. Practically speaking, adding tactile information to audiovisual media can be achieved through the development of sophisticated tools that take into account context, target audience, and several other factors.

Key requirements for such tools include the ability to reuse tactile information, to combine various tactile forms (such as pressure and temperature), and to couple this material with the audiovisual content, flexibly and precisely.[1] These are requirements that, thus far, have been largely overlooked by the research community. (See the ''Related Work'' sidebar for information about previous efforts.) This article presents an overview of an immersive movie system designed to augment audiovisual content with tactile effects delivered to the hands. While other researchers have discussed kinesthetic or force-feedback cues, this article's focus on tactile information is a relatively unexplored approach. The modality of tactile, on-skin sensations differs enough from that of the physical pushes and pulls of force feedback to warrant its consideration as a separate topic, not only because of the technical differences but also because of the fundamental conceptual or aesthetic differences.

Role of tactile content

This article defines an enhanced tactile movie as one that features tactile content synchronized with traditional audiovisual media, the purpose of which is to enhance an audience's enjoyment by conveying the artistic and semantic intentions of the director. Imagine a horror movie in which you could feel a ghost brush against your hand. We suspect that, much like using music or sound effects in film to enhance certain scenes, tactile content will be similarly used mainly as a

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Related Work

Several previous research efforts have explored haptics in the context of multimedia systems. One team of researchers discussed the theoretical role of haptics in a broadcasting system,[1] while another developed a tactile jacket intended to provide emotionally evocative content.[2] In our previous research, we presented haptic-broadcasting scenarios and developed a system capable of supporting them.[3,4] Another research effort created a system to produce tactile sensations derived from ball trajectories in televised sporting events, such as soccer games.[5]

Other work in this area has focused on haptic content authoring. Notable systems include an authoring tool that supports modeling haptic characteristics, such as stiffness, friction, and damping, in virtual environments.[6] Other tools have supported the creation of tactile content in the form of simple vibrations.[7,8] A key example of this kind of tool is VibeTonz, a commercial waveform-construction system modeled after audio-editing tools. Generally, tools of this kind focus on tactile patterns for individual actuators with parameters such as amplitude and frequency of vibration for a single tactile cue.

There are currently no projects we are aware of that have considered the complexities of authoring for multiple tactile actuators and different forms of tactile display, spread over the surface of the skin. It's clear that manual creation of such tactile data without sophisticated tools would be challenging and laborious. Assuming that the development of general authoring tools capable of creating a range of media will increase the feasibility and richness of this kind of tactile-augmented content, this article describes a tactile movie-authoring tool to address these issues.

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supplemental effect rather than continuously used through an entire movie. Due to the added immersion it facilitates, haptic feedback is already an important element of many virtual environments and some telecommunication systems.[2] In the context of a movie, haptics not only can increase immersion in the story, but also can encourage empathy with the portrayed characters, allowing viewers to step into the shoes of the actors and engage with a plot on an emotional level. In addition, tactile cues can convey unique information, such as temperature and contact. In much the same way that audio is skillfully employed to portray minor and major mood, atmospheric uses of tactile content have the potential to shape the audience's experience and can be used as a mode of interpretation and artistic expression.

We translated this range of possible uses into a functional set of requirements for tactile information that can be added meaningfully to audiovisual media, and identified three specific modes: first-person sensations, third-person sensations, and background effects. First-person sensations are derived from onscreen character experiences, such as touching an object or riding a horse. The goal of this mapping is to highlight the experiences of the characters shown on the screen and enable viewers to feel what the actors are touching or experiencing. Third-person sensations refer to the presentation of object movement shown on the screen. For instance, a possible application could be in sporting scenarios to describe the motion of a grand prix car as it races around the track or the motion of a soccer ball after it's kicked. Finally, background tactile effects refer to nonvisual, ambient scene content to establish mood or reflect environmental details such as wind, general emotional states, or tension. For example, tactile content could

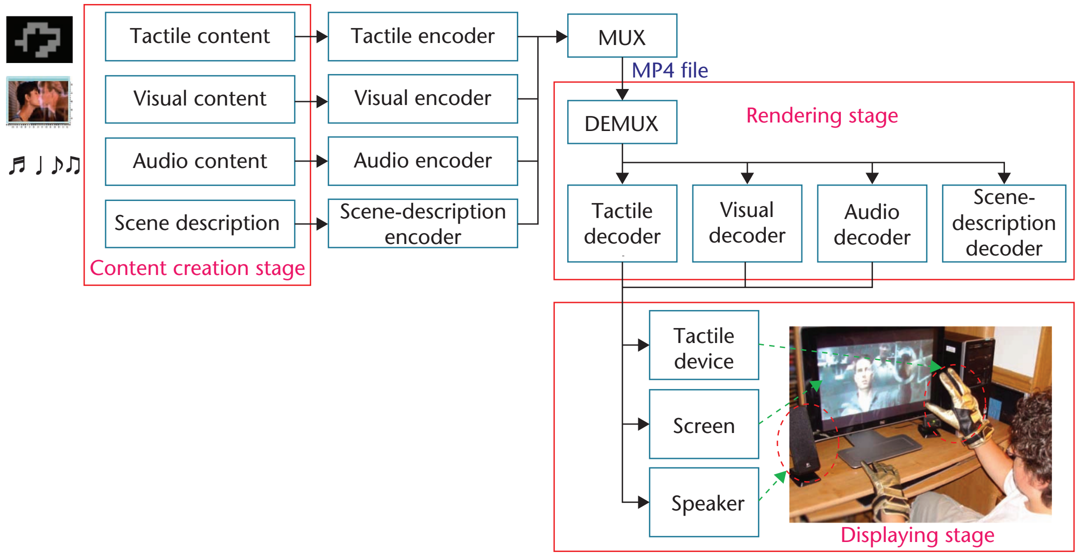


Figure 1. Overall tactile movie system configuration.

complement a character's tense emotional state with a racing heartbeat, or emphasize a sudden shock through an unexpected contact.

Although each of these mappings could be deployed individually, combinations of these three approaches are possible. For example, the trajectory of a falling snowflake could be displayed, followed by the diminishing physical contact experienced when it's caught on a character's palm and starts to melt. Presenting such rich feedback requires an advanced multi-actuator tactile system.

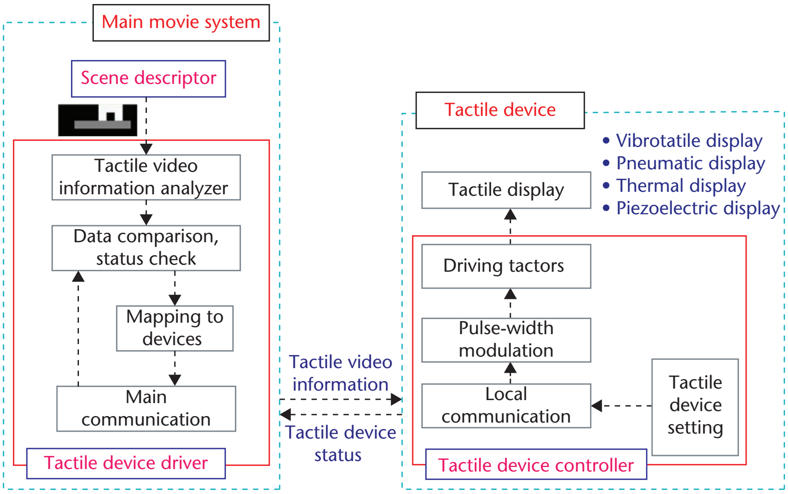
Tactile glove design

To design our tactile movie system, we relied on MPEG-4 to integrate haptic data into audiovisual media though a tactile content-authoring tool and glove output device. The MPEG-4 framework supports the harmonious integration of various media types, providing a unifying system that can enable novel feats such as seamless interaction between a cartoon character and an actor in a studio. However, because MPEG-4 does not support tactile media, we extended MPEG-4 Binary Format for Scene by adding a new node for MPEG-4, called *TactileDisplay*. BIFS is a scene-descriptor format capable of encapsulating the spatio-temporal arrangements of numerous heterogeneous media elements in a single scene.[3] In this system, tactile content is represented as gray-scale video (called *tactile video*) within the TactileDisplay node and synchronized with audiovisual content.[4]

Figure 1 illustrates a block diagram of our tactile movie system based on the MPEG-4 framework. It also depicts the entire media process, from creation of the content to its display to an end user. In the media-creation process, tactile content is generated by an experienced tactile director and synchronized with the audiovisual media. One audio stream and two video streams (one representing the video, the other the tactile video) are generated and temporally synchronized according to the scene descriptor. These streams are then compressed with suitable domain-specific encoders (such as MP3 for audio) and transmitted progressively according to information relating to synchronization and presentation. During the rendering and display process, a compositor parses and forms the scene by sending all media elements to relevant video, audio, or tactile renderers and display devices. Finally, a user watches the content and experiences tactile sensations by wearing a tactile device. We have described the specifics of this authoring process in additional detail in another article.[4]

To experience immersive 3D scenes at IMAX theaters, viewers wear electronic liquid-crystal shutter glasses. Similarly, tactile displays are required to experience tactile media. These displays can conceivably be placed on any part of the body, such as the back, the arm, the forehead, or the abdomen. In this article, we focus on providing tactile cues to the hands because the hands are arguably the most suitable candidate location for a movie system. Scenes that involve characters touching one another or manipulating objects with their hands are commonplace. Moreover, the hands possess the highest level of tactile acuity and wearing

(a)



(b)

Figure 2. (a) A vibrotactile display glove and (b) tactile rendering process.

gloves is socially acceptable. When it comes to the actual glove hardware, there are numerous options for tactile actuators. These include electrodes, piezoelectric ceramics, or vibrating motors. In the work described here, we used vibrating motors because the required components are safe, mechanically simple, and economical.

To provide sensations over an area of the skin, an arrangement of many actuators can be used, and rendering techniques can be developed to present cues of varying magnitudes. In light of this consideration, we designed the gloves as a general-purpose, multimedia tactile display that can accommodate a wide range of users while still providing a relatively tight fit. To determine the initial prototype size, we achieved a compromise by using two individuals of average hand size (one male, one female). We used a 3D scanner to capture the hands in various poses and to create plaster models that dictated the final design of the gloves. The gloves consist of stretchable sport fabrics and are tailored to maximize flexibility. The electronics are located between inner and outer layers, which are connected by Velcro. We described the design process in more detail elsewhere.[5]

The gloves and the tactors are shown in Figure 2a. Four tactile actuators are attached to the front part of each digit of the inner glove. This allows the rectangular tactile video to be directly mapped onto the tactile array, albeit with some distortion due to varying finger position. The electrical system of the displays consists of four key components: a Lithium polymer battery, a microcontroller (RF Engine MPS-128N), a Bluetooth communication module (Comfile Acode-300), and vibrating motors (Samsung Electro-Mechanics DMJBRK30O, 10-millimeter diameter, 3-mm thick). All control hardware is embedded in the glove wrist bands. The control of the gloves is wireless.

The tactile device controller is connected to the actual tactile hardware and translates the gray-scale video representation into an array of tightly synchronized, temporally varying actuation intensities. Figure 2b depicts this process. Initially, the compositor provides the decoded gray-scale tactile video frame associated with the current position in the movie timeline. This information typically contains the actuation intensity of each element in the tactile array. However, in cases where the tactile array size does not match the tactile video size, resampling generates a fit to the number of tactors in the array. This mapped data is then transmitted wirelessly to the tactile device controller, which activates the motors. We use pulse width modulation to render stimuli of varying magnitude according to the intensities specified in the video. Because we designed the tactile device driver to support tactile information of varying dimensions (including various sizes of arrays and depths of intensity), the system is highly customizable and can be used to drive devices of varying shapes and configurations.

Tactile movie authoring

The emergence of interactive Web technologies has ushered in an age of user-created

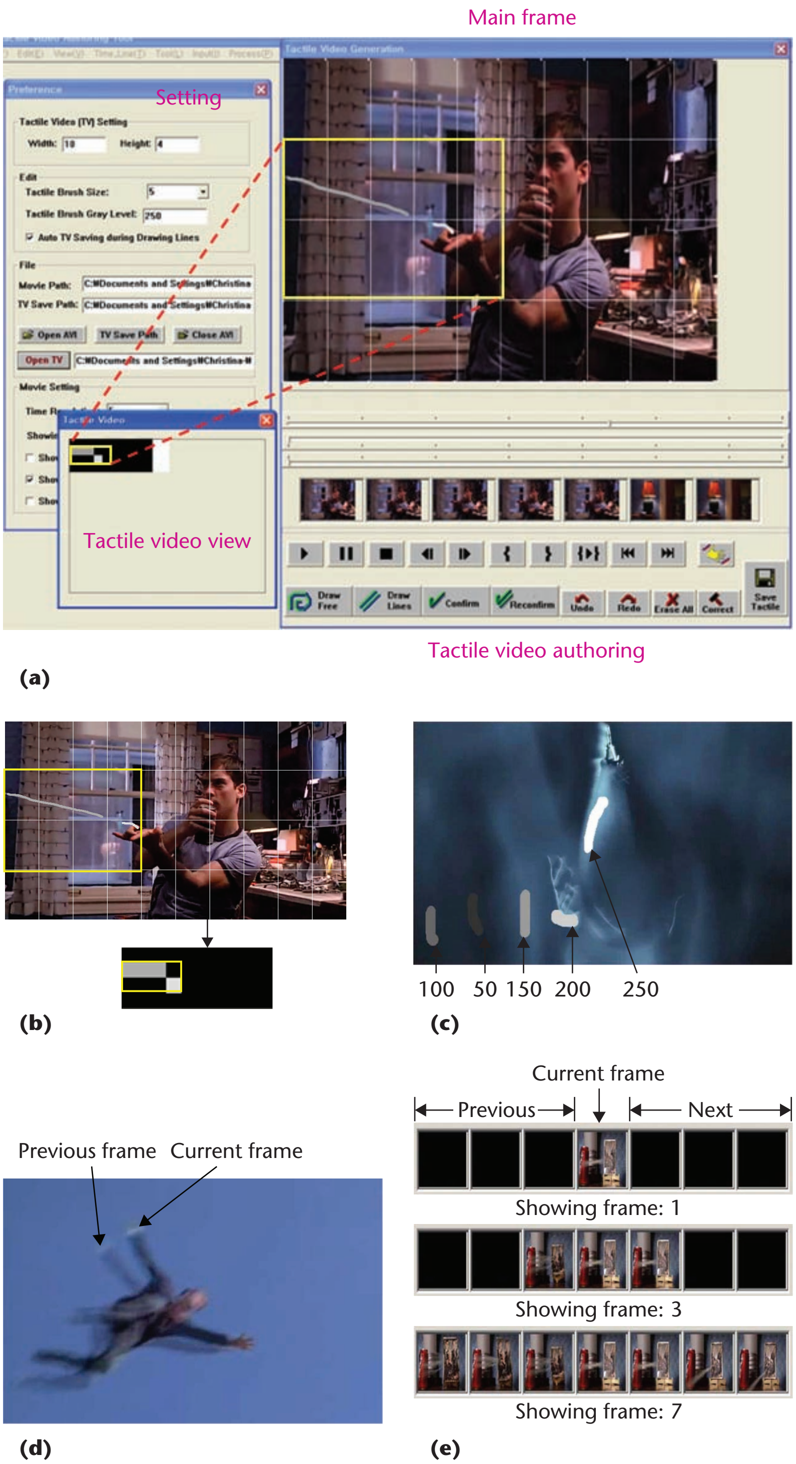


Figure 3. Features of the tactile authoring tool interface: (a) a screenshot of the tactile authoring tool, (b) grid aid line according to the size of tactile displays, (c) intensities of the tactile brush, (d) overlapping two frames, and (e) previous and next frames for temporal authoring.

content. People are posting their images, audio, and movie clips in great numbers. This trend has led to a greater interest in the development of media-authoring tools for nonexperts. However, few tools support tactile information. To remedy this situation, this article presents a prototype of a tool for creating tactile content. The authoring tool defines and supports the process of generating and editing tactile content. It also supports precise synchronization of this content with audiovisual media and multiple tactile channels to provide various tactile sensations on different hardware. In a movie system, tactile content needs to relate to audiovisual media on either a scene-by-scene or a frame-by-frame basis. Without such a tool, generating tactile content manually would be an extremely time-consuming process. Because this issue is central to the focus of our work, we designed a tactile authoring tool.

Visual media typically consists of a series of frames of information, making this a clear choice of metaphor for a tactile authoring. It's also well matched to the use of gray-scale video as a representational format for tactile information and indicates that the final output of a tactile authoring process should be gray-scale tactile video at a frame rate equivalent to the video content it accompanies. Studies on the perception of moving tactile cues on the skin suggest that a typical video refresh rate of 25 frames per second is a reasonable update rate for tactile cues.[6] The required resolution of the tactile video can be relatively low and should ideally match the physical resolution (the number of individual output devices, or tactors) of a tactile display device.

In our authoring tool, we create a tactile video by drawing lines with a tactile brush, which is analogous to a paintbrush in a graphical drawing application. The drawing surface is a semitransparent tactile canvas located on top of a video display window. Graphics in the system show the current frame of the visual media with an overlay of lines representing tactile brush strokes. This setup provides a fully synchronized, seamless workspace for tactile media creation. The cells of the tactile array are spatially mapped to this tactile video so that the top-left and bottom-right of each are aligned.

Figure 3a shows a screenshot of the authoring tool and its four main onscreen areas: main frame; tactile authoring; tactile video; and settings. The main area contains all other elements and supports data transfer between frames. The authoring area shows the visual movie and overlays tactile information on the visual scene. The tool includes sliders to control the movie timeline, tactile authoring buttons, and a test function that allows rapid content previewing to ensure desired effects are achieved. The setting area includes file-handling operations and other general settings, such as the size of the tactile array, the gray-scale video being used, and the parameters of the tactile brush. The tool supports graphical feedback, such as the display of gridlines shown in Figure 3b for a 10 $\times$ 4 array.

Figure 3c shows five arbitrary intensities of the tactile brush as different intensities (0 to 255) of gray-scale brightness. To accommodate the capabilities many tactile devices, the gray-scale setting can be down-sampled to a lower resolution. For example, the tactile gloves described in this article can display only eight intensity levels, so the 8-bit, gray-scale value is divided by 32 to produce a suitable intensity. Although our device relies on vibration, the gray-scale values can control the magnitude of other forms of tactile stimuli, such as thermal or electrotactile effects. In addition, the authoring tool supports varying brush thicknesses, enabling users to paint areas of tactile video.

Our authoring tool includes functionality to help authors create temporally varying effects. Figure 3d shows an example of one of these techniques, which overlaps two frames of the visual content to show the direction and extent of motion in the scene more effectively. Figure 3e depicts an extension of this technique in the form of a timeline of small subscreens that display a short sequence of frames around the one currently being edited. The advantage of enabling this function is that an author can keep track of the immediate past and future of a scene during editing. For example, in Figure 3e, it's easy to see how the motion of onscreen elements is progressing.

Lastly, the tactile video view window shows the output of the tactile video synchronized with visual scenes, separate from the video overlay. When the authoring process is complete, the information can be encoded with H.264/AVC or saved without encoding. Then the video can be compressed with any standard encoder. Existing tactile videos can be loaded into the tool for further editing, and the resolution of stored videos can be changed to map them to tactile devices through upscaling or downscaling.

The intensity of each gray-scale value in a tactile video determines the magnitude of the cue to be delivered to each tactor. In this way, each pixel of the tactile video can be thought of as a *taxel* controlling the intensity of a cue presented in a particular spatial position on a display device. This metaphor is most appropriate for tactile display devices featuring tactors arranged in roughly rectangular grids. If displays take a different form (say, arranged over the body) then additional work would have to be done to define an appropriate mapping between visual and tactile content. To illustrate this concept, Figure 4a (next page) shows an example of one frame of a 10 $\times$ 5-pixel, gray-scale video mapped to an equivalent 10 $\times$ 5 tactile display consisting of a uniform grid of vibrating motors. In the figure, lighter pixels correspond to more intense tactile cues. The use of gray-scale video has been proposed previously for haptic broadcasting systems.[7] But adapting this approach to display stimulus intensity over a grid of tactors is novel and first explored in this article.

At the authoring stage, the tactile content can be generated frame by frame or automatically saved in a play mode by drawing on a tactile canvas. In addition, a temporal tactile trajectory can be created by drawing while the audiovisual media is advancing in the editor. Figure 4b and 4c show a tactile effect matching the actor's onscreen movement. While the movie is playing, a line is drawn according to the bottom-right to top-left sequence shown in Figure 4b. This time-varying information is automatically saved and mapped to the tactile device as shown in Figure 4b. Entry of tactile information by sketching in this way can be a useful mechanism to synchronize tactile feedback with visual media. After a sketch is drawn, it can be edited further to customize the tactile sensations with different simulation intensities or to create new arrangements with active tactors. The features of this authoring tool make the process of creating tactile video clips relatively easy.

Evaluations

We conducted three evaluations of the system. The first was objective and measured latency, a key aspect of the performance of a multimedia display system. The second and third evaluations measured user perceptions and opinions of the cues delivered by the

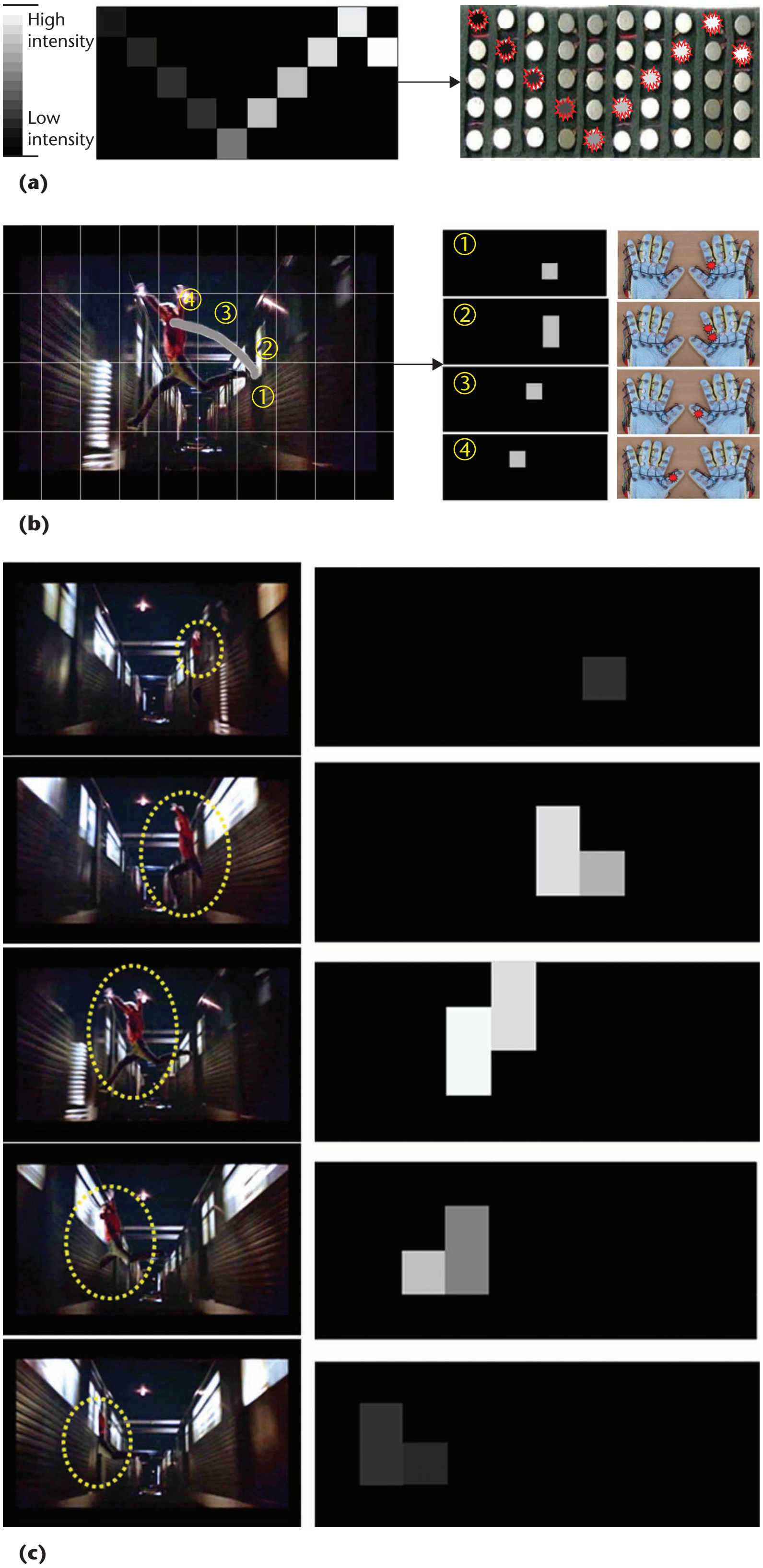


Figure 4. (a) Mapping one frame of a tactile video to a tactile display. The marked vibrators are activated at the same time with different intensities according to the gray-scale video. (b) Mapping a drawn line to a sequence of video with the tactile device. (c) Tactile video matched with movie scenes.

system according to the metaphors of first person, third person, and background effect.

Latency evaluation

The latency study measured the lag between a software command to issue a tactile cue and the presentation of that cue on the tactile display with sufficient intensity to be perceived by a human. This test measured the synchronization of the tactile information to the audiovisual media and revealed the technological lags affecting the system, including Bluetooth transmission time, mechanical activation time of the motors, and processing overhead. To perform this measurement, we transmitted a control signal from the tactile video to the vibrotactile glove system through the regular wireless communication channel and activated one of the tactors. An accelerometer (Analog Devices ADXL103) mounted on the tactor detected the onset and magnitude of the vibrations. We fed this sensor data through a low-pass filter to reduce noise and used a trigger generator circuit to record and compare the time between when the activation was issued on the host PC and when it resulted in an output from the tactor.

We found the motor commenced activation about 50 milliseconds after the signal was issued but did not reach full intensity until approximately 92 milliseconds after activation (see Figure 5). To relate this data to human perceptual capabilities, we adapted Jung et al.'s findings on vibro-tactile sensitivity.[8] Doing so involved converting acceleration amplitude (A_{acc}, expressed in Gs) to amplitude in position (A_{pos}, expressed in meters) to create a psychophysical measure of vibration magnitude using the formula $A_{pos} = A_{acc}/4\pi^2 f^2$ (where f is the dominant spectral frequency of the vibration, or 167 Hz in the case of the motors used in this work). These figures can then be related to the psychophysical literature on vibrotactile perception,[9] which suggests that the detection threshold will lie at an A_{pos} of 0.251 micrometers, a figure that corresponds to an A_{acc} of 0.27 G. Figure 5 shows the detection threshold was reached at 72 milliseconds after the signal was issued from the host PC. Although this is relatively short onset, it may be beneficial to include an offset duration automatically in the display of the vibrotactile content.

Objective evaluation

As mentioned, different movie effects associated with first person, third person, and background mood can elicit substantially different responses from audiences viewing other media formats.[10] To determine the impact of these modes for tactile feedback, we selected three movie clips of approximately 30 seconds in length (excerpts from the feature films *Spider-man*, *Ghost*, and *For Horowitz*). For each clip, we used our authoring tool to produce three tactile tracks, one according to each of the three modes. This process initially took five minutes each (for rough sketches) and then an additional hour (to produce polished sets of cues), leading to nine media segments. In a series of pairwise comparisons, we showed these segments to 10 participants: five females and five males between 22 and 28 years old, six of whom had prior experience with haptic devices and four of whom were regular computer-game players.

We exposed users repeatedly to pairs of tactile media clips and asked them to make a preference choice. In each set of three visually identical tracks, each segment was compared to every other segment twice, amounting to a total of 18 comparisons for 36 data points per participant. During the experiment, participants were seated in a quiet office wearing the tactile gloves and headphones. The results of the comparisons were recorded by vocal report to a researcher after the completion of each trial. The trials were delivered in a fully random order to prevent practice and fatigue effects.

The general results of this study, shown in Figure 6a, indicate a clear preference for first-person feedback, whereas there is little to distinguish the background and third-person approaches. These observations were performed using statistical tests: a variance analysis revealed a significant trend ($F(2, 9) = 24.6$, $p < 0.001$) and pairwise comparisons indicated that the first-person mode was preferred over both the others (at $p < 0.001$). No difference was found between the third-person mode and background effects ($p = 0.64$). A closer examination of these results between these two metaphors, illustrated in Figure 6b, showed considerable variations across the three different tactile movies. We did not conduct a formal data analysis due to insufficient data gathered, but the magnitude of the variation in preference suggests that users are making choices according to the suitability of each metaphor to the particular scene in question, rather than according to any more universal predisposition.

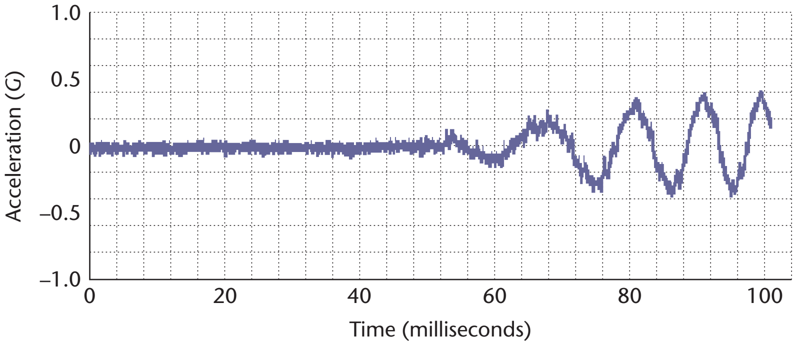


Figure 5. Measured acceleration versus time.

Subjective evaluation

We conducted a subjective evaluation of the system (enhanced with a simple thermal display) at the World IT Show held in June 2008 in Korea. This evaluation involved public demonstrations followed by questionnaires. The demonstrations involved the presentation of three short tactile movie clips that explored the different display paradigms. Each was approximately 150 seconds long. All movies

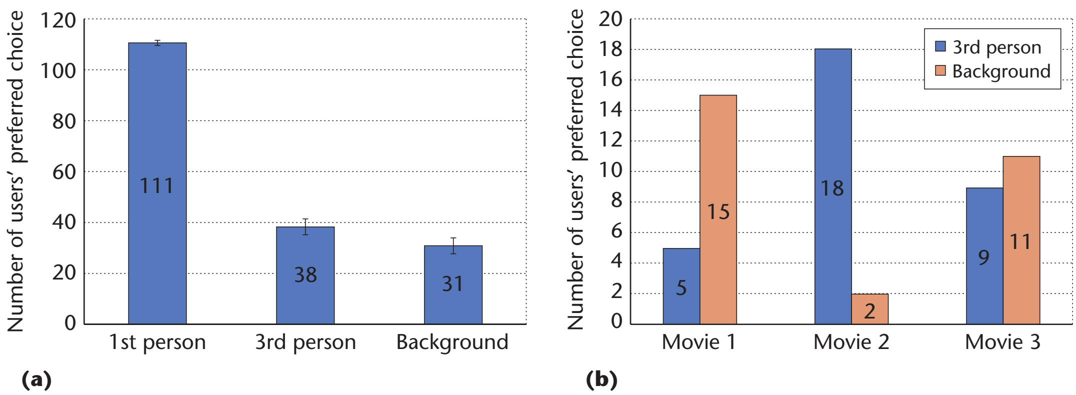


Figure 6. Results from objective user study on metaphors for adding tactile feedback to video content: (a) overall results (bars show standard deviation) and (b) detail between third person and background effects.

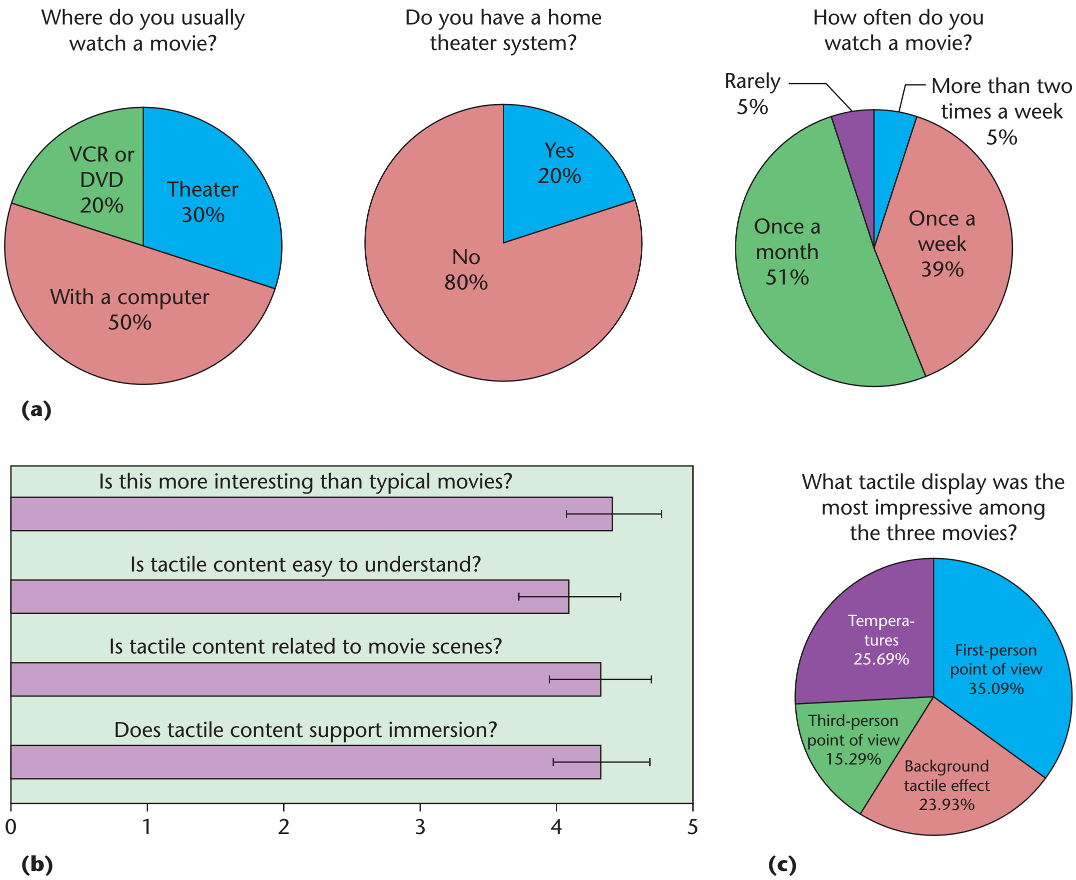


Figure 7. Results of subjective evaluation: (a) question i-iii, (b) question iv-vii, and (c) question viii.

included first person, third person, and background sensations. To avoid potential bias, we randomized the order of clips presentation.

We gathered a total of 80 responses from visitors between 17 and 43 years old. Participants included school children and adults. The technology-focused nature of the exhibition attracted attendees with an interest in computers and digital media, potentially biasing the data. Figure 7 shows the results of the questionnaire. Questions i to iii capture the participants' movie-watching behavior. Questions iv to vii show that participants were both interested in the system and felt that it enhanced the entertainment value of movies. Although data gathered in such evaluations is generally acknowledged to be subject to positive report biases, the findings are still encouraging. Question viii explicitly asks about preference for different forms of feedback. As with the previous study, the results indicate that tactile content related to the first-person mode is preferred. Subjective comments on the system focused on the importance of matching and synchronizing the tactile content to the audiovisual ones.

Conclusions

One important aspect of adding tactile cues to a video scene that this article has not addressed is the choice of attention focus. The process of adding tactile feedback to scenes is analogous to selecting a background sound. The range of options is diverse and there is little objective criteria to act as guidelines. As this media format becomes more developed, a tactile language may emerge in much the same way that films currently rely on rich audiovisual languages to express atmosphere and stylistic form. Future research on the nature of such a language would be a valuable contribution to the work in this article.

Another important point of consideration is that the current system only applies cues to the hands. Although the hands are arguably the most important parts of the body for haptic sensation, it's equally true that viewers might experience some confusion if contact with other body parts of an actor are displayed to the hands. For example, in a highly physical action scene, our system might be able to display little that directly relates to the onscreen activity. More work is required to determine the limits of the applicability of the hands-only approach described here. Even so, focusing on the hands is convenient and does not require viewers to wear equipment that is cumbersome or unwieldy. Moreover, interpretation is clearly important and tactile feedback to the hands can enhance an overall media experience without attempting to mimic reality. Background music, for example, has no place in most real-world situations, but is used skillfully by film makers to enrich the viewing experience. It might be possible to use tactile media in the same way.

Another area for future development of the system is in automatic capture of tactile media. For example, if actors wore special equipment with sensors sensitive to touch, pressure, and temperature, it would be possible to record haptic information automatically, avoiding the requirement of a manual media-creation process for first-person sensations. In a similar fashion, third-person sensations could be generated automatically by the development of appropriate image-processing techniques to capture motion. Furthermore, systems that produce saliency maps from video may be able to highlight and detect key features and generate appropriate tactile cues. The processing of audio streams may also lead to effective tactile tracks, particularly with regard to the generation of background tactile sensations. However, even given these advances, it seems likely that manual editing of tactile media would remain a requirement to convey intent and support artistic expression precisely. A media format that is created only by automation likely would be ultimately shallow and fail to offer audiences a compelling experience. In this light, the tool and approach advocated in this article will likely remain relevant to the future development of tactile information as a rich multimedia format. **MM**

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