US 20060017691A1

(19) United States

(12) Patent Application Publication

(10) Pub. No.: US 2006/0017691 A1

(43) Pub. Date: Jan. 26, 2006

Cruz-Hernandez et al.

(54) SYSTEM AND METHOD FOR CONTROLLING AUDIO OUTPUT ASSOCIATED WITH HAPTIC EFFECTS

(76) Inventors: **Juan Manuel Cruz-Hernandez**, Montreal (CA); **Danny A. Grant**, Montreal (CA)

Correspondence Address:
**David B. Ritchie**
**THELEN REID & PRIEST LLP**
**P.O. BOX 640640**
**SAN JOSE, CA 95164-0640 (US)**

(21) Appl. No.: **10/983,231**

(22) Filed: **Nov. 8, 2004**

**Related U.S. Application Data**

(60) Provisional application No. 60/590,432, filed on Jul. 23, 2004.

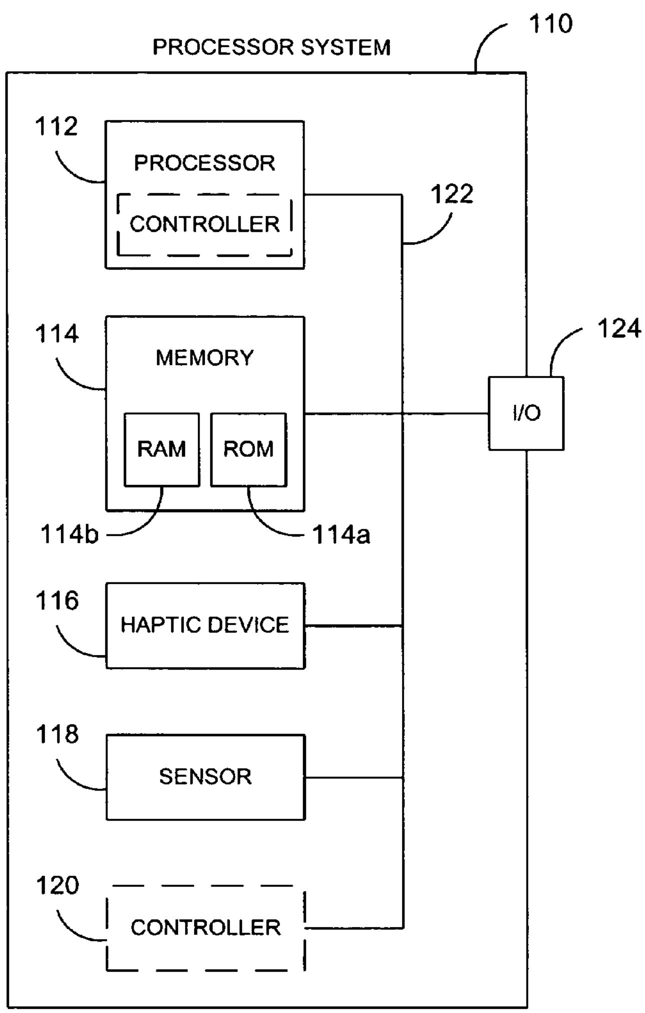
**Publication Classification**

(51) **Int. Cl.**
*G09G 5/00* (2006.01)

(52) **U.S. Cl.** .............................................................. **345/156**

(57) **ABSTRACT**

An apparatus, a processor-readable medium, and a method are provided that are configured to cause a haptic effect and an audio effect to be output substantially concurrently. The haptic effect has a frequency and the audio effect has a frequency different from the frequency of the haptic effect. At least one of the frequency of the haptic effect and the frequency of the audio effect is varied while maintaining substantially constant an average energy of the haptic effect. Varying the frequency of the audio effect can cause a perceived frequency of the haptic effect to change.



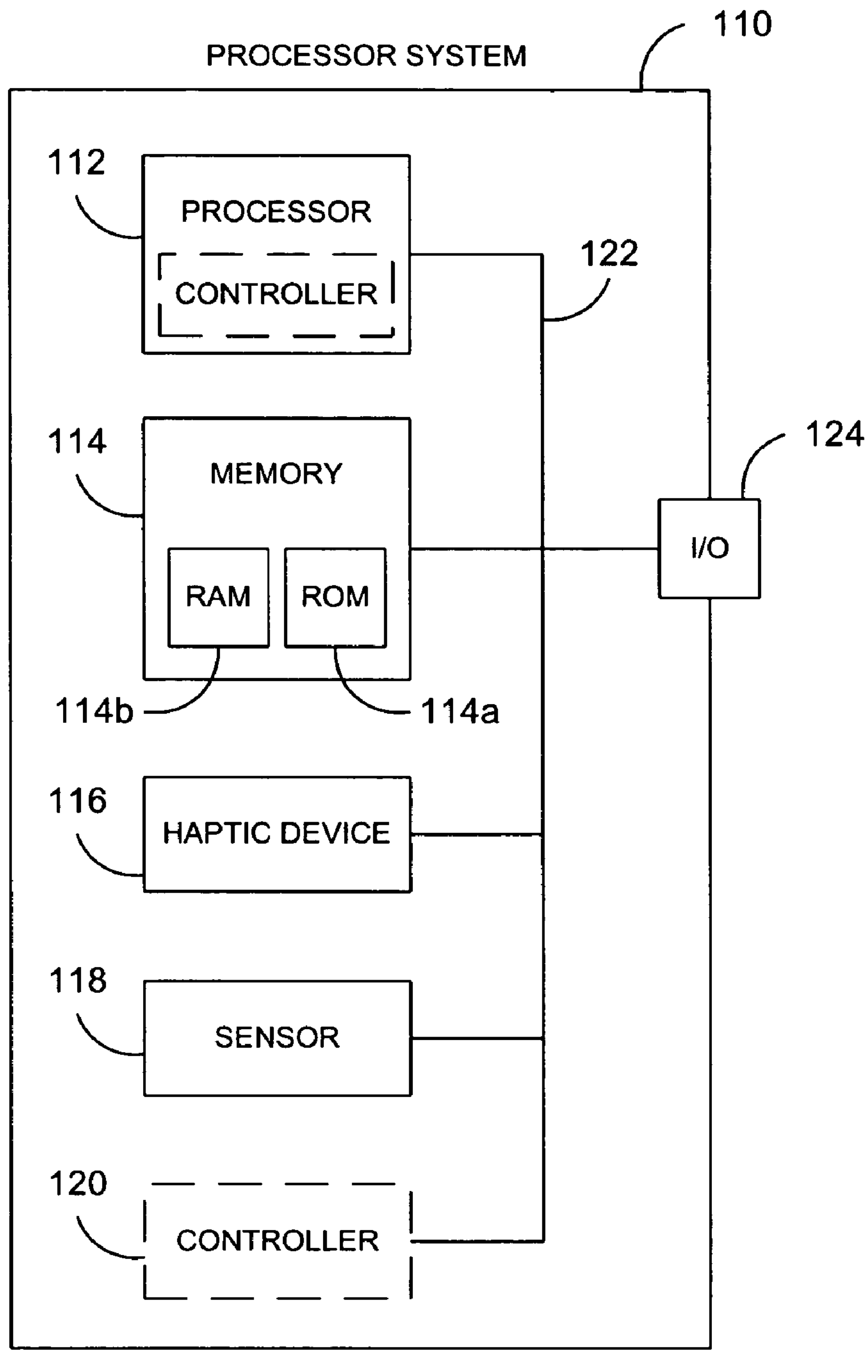

110
PROCESSOR SYSTEM
112
PROCESSOR
CONTROLLER
122
114
MEMORY
RAM
ROM
124
I/O
114b
114a
116
HAPTIC DEVICE
118
SENSOR
120
CONTROLLER

Fig. 1

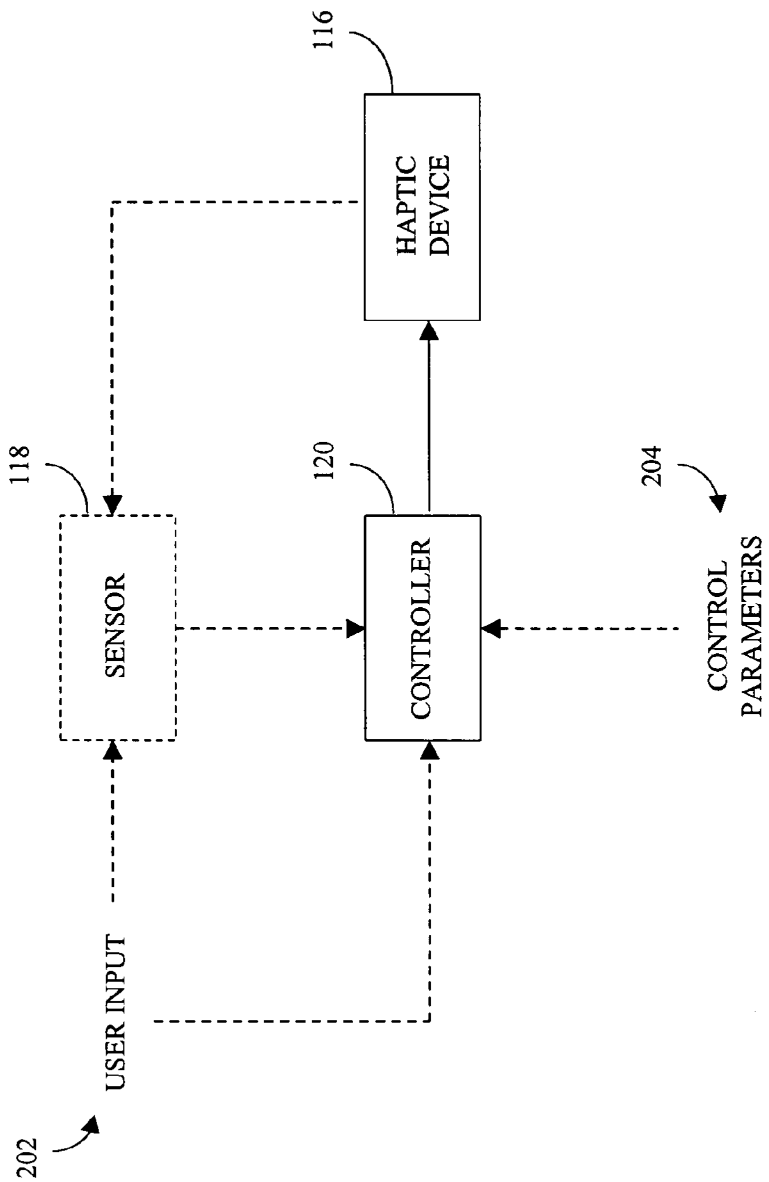

116
HAPTIC DEVICE
118
SENSOR
120
CONTROLLER
204
CONTROL PARAMETERS
USER INPUT
202

Fig. 2

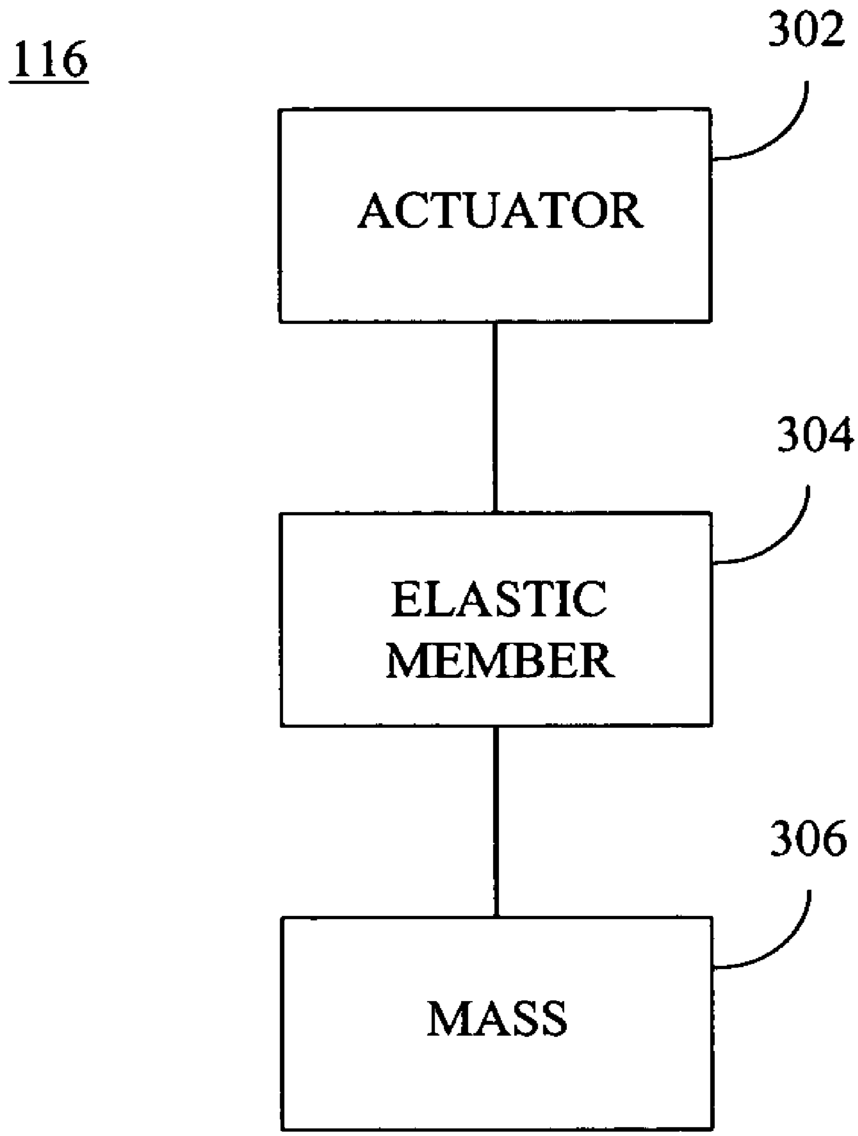



Fig. 3

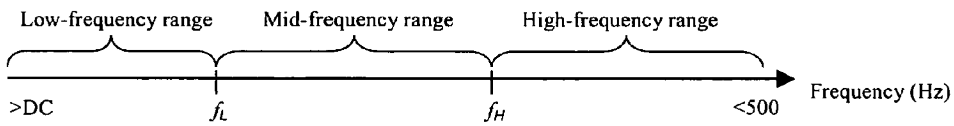

Low-frequency range
Mid-frequency range
High-frequency range
Frequency (Hz)
>DC
$f_L$
$f_H$
<500

*Fig. 4*

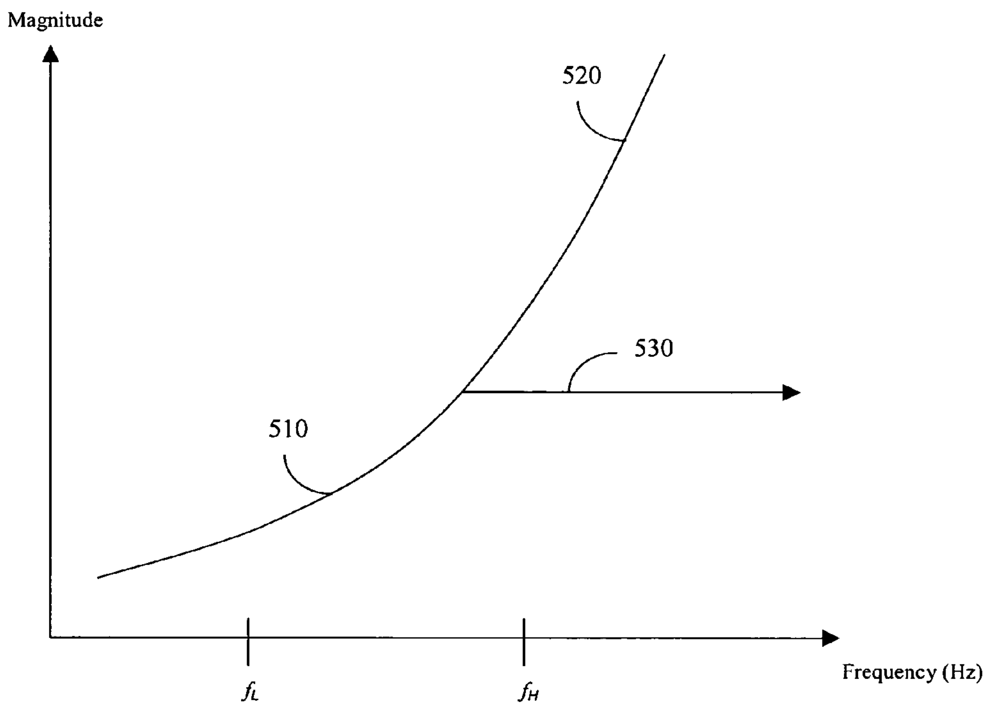

Magnitude
520
530
510
Frequency (Hz)
$f_L$
$f_H$

*Fig. 5*

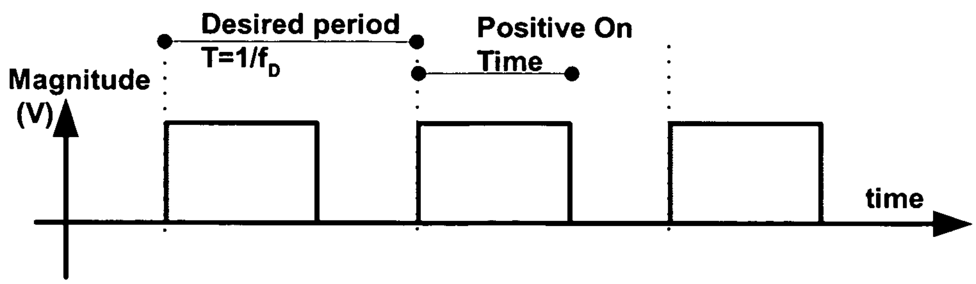

Desired period
T=1/f_D
Positive On
Time
Magnitude
(V)
time

*Fig. 6*

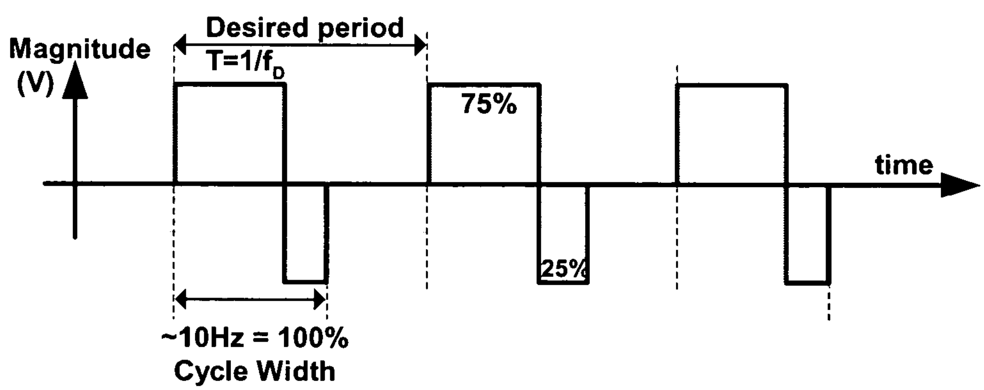

Magnitude
(V)
Desired period
T=1/f_D
75%
time
25%
~10Hz = 100%
Cycle Width

*Fig. 7*

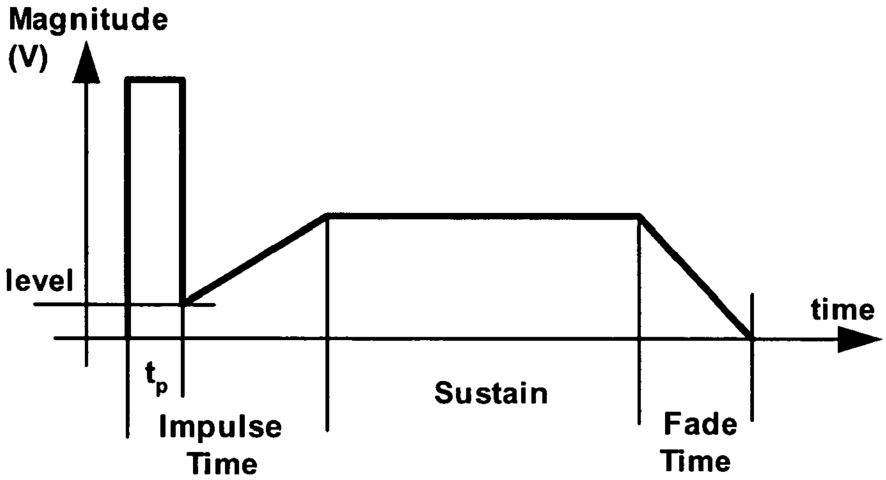

Magnitude
(V)
level
time
$t_p$
Impulse
Time
Sustain
Fade
Time

*Fig. 8*

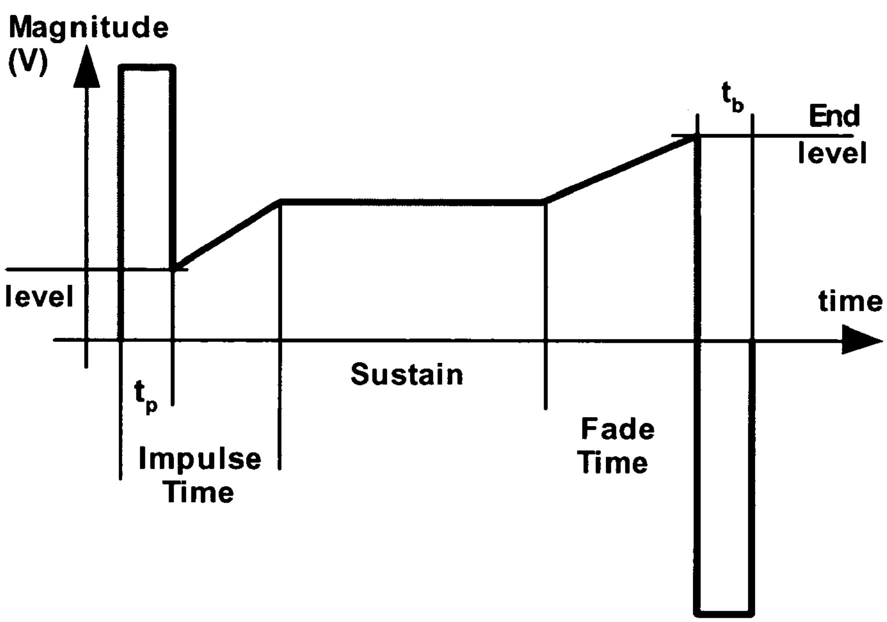

Magnitude
(V)
$t_b$
End
level
level
time
$t_p$
Sustain
Impulse
Time
Fade
Time

*Fig. 9*

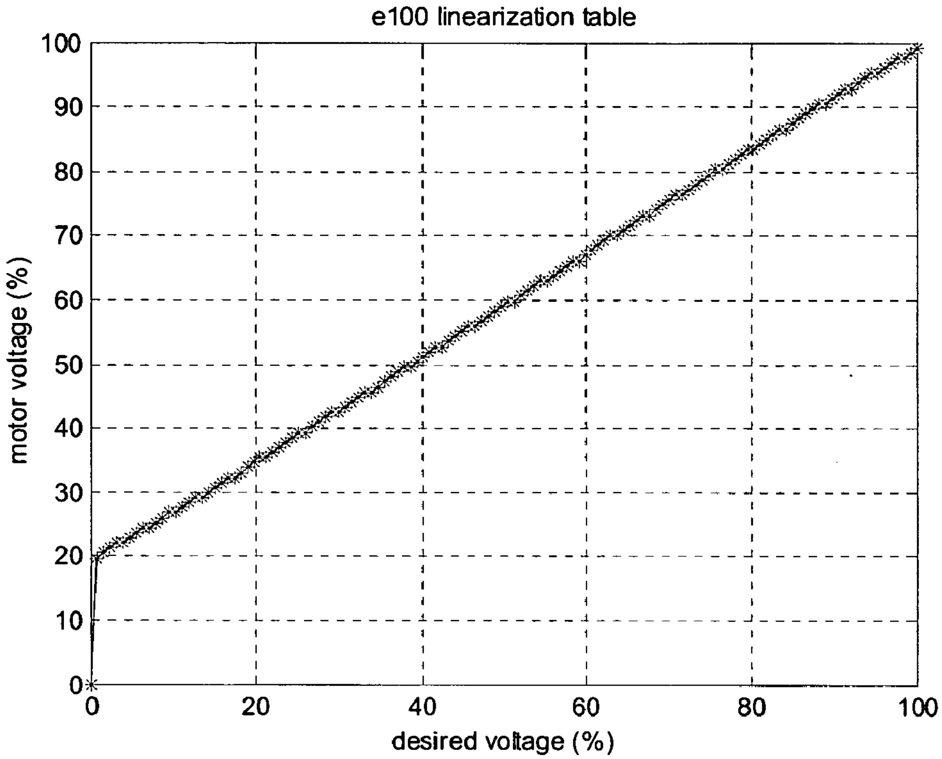

e100 linearization table
motor voltage (%)
desired voltage (%)
0
10
20
30
40
50
60
70
80
90
100
0
20
40
60
80
100

*Fig. 10*

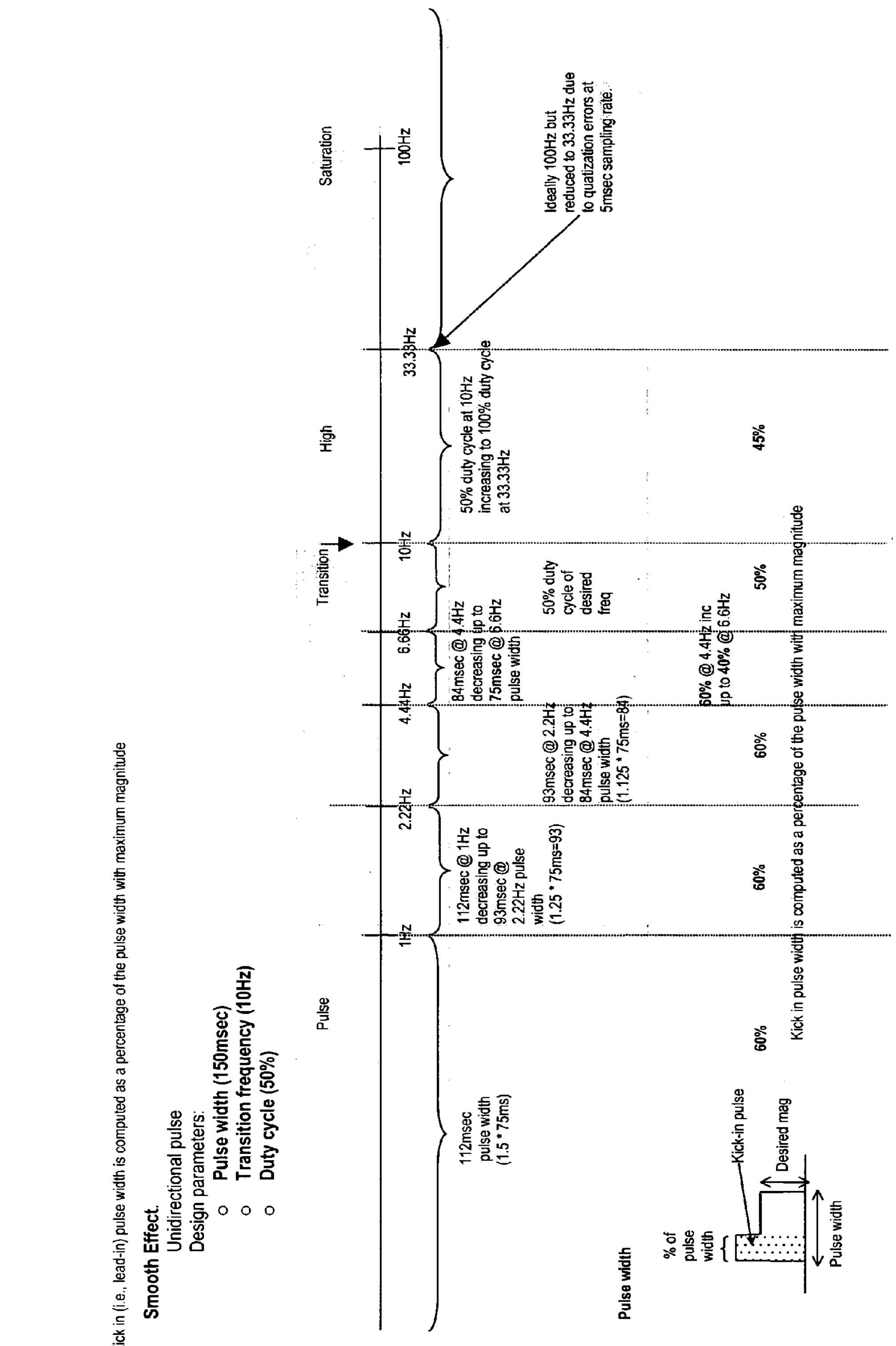

Kick in (i.e., lead-in) pulse width is computed as a percentage of the pulse width with maximum magnitude
Smooth Effect.
Unidirectional pulse
Design parameters:
Pulse width (150msec)
Transition frequency (10Hz)
Duty cycle (50%)
Pulse
Transition
High
Saturation
1Hz
2.22Hz
4.44Hz
6.66Hz
10Hz
33.33Hz
100Hz
112msec pulse width (1.5 * 75ms)
112msec @ 1Hz decreasing up to 93msec @ 2.22Hz pulse width (1.25 * 75ms=93)
93msec @ 2.2Hz decreasing up to 84msec @ 4.4Hz pulse width (1.125 * 75ms=84)
84msec @ 4.4Hz decreasing up to 75msec @ 6.6Hz pulse width
50% duty cycle of desired freq
50% duty cycle at 10Hz increasing to 100% duty cycle at 33.33Hz
Ideally 100Hz but reduced to 33.33Hz due to quatization errors at 5msec sampling rate.
Pulse width
60%
60%
60%
60% @ 4.4Hz inc up to 40% @ 6.6Hz
50%
45%
Kick in pulse width is computed as a percentage of the pulse width with maximum magnitude
% of pulse width
Kick-in pulse
Desired mag
Pulse width

*Fig. 11*

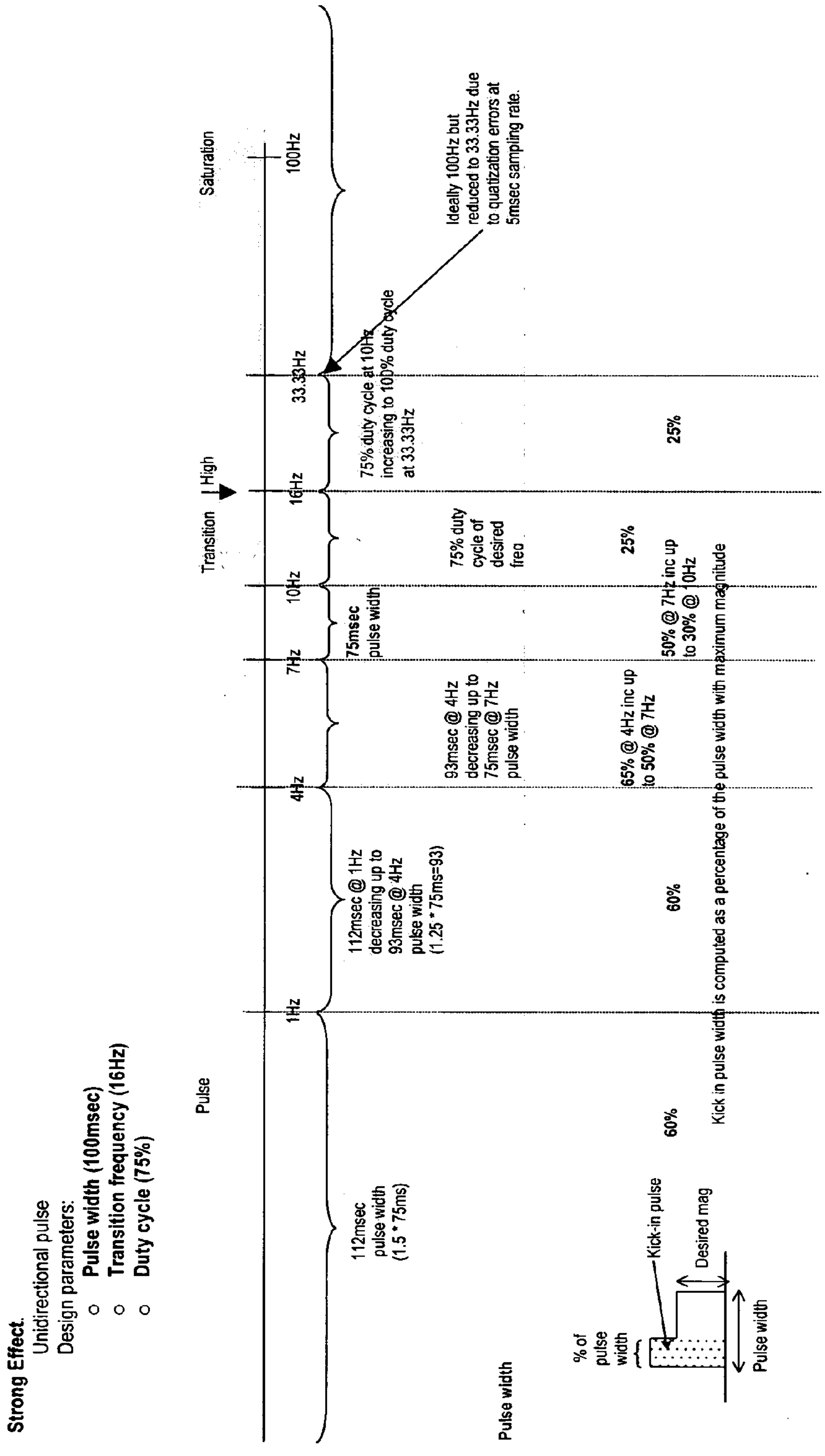
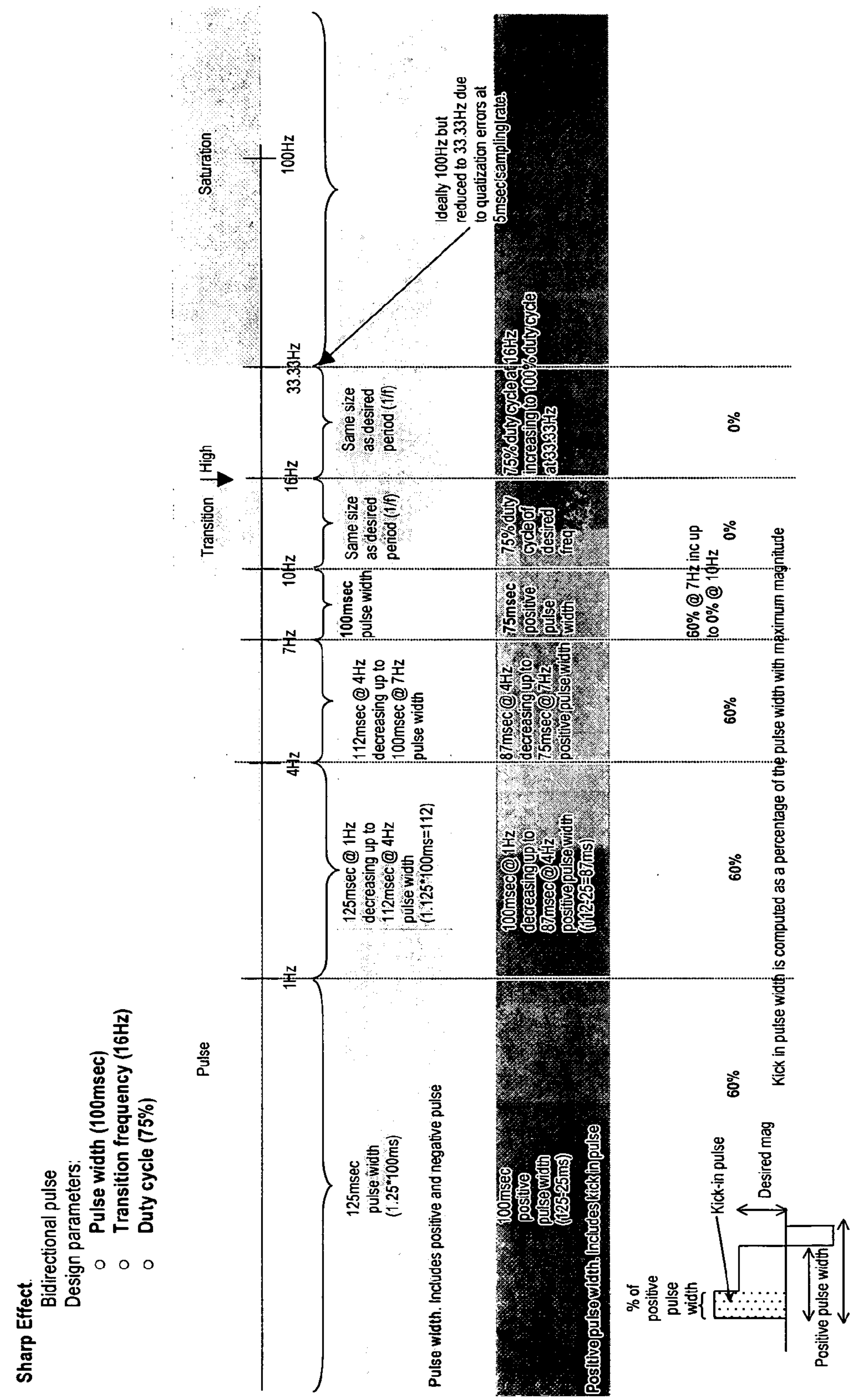

Strong Effect.
Unidirectional pulse
Design parameters:
○ Pulse width (100msec)
○ Transition frequency (16Hz)
○ Duty cycle (75%)
Pulse
Saturation
Transition
High
1Hz
4Hz
7Hz
10Hz
16Hz
33.33Hz
100Hz
112msec pulse width (1.5 * 75ms)
112msec @ 1Hz decreasing up to 93msec @ 4Hz pulse width (1.25 * 75ms=93)
93msec @ 4Hz decreasing up to 75msec @ 7Hz pulse width
75msec pulse width
75% duty cycle of desired freq
75% duty cycle at 10Hz increasing to 100% duty cycle at 33.33Hz
Ideally 100Hz but reduced to 33.33Hz due to quatization errors at 5msec sampling rate.
Pulse width
60%
60%
65% @ 4Hz inc up to 50% @ 7Hz
50% @ 7Hz inc up to 30% @ 10Hz
25%
25%
Kick in pulse width is computed as a percentage of the pulse width with maximum magnitude
% of pulse width
Kick-in pulse
Desired mag
Pulse width

*Fig. 12*



Sharp Effect.
Bidirectional pulse
Design parameters:
Pulse width (100msec)
Transition frequency (16Hz)
Duty cycle (75%)
Pulse
Transition
High
Saturation
1Hz
4Hz
7Hz
10Hz
16Hz
33.33Hz
100Hz
Ideally 100Hz but reduced to 33.33Hz due to quatization errors at 5msec sampling rate.
Pulse width. Includes positive and negative pulse
125msec pulse width (1.25*100ms)
125msec @ 1Hz decreasing up to 112msec @ 4Hz pulse width (1.125*100ms=112)
112msec @ 4Hz decreasing up to 100msec @ 7Hz pulse width
100msec pulse width
Same size as desired period (1/f)
Same size as desired period (1/f)
Positive pulse width. Includes kick in pulse
100msec positive pulse width (125-25ms)
100msec @ 1Hz decreasing up to 87msec @ 4Hz positive pulse width (112-25=87ms)
87msec @ 4Hz decreasing up to 75msec @ 7Hz positive pulse width
75msec positive pulse width
75% duty cycle of desired freq
75% duty cycle at 16Hz increasing to 100% duty cycle at 33.33Hz
Kick in pulse width is computed as a percentage of the pulse width with maximum magnitude
60%
60%
60%
60% @ 7Hz inc up to 0% @ 10Hz
0%
0%
% of positive pulse width
Kick-in pulse
Desired mag
Positive pulse width
Pulse width


Fig. 13

# SYSTEM AND METHOD FOR CONTROLLING AUDIO OUTPUT ASSOCIATED WITH HAPTIC EFFECTS

## CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit under 35 U.S.C. 119(e) of U.S. Provisional Application Ser. No. 60/590,432, entitled "System and Method for Controlling Audio Output Associated with Haptic Effects," filed Jul. 23, 2004, which is incorporated herein by reference in its entirety

## BACKGROUND

[0002] The invention relates generally to haptic feedback devices. More specifically, the invention relates to a system and method for controlling audio output associated with haptic effects.

[0003] Devices that provide haptics, such as tactile feedback, have enjoyed increased popularity in recent years. These devices are used in a variety of different applications. For example, devices providing haptics are popular in various applications, where the haptic feedback enhances the overall gaming experience of a user. For example, haptic-enabled controllers, such as mouse devices, can be configured to provide haptic feedback to a user while the user interacts with an operating system (OS), or other application.

[0004] Existing devices, however, do not effectively control audio output associated with haptic feedback. Accordingly, it would be desirable to control effectively audio output associated with haptic effects.

## BRIEF DESCRIPTION OF THE DRAWINGS

[0005] **FIG. 1** is a block diagram of a processor system, according to an embodiment of the invention.

[0006] **FIG. 2** is a diagram illustrating a haptic device, a controller, and a sensor, according to an embodiment of the invention.

[0007] **FIG. 3** is a block diagram of a haptic device, according to an embodiment of the invention.

[0008] **FIG. 4** is a diagram of multiple frequency ranges of haptic effects output by a haptic device, according to an embodiment of the invention.

[0009] **FIG. 5** is a plot of a magnitude versus frequency response of a haptic device, according to an embodiment of the invention.

[0010] **FIG. 6** is a diagram of a control signal used to control a haptic device, according to an embodiment of the invention.

[0011] **FIG. 7** is a diagram of a control signal used to control a haptic device, according to an embodiment of the invention.

[0012] **FIG. 8** is a diagram of a control signal used to control a haptic device, according to an embodiment of the invention.

[0013] **FIG. 9** is a diagram of a control signal used to control a haptic device, according to an embodiment of the invention

[0014] **FIG. 10** is a diagram of linearization of voltages of a haptic device, according to an embodiment of the invention.

[0015] **FIG. 11** is a diagram of various parameters associated with a smooth effect according to an embodiment of the invention.

[0016] **FIG. 12** is a diagram of various parameters associated with a strong effect according to an embodiment of the invention.

[0017] **FIG. 13** is a diagram of various parameters associated with a sharp effect according to an embodiment of the invention.

## DESCRIPTION

[0018] A system and method for controlling audio output associated with haptic effects are described. More specifically, audio output associated with haptic effects can be controlled to modify a perceived experience of the haptic effects. For example, by modifying the audio output, a user can be made to perceive a frequency of a haptic effect as being different than the actual frequency.

[0019] According to one or more embodiments of the invention, control signals can be configured to cause haptic effects to be output across a wide range of frequencies. These control signals can independently control haptic effects within any frequency range from among multiple frequency ranges. This can occur, for example, using either a single controller or multiple controllers configured to output control signals from each frequency range. For example, a single controller can output control signals that independently control haptic effects in each of multiple frequency ranges. Alternatively, multiple controllers can be used, such that each controller outputs control signals within a single frequency range of multiple frequency ranges, each controller being uniquely associated with each frequency range.

[0020] Audio output associated with a haptic effect is generated in at least one frequency range of multiple frequency ranges when that haptic effect is output in response to a corresponding control signal. For example, when a haptic effect is output by a haptic device in response to a control signal, the haptic device can also create audible sound or, in other words, an audio output based on the movement of the haptic device. The audio signal heard by a user can correspond to a frequency of a haptic effect that is beyond the tactile detection capabilities of the user. In other words, although a user cannot feel a difference in the frequency of a haptic effect above a certain threshold frequency, the user can hear audio associated with such higher frequencies. Thus, although varying such tactile-imperceptible frequencies will not cause a user to feel a difference in a frequency of a haptic effect, the user will be able to hear such a variation. Because a user can hear an increase or decrease in frequency of the audio output, the user will perceive that the haptic effect has changed, and in many cases will believe that he or she has felt the change in the overall experience.

[0021] One or more embodiments of the invention provide an extended perceived frequency range of haptic effects. More specifically, in addition to the range of haptic effects that can be tactilely detected by the user, a range of effects that are detected audibly by a user can be can be added such that the perceived overall experience has a greater frequency range. Because a user is able to sense an increased range of frequencies, more information can be communicated to the user using such combination of haptic effects and audio output.

[0022] When pulse-like control signals are used to generate haptic effects, control signals having a constant average energy can be used to provide a variety of different audio output frequencies. The different audio output frequencies can cause a user to believe that he or she is sensing tactilely a different frequency of a haptic effect, even though tactilely sensing such a difference would not be possible. Thus, according to one or more embodiments of the invention, a variety of overall experiences (each having a haptic component and an audio component) caused by a corresponding variety of control signals, each of which has the same average energy, is able to be sensed by a user via a combination of the haptic effect and the associated audio output, even though the variety of haptic effects alone would be perceived as having the same feel without the audio output. The average energy can be maintained constant by varying the frequency and/or duty cycle of a control signal inversely with the magnitude of a control signal. Thus, as the frequency of the control signal is increased, the magnitude decreases and, conversely, as the frequency of the control signal decreases, the magnitude increases, to maintain a constant average energy of the carrier signal.

[0023] **FIG. 1** is a block diagram of a processor system, according to an embodiment of the invention. The processor system **110** illustrated in **FIG. 1** can be, for example, a commercially available personal computer, portable electronic device, or a less complex computing or processing device (e.g., a device that is dedicated to performing one or more specific tasks). For example, the processor system can be a mobile telephone, a PDA, a portable gaming system, an MP3 player, or the like. Alternatively, the processor system **110** can be a terminal dedicated to providing an interactive virtual reality environment, such as a gaming system, or the like. Although each component of the processor system **110** is shown as being a single component in **FIG. 1**, the processor system **110** can include multiple numbers of any components illustrated in **FIG. 1**. Additionally, multiple components of the processor system **110** can be combined as a single component.

[0024] The processor system **110** includes a processor **112**, which according to one or more embodiments of the invention, can be a commercially available microprocessor capable of performing general processing operations. Alternatively, the processor **112** can be an application-specific integrated circuit (ASIC) or a combination of ASICs, which is designed to achieve one or more specific functions, or enable one or more specific devices or applications. In yet another alternative, the processor **112** can be an analog or digital circuit, or a combination of multiple circuits.

[0025] Alternatively, the processor **112** can optionally include one or more individual sub-processors or coprocessors. For example, the processor can include a graphics coprocessor that is capable of rendering graphics, a math coprocessor that is capable of efficiently performing complex calculations, a controller that is capable of controlling one or more devices, a sensor interface that is capable of receiving sensory input from one or more sensing devices, and so forth.

[0026] The processor system **110** can also include a memory component **114**. As shown in **FIG. 1**, the memory component **114** can include one or more types of memory. For example, the memory component **114** can include a read only memory (ROM) component **114***a* and a random access memory (RAM) component **114***b*. The memory component **114** can also include other types of memory not illustrated in **FIG. 1** that are suitable for storing data in a form retrievable by the processor **112**. For example, electronically programmable read only memory (EPROM), erasable electrically programmable read only memory (EEPROM), flash memory, as well as other suitable forms of memory can be included within the memory component **114**. The processor system **110** can also include a variety of other components, depending upon the desired functionality of the processor system **110**. The processor **112** is in communication with the memory component **114**, and can store data in the memory component **114** or retrieve data previously stored in the memory component **114**.

[0027] The processor system **110** can also include a haptic device **116**, which is capable of providing a variety of haptic output. For example, the haptic device **116** can be configured to output basis haptic effects, such as periodic effects, magnitude-sweep effects, or timeline haptic effects, each of which is described in greater detail below. According to one or more embodiments of the invention, the haptic device **116** can include one or more force-applying mechanisms, which are capable of outputting haptic effects or force, to a user of the processor system **110** (e.g., via the housing of the processor system **110**). These effects or forces can be transmitted, for example, in the form of vibrational movement caused by the haptic device **116** (e.g., caused by a rotating mass, a piezo-electric device, or other vibrating actuator), or in the form of resistive force caused by the haptic device **116**.

[0028] The processor system **110** can also, according to one or more embodiments of the invention, include a sensor **118** that is capable of receiving input from a user, the haptic device **116**, or is otherwise capable of sensing one or more physical parameters. For example, according to one or more embodiments of the invention, a sensor **118** can be configured to measure speed, intensity, acceleration, or other parameters associated with a haptic effect output by the haptic device **116**. Similarly, the sensor **118** can be configured to sense environmental or ambient conditions of the processor system's surroundings. The sensor **118** can interface and communicate with the processor **112** by way of a sensor interface (not shown) within the processor **112**.

[0029] The processor system **110** can also include a controller **120**, which can optionally be internal to the processor **112**, or external thereto, as shown in **FIG. 1**. The controller **120** can be configured to control the haptic device **116** when the processor **112** is not directly controlling the haptic device **116**. Similarly, the controller **120** can control the memory **114** and/or the sensor **118**, as well as devices external to the processor system **110** by way of an input/output (I/O) component **124** (described below).

[0030] The various components of the processor system **110** can communicate with one another via a bus **122**, which is capable of carrying instructions from the processor **112** and/or the controller **120** to other components, and which is capable of carrying data between the various components of the processor system **110**. Additionally, signals received via the sensor **118** can be communicated to the processor **112** or the controller **120** by way of the bus **122**. Data retrieved from or written to memory **114** can be carried by the bus **122**, as are instructions to the haptic device **116**. Instructions to the haptic device **116** can be provided in the form of haptic-effect signals (e.g., basis haptic-effect signals), for example, which can be provided by the processor **112**, the controller **120**, or devices external to the processor system **110**.

**[0031]** The components of the processor system **110** can communicate with devices external to the processor system **110** by way of an input/output (I/O) component **124** (accessed via the bus **122**). According to one or more embodiments of the invention, the I/O component **124** can include a variety of suitable communication interfaces. For example, the I/O component **124** can include, for example, wireless connections, such as infrared ports, optical ports, Bluetooth wireless ports, wireless LAN ports, or the like. Additionally, the I/O component **124** can include, wired connections, such as standard serial ports, parallel ports, universal serial bus (USB) ports, S-video ports, large area network (LAN) ports, small computer system interface (SCSI) ports, and so forth.

**[0032]** **FIG. 2** is a diagram illustrating a haptic device, a controller, and a sensor, according to an embodiment of the invention. **FIG. 2** also shows data values provided to the system (e.g., user input **202** and control parameters **204**). The elements shown in **FIG. 2** can be used with the processor system **110**, or a similar device.

**[0033]** The controller **120** is configured to output control signals that are configured to cause haptic effects to be output by the haptic device **116**. As shown in **FIG. 2**, user input **202** can optionally be provided (e.g., via the I/O component **124** shown in **FIG. 1**) and/or received by an optional sensor **118**. The user input **202** can also optionally be provided directly to a controller **120** (e.g., by way of the sensor **118**, or some other devices configured to accept and convey user input). The sensor **118** can also optionally receive information from the haptic device **116**. For example, the sensor **118** can sense the actual movements of the haptic device **116**.

**[0034]** According to an arrangement of the system shown in **FIG. 2**, the controller **120** can optionally receive data from the sensor **118**, and can optionally receive user input **202** and control parameters **204**. Based on any data received from the sensor **118**, any received user input **202**, and/or any received control parameters **204**, the controller **120** controls the haptic output of the haptic device **116** (e.g., the controller **120** sends control signals configured to cause haptic effects). For example, the controller **120** can execute a feedback algorithm, controlling the haptic device **116** based on feedback received from the haptic device **116**. The controller **120** controls the output of the haptic device **116** by a control signal that the controller **120** outputs to the haptic device **116**.

**[0035]** The control signal output by the controller **120** can be based on a number of parameters, including, for example, control parameters **204**. For example, control parameters **204** and other parameters that can be used by the controller **120** to control the haptic device **116** can be stored in the memory component **114** of the processor system **110**, or by another suitable memory component. For example, the control parameters **204** can include input from an electronic system, a portable gaming device, a cellular telephone, or the like. According to one or more embodiments of the invention, the controller receives control parameters (e.g., gaming device input, cellular telephone input, etc.), and does not include a sensor. According to such embodiments, user input can optionally be received directly by the controller, or can be omitted entirely, depending upon the desired function of the system in which the controller is used.

**[0036]** According to one or more embodiments of the invention, the system shown in **FIG. 2** can be used in a stand-alone device, such as a mobile telephone, portable electronic device (e.g., a PDA, etc.), or other device. In a mobile telephone embodiment, for example, haptic output can be provided in the form of haptic effects via the haptic device **116** in response to status events (e.g., a message received signal, a network indicator signal, etc.), user input (e.g., mode changes, keypad dialing, option selections, etc.), incoming calls, or other events. Alternatively, the system shown in **FIG. 2** can be used in a configuration where a processor, such as the processor **112** of the processor system **110** shown in **FIG. 1**, can be connected to an external device, and the processing tasks can be divided among the devices, as desired.

**[0037]** The controller **120** can generate a variety of different control signals to drive the haptic device **116**, several of which will be described in greater detail below. For example, the controller **120** can send a control signal to the haptic device **116**, which is configured to cause the haptic device **116** to output a corresponding haptic effect. Examples of such control signals include, pulse width modulation (PWM) signals (e.g., pulse signals having a given duty cycle), sinusoidal signals, and other periodic signals (e.g., triangle waves, square waves, etc.). Additionally, the controller **120** can modulate control signals using one or more haptic envelopes.

**[0038]** The controller **120** also can be configured to provide a lead-in pulse at the beginning of a control signal, and/or a braking pulse, at the end of a control signal, which are configured to decrease response time of the haptic device **116**. For example, the lead-in signal reduces the time for the haptic device **116** to initiate outputting a haptic effect associated with the control signal. The braking pulse, on the other hand, decreases the time it takes for the haptic device **116** to cease a haptic effect currently being output. In addition to signals described above, such as periodic signals, the controller **120** can output a variety of other control signals, such as non-periodic signals, that are configured to cause the haptic device **116** to output haptic effects.

**[0039]** **FIG. 3** is a block diagram of a haptic device **116** shown in **FIGS. 1 and 2**. As shown in **FIG. 3**, the haptic device **116** includes an actuator **302**, an elastic member **304** and a mass **306**. The haptic device **116** is configured to provide haptic feedback. The actuator **302** is operably connected to the elastic member **304**, and the elastic member **304** is operably connected to the mass **306**. The actuator **302** can include, for example, a motor (e.g., a brush motor, a brushless motor, etc.). The elastic member can provide a desired amount of coupling rigidity between the actuator and the mass **306**.

[**0040**] When control signals are received by the haptic device **116**, the actuator **302** provides force to the elastic member **304**. Some of the force applied to the elastic member **304** is translated to the mass **306**, and causes the mass **306** to move. By causing the mass **306** to move, haptic effects commanded by the control signals are output by the haptic device, and can be output to a user. The actuator **302** can be configured, for example, to cause the mass to rotate in response to the control signals received by the haptic device. Alternatively, the actuator can move the mass **306** in other directions (e.g., vibrating the mass, moving the mass laterally, etc.).

[**0041**] The configuration shown in **FIG. 3** is only one example of a configuration of a haptic device **116**. Other configurations that vary from the configuration shown in **FIG. 3** can be used as a haptic device **116**, according to one or more embodiments of the invention. For example, the elastic member **304** can be coupled to the mass **306** by a flexible coupling; the elastic member **304** can be coupled to the actuator **302** by a flexible coupling. In an alternative embodiment, the elastic member can be coupled between actuator and a mechanical ground, and the actuator can be directly coupled to the actuator. Examples of haptic devices that can be used in connection with one or more embodiments of the invention include an eccentric-rotating-mass (ERM) haptic device and a harmonic ERM (HERM) haptic device, described in detail in copending U.S. patent application Ser. No. 10/301,809, which is incorporated by reference herein in its entirety.

[**0042**] **FIG. 4** is a diagram of multiple frequency ranges of haptic effects that can be output by a haptic device **116**, according to an embodiment of the invention. A low-frequency range extends from approximately DC (i.e., 0 Hz) to a low-frequency limit $f_L$, which can vary depending upon the control signal being used to cause a haptic effect and the desired characteristics of the haptic effect. A mid-frequency range extends from the low-frequency threshold frequency $f_L$ to a high-frequency threshold frequency $f_H$, which can vary depending upon the control signal being used to cause a haptic effect and the desired characteristics of the haptic effect. A high-frequency range extends from the high-frequency threshold frequency $f_H$ to all higher frequencies.

[**0043**] According to one or more embodiments of the invention, at least one frequency range from the frequency ranges shown in **FIG. 4** can have an audio output associated with the haptic effect. The audio output can occur for haptic effects having a frequency within the at least one frequency range or for haptic effects having a frequency beyond the at least one frequency range, depending upon the desired performance of the system.

[**0044**] For example, according to one or more embodiments of the invention, the mid-frequency range shown in **FIG. 4** can have an audio output associated with a haptic effect having a frequency within the mid-frequency range. The haptic effect having a frequency within the mid-frequency range can be varied in a manner such that the associated audio output varies, while any changes in the frequency of the haptic effect remains tactilely undetectable to a user. Because the audio output varies (e.g., changes frequency of the audio output), a user aurally detects the change in the audio output, and believes that he or she has tactilely detected a change in the haptic effect. Said another way, by varying the audio output, the user may perceive that the overall effect (the combination of a haptic effect and an audio effect) has changed and attribute such a change, at least in part, to the user's tactile experience. Additionally, in one or more embodiments, the average energy of a control signal used to cause the haptic effect to be output can be maintained substantially the same while the associated audio output is varied, causing a user to detect an increase in the audio output and believe that he or she has tactilely perceived a change in the haptic effect.

[**0045**] Although **FIG. 4** illustrates only three frequency ranges, the number of frequency ranges used according to one or more embodiments of the invention can be varied. For example, many more frequency ranges can be used, among which multiple frequency ranges can include an audio output associated with the haptic effects having frequencies within those frequency ranges.

[**0046**] Haptic effects having frequencies within each of the frequency ranges shown in **FIG. 4** can be separately controlled. This can occur, for example, using a single controller, that separately controls the haptic effects associated with each of the frequency ranges shown in **FIG. 4**. Alternatively, each frequency range shown in **FIG. 4** can have a uniquely associated controller, which is configured to control haptic effects having frequencies within that frequency range.

[**0047**] **FIG. 5** is a plot of a magnitude versus frequency of a haptic effect, according to an embodiment of the invention. The plot shown in **FIG. 5** is not drawn to scale, and is intended only as an example of the correlation between the magnitude and frequency of a haptic effect, and how a user perceives them. The magnitude versus frequency response shown in **FIG. 5** indicates that, as the frequency of a haptic effect is increased, the magnitude of that haptic effect appears also to increase to a user. A first portion **510** of the curve shown in **FIG. 5** represents a region of haptic effect frequencies within which a user can detect changes in frequency. Within some region of frequencies (e.g., beginning near the high-frequency threshold frequency $f_H$ in the plot of **FIG. 5**), referred to as a diminished-sensitivity region, a user perceives some increases in the frequency of a haptic effect as increases in magnitude (and not the frequency) without being able to detect tactilely the increases in frequency. A second portion **520** of the curve shown in **FIG. 5** represents this region, where the user has difficulty tactilely detecting changes in frequency. Near where the diminished-sensitivity region begins (i.e., the area of intersection of the first portion **510** and the second portion **520** of the curve shown in **FIG. 5**), a user's perception of increasing frequencies of combination of a haptic effect and audio output is illustrated using a line **520**. Similar lines can be drawn to illustrate a user's perception of increasing frequencies of a combination of a haptic effect and an audio output is generated by the haptic device.

[**0048**] According to one or more embodiments of the invention, a pulse-like, periodic control signal is configured to cause the haptic effects to be output having frequencies within each of the ranges shown in **FIG. 4**. Examples of such signals are discussed in greater detail below. Generally speaking, the period between pulse features of the control signal corresponds to a low-frequency component (e.g., a haptic envelope) of a haptic effect at lower frequencies. At lower frequencies, it is these low-frequency components (perceived as pulses) that are most easily tactilely detected by a user. As the period between the pulses of the control signal decreases (i.e., the frequency of the pulses increases), the haptic device **116** reaches a state where it is moving almost the entire period, even during the portions of the period when no pulse in the control signal exists. Over increasing control signal frequencies where this begins to occur, the haptic device **116** is said to be operating in "saturation mode." For example, in the case of a rotating-mass device, when the haptic device **116** reaches the saturation mode, despite the fact that the control signal pulses are not continuously on and, therefore, are causing low-frequency components in the haptic effect, the mass of the device continues to rotate. The saturation mode may or may not correspond to the diminished-sensitivity region, depending upon the physical characteristics of the haptic device **116** or other parameters.

**[0049]** When an audio output associated with a haptic effect is output at the same time as the haptic effect, a user perceives the frequency of the haptic effect to increase due to an increase in the frequency of the audio output. This is illustrated, for example, by a line **530** extending from the magnitude versus frequency curve shown in **FIG. 5**. This perceived change in frequency of the haptic effect due to the audio output can occur, for example, at the beginning of the diminished-sensitivity region (i.e., where it begins to be difficult for a user to tactilely detect variations in frequency). According to one or more embodiments of the invention, the perceived increased frequency of the haptic effect occurs when the haptic device is being driven within the mid-frequency range (i.e., a frequency between $f_L$ and $f_H$), as shown in **FIG. 5**. Using the audio output to increase the frequency range a user perceives a haptic device to have allows a user to experience an increased perceived frequency range in the overall experience, and specifically the perceived haptic effect, without being limited by the performance range of the haptic device. Although not shown, multiple lines similar to the illustrated line **530** can be used to represent an audio output changing the frequency that a user perceives either within or outside of the diminished-sensitivity region. Also, although the line **530** representing a frequency perceived by a user indicates an essential constant perceived magnitude, it also is possible to change the magnitude perceived by a user, depending upon the audio output that is produced.

**[0050]** Several signals are described below in greater detail. These signals are only examples, however, and it should be recognized that there are many other signals that are suitable for acting as control signals, depending upon the desired haptic effects to be output and audio output to be produced. Examples of control signals that can be used in connection with one or more embodiments of the invention are described in detail in copending U.S. patent application Ser. Nos. 09/669,029 and 10/671,465, each of which is incorporated by reference herein in its entirety. Similarly, other control signals, as well as haptic devices that can be used in connection with one or more embodiments of the invention are described in detail in U.S. Pat. No. 6,275,213, which is incorporated by reference herein in its entirety.

**[0051]** **FIG. 6** is a diagram of a control signal used to control a haptic device, according to an embodiment of the invention. The control signal shown in **FIG. 6** can be used to closely control the frequency of a haptic effect. The control signal shown in **FIG. 6** is a series of pulses, each having a positive on-time. The pulses are periodic, having a period that corresponds to the desired frequency of the haptic effect to be output, as defined by Equation 1 below:

$$T = \frac{1}{f_D}, \tag{1}$$

where T is the period of the control signal (i.e., the time period between two adjacent pulses of the control signal), and $f_D$ is the desired frequency of the output of the haptic effect.

**[0052]** Changes in magnitude of a haptic effect caused by the control signal shown in **FIG. 6** can be conveyed by proportional changes of magnitude of the pulses of that control signal. A change in magnitude of the output haptic effect that is based on the control signal shown in **FIG. 6** varies proportionately to the change in magnitude of the control signal. The duration of the pulses (i.e., the positive on-time or duty cycle) can be selected according to the values shown in Table 1 below to provide a distinct frequency pattern, depending upon the frequency range of the haptic effect being selected.

TABLE 1

Duty cycle/on-time values for control signal of FIG. 6

| Frequency Range | Frequencies | Duty Cycle/On-Time |
|---|---|---|
| Low | $f_D \leqq 6.66$ Hz | 75 ms |
| Mid | 6.66 Hz $< f_D \leqq 10$ Hz | 50% |
| High | 10 Hz $< f_D \leqq 100$ Hz | 50% @ 10 Hz |
| | $f_D > 100$ H | 100% @ 100 Hz and above |

**[0053]** The frequency ranges shown in Table 1 above can correspond to the three ranges shown in **FIG. 4** (with "other" being included in the high-frequency range), according to one or more embodiments of the invention. To achieve higher desired frequencies $f_D$ of a haptic effect, the duty cycle of the control signal is increased. For example, in the transition from 10 Hz to 100 Hz in the high-frequency range, the duty cycle increases from 50% to 100%. This increase in duty cycle can be a linearly increase, or another type of increase, if desired.

**[0054]** The duration of the pulses (i.e., the positive on-time, or duty cycle) can alternatively be selected according to the values shown in Table 2 below to provide a strong haptic effect magnitude, depending upon the frequency range of the haptic effect being selected.

TABLE 2

| Duty cycle/on-time values for control signal of FIG. 6 | | |
|---|---|---|
| Frequency Range | Frequencies | Duty Cycle/On-Time |
| Low | $f_D \leqq 10$ Hz | 75 ms |
| Mid | 10 Hz < $f_D \leqq 16$ Hz | 75% |
| High | 16 Hz < $f_D \leqq 100$ Hz | 50% @ 10 Hz |
| | $f_D$ > 100 Hz | 100% @ 100 Hz and above |

[0055] The frequency ranges shown in Table 2 above can also correspond to the three ranges shown in **FIG. 4** (with "other" being included in the high-frequency range), according to one or more embodiments of the invention. To achieve greater magnitude of a haptic effect, the length of the duty cycle of the control signal is increased in the high-frequency range. As discussed above, the duty cycle can be increased linearly, or in some other desirable manner.

[0056] **FIG. 7** is a diagram of a control signal used to control a haptic device, according to another embodiment of the invention. The control signal shown in **FIG. 7** is a bi-directional control signal that includes multiple bi-directional pulses, and is configured to create a haptic effect with a strong magnitude. These bi-directional pulses are periodic, and have a period corresponding to the desired frequency $f_D$ of the haptic effect to be output (defined by Equation 1 above). Seventy-five percent of the bi-directional pulse is a positive pulse portion, and twenty-five percent of the bi-directional pulse is a negative pulse portion. Values associated with the pulse size for various frequency ranges are shown below in Table 3.

TABLE 3

| Duty cycle values for control signal of FIG. 7 | | |
|---|---|---|
| Frequency Range | Frequencies | Duty Cycle/On-Time |
| Low | $f_D \leqq 10$ Hz | 10 Hz (75% $V^+$ pulse, 25% $V^-$ pulse) |
| Mid | 10 Hz < $f_D \leqq 16$ Hz | 75% |
| High | 16 Hz < $f_D \leqq 100$ Hz | 75% @ 16 Hz |
| | $f_D$ > 100 Hz | 100% @ 100 Hz and above |

[0057] In Table 3, the three frequency ranges can correspond, for example, to the three frequency ranges shown in **FIG. 4**. To vary the magnitude of a haptic effect, the magnitude of the pulse is varied proportionally to the desired increase or decrease of magnitude. Haptic effects to be output in the high-frequency range cause a user to perceive that the magnitude and frequency change proportionally to any changes in the desired frequency of the control signal shown in **FIG. 7**.

[0058] **FIG. 8** is a diagram of a control signal used to control a haptic device, according to an embodiment of the invention. The control signal shown in **FIG. 8** is a magnitude-sweep control signal (also referred to as a "mag-sweep" signal), which sweeps through a variety of magnitude values to cause a desired haptic effect to be output. The magnitude-sweep control signal shown in **FIG. 8** can cause a corresponding haptic effect to be output, or can be used to modulate another control signal (e.g., a periodic signal such as the signals shown in **FIG. 6** and **FIG. 7**).

[0059] A lead-in pulse is provided at the beginning of the control signal shown in **FIG. 8**, which improves response time of the haptic device being controlled by the control signal. The duration $t_p$ of the pulse is varied as a function of the magnitude level of the beginning of the effect (e.g., at a level desired to begin the impulse portion of the signal, or the ramp-up portion of the signal). The smaller the magnitude levels at the beginning of the effect, the shorter the duration $t_p$ of the lead-in pulse and, similarly, the larger the magnitude levels at the beginning of the signal, the longer the duration $t_p$ of the lead-in pulse. The duration $t_p$ of the pulse can be varied according to the percentage of maximum control signal magnitude (e.g., the voltage magnitude) that one desires to reach by the end of the pulse (e.g., at the value indicated as "level" in **FIG. 9** and denoted L in Table 4), as shown below in Table 4.

TABLE 4

| Duration $t_P$ of the lead-in pulse in FIG. 8 | |
|---|---|
| \|Maximum Voltage\| % | $t_P$ |
| 0% ≦ L ≦ 47% | 0 |
| 47% ≦ L ≦ 70% | 25 ms |
| 70% ≦ L ≦ 100% | 50 ms |

[0060] **FIG. 9** is a diagram of a control signal used to control a haptic device, according to an embodiment of the invention. The control signal shown in **FIG. 9** is a magnitude sweep signal, similar to the control signal shown in **FIG. 8**, but having both a lead-in pulse and a braking pulse. Because the braking pulse is a negative pulse, the control signal shown in **FIG. 9** can also be considered a bi-directional signal. The braking pulse generally is executed to cause a large change in voltage to stop the actuation of a haptic device (i.e., to stop a device from outputting a haptic effect currently being output, such as stopping the rotation of a rotational haptic device).

[0061] The braking pulse is of opposite polarity to the lead-in pulse, and the rest of the signal. The duration $t_b$ of the braking pulse varies as a function of the magnitude level of the signal at the end of the effect (i.e., immediately prior to initiating the braking pulse). The smaller the magnitude level at the end of the effect (i.e., at the end of the control signal shown in **FIG. 9**), the shorter the duration of the braking pulse that is required. Various lengths of possible braking pulses are shown below in Table 5 according to the corresponding percentage of voltage magnitude (e.g., the voltage magnitude) at the end of the signal (e.g., at the value indicated as "End level" in **FIG. 10** and denoted EL in Table 5) shown in **FIG. 9**.

TABLE 5

| Duration $t_b$ of the braking pulse in FIG. 9 | |
|---|---|
| \|Maximum Voltage\| % | $t_b$ |
| 0% ≦ EL ≦ 47% | 0 |
| 47% ≦ EL ≦ 70% | 25 ms |
| 70% ≦ EL ≦ 100% | 50 ms |

[0062] **FIG. 10** is a diagram of linearization of voltages of a haptic device, according to an embodiment of the invention. The actuator of the haptic device may require increased voltage over the desired voltage to initiate and achieve the intended effects. **FIG. 10** illustrates an example of a linearization table for such an actuator. As shown in the linearization table of **FIG. 10**, the percentage of motor voltage to begin movement of the motor can be about twenty percent.

[0063] Each of the control signals described above in connection with **FIGS. 9-10** can be used with a haptic device that produces an audio output, in addition to outputting a haptic effect, when driven by the control signal. As the control signal changes the rate of movement associated with such haptic devices, the audio output also can change. This can occur, for example, by varying a magnitude, frequency, and/or pulse of the control signal. Thus, by using the control signal to vary the audio output produced by a haptic device, the control signal can cause a user to sense a change in the frequency in the overall effect and to perceive a change in the haptic effect output by the haptic device.

[0064] Additional information and examples regarding control signals according to one or more embodiments of the invention are illustrated below in Tables 6-10. For example, Table 6 shows the number of available controller input frequencies for different frequency ranges for the smooth controller. Table 7 shows the number of available controller input frequencies for different frequency ranges for the strong and sharp controllers. Table 8 shows motor inputs for various frequency ranges for smooth, strong and sharp controllers. Table 9 shows desired perceived frequency and perceived magnitude for various frequency ranges for smooth, strong and sharp controllers. Table 10 shows actual acceleration frequency, perceived frequency and perceived magnitude for various frequency ranges for smooth, strong and sharp controllers.

TABLE 6

Controller input frequencies for the smooth controller

| Controller Range | Frequency Range | # of available frequencies at 200 Hz sampling | # of available frequencies at 1 kHz sampling |
|---|---|---|---|
| Low | <6.6 Hz | 170 between (1 Hz and 8 Hz) | 850 between (1 Hz and 6.6 Hz) |
| Transition | 6.6–10 Hz | 10 | 50 |
| High | 10–100 Hz | 19 | 90 |

[0065]

TABLE 7

Controller input frequencies for the strong and sharp controllers

| Controller Range | Frequency Range | # of available frequencies at 200 Hz sampling | # of available frequencies at 1 kHz sampling |
|---|---|---|---|
| Low | <10 Hz | 180 between (1 Hz and 10 Hz) | 900 between (1 Hz and 10 Hz |
| Transition | 10–16 Hz | 8 | 37 |
| High | 16–100 Hz | 11 | 52 |

[0066]

TABLE 8

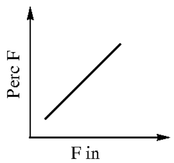
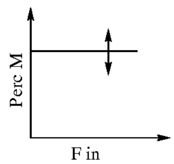
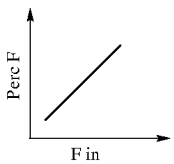
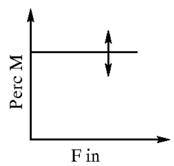
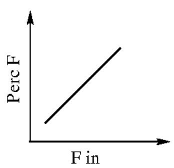
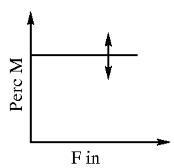
Motor input for various frequency ranges for smooth, strong and sharp controllers

| Controller Range | Frequency Range | Motor input: Smooth | Motor input: Strong | Motor input: Sharp |
|---|---|---|---|---|
| Low | <6.6 Hz Smooth <10 Hz Strong, Sharp | Unidir Pulse @ 6.6 Hz with 50% duty cycle | Unidir Pulse @ 10 Hz with 75% duty cycle | Bidir Pulse @ 10 Hz with 75% duty cycle |
| Transition | 6.6–10 Hz Smooth 10–16 Hz, Strong Sharp | Unidir Pulse at chosen input frequency at 50% duty cycle | Unidir Pulse at chosen input frequency at 75% duty cycle | Bidir Pulse at chosen input frequency at 75% duty cycle |
| High | 10–100 Hz Smooth 16–100 Hz, Strong Sharp | Unidir Pulse at chosen input frequency and duty cycle increases from 50% to 100% | Unidir Pulse at chosen input frequency and duty cycle increases from 75% to 100% | Bidir Pulse at chosen input frequency and duty cycle increases from 75% to 100% |

[0067]

TABLE 9

Desired perceived frequency and perceived magnitude for various frequency ranges for smooth, strong and sharp controllers

| Controller Range | Frequency Range | Desired Perceived Frequency | Desired Perceived Magnitude | Comments |
|---|---|---|---|---|
| Low | <6.6 Hz Smooth <10 Hz Strong, Sharp |  |  | Controller input frequency matches, actual and perceived output frequency. Perceived magnitude is variable with PWM |
| Transition | 6.6–10 Hz Smooth 10–16 Hz Strong, Sharp |  |  | Controller input frequency creates actual frequency with envelope. (If continuous spinning, then input frequency does not match output frequency.) Average energy delivered is the same. |
| High | 10–100 Hz Smooth 16–100 Hz, Strong Sharp |  |  | Controller input frequency creates continuous spinning where that does not match output frequency Average energy delivered is increasing. |

[0068]

TABLE 10

Actual acceleration frequency, perceived frequency and perceived magnitude for various frequency ranges for smooth, strong and sharp controllers

| Controller Range | Controller Input Frequency Range | Actual Acceleration frequency | Perceived frequency | Perceived Magnitude |
|---|---|---|---|---|
| Low | <6.6 Hz Smooth <10 Hz Strong, Sharp | Controller input frequency matches, actual. | Controller input frequency matches perceived. | Perceived magnitude is variable with PWM |
| Transition | 6.6–10 Hz Smooth 10–16 Hz Strong, Sharp | Controller input frequency matches envelope frequency. | User perceives envelope frequency | Perceived magnitude is variable with PWM. |
| High | 10–100 Hz Smooth 16–100 Hz, Strong Sharp | Controller input frequency does NOT match actual frequency. | Controller input frequency does NOT match perceived frequency. | As controller input frequency is increased, magnitude is perceived to increase. |

[0069] **FIG. 11** is a diagram of parameters associated with a smooth effect according to an embodiment of the invention. **FIG. 12** is a diagram of parameters associated with a strong effect according to an embodiment of the invention. **FIG. 13** is a diagram of parameters associated with a sharp effect according to an embodiment of the invention.

[0070] A system and method for controlling audio output associated with haptic effects are discussed. Specific embodiments have been described above in connection with separately controlling multiple frequencies, either using a single controller or using multiple controllers, each of the multiple controllers being equally associated with a frequency range. Additionally, other embodiments have been discussed in connection with controlling an audio output associated with a haptic effect in at least one of the frequency ranges. Also, the audio effect can be changed, such that a user senses a change in frequency in the overall effect and perceives that change in a haptic effect; in some cases, this can occur above the frequency range where a user can tactilely detect variations in frequency (e.g., within a diminished-sensitivity region). Thus, as the frequency of the audio effect is increased, the user perceives an increase in a frequency of the haptic effect associated with the audio effect, even where such an increase results in a change in haptic frequencies within the diminished-sensitivity region. Similarly, as the frequency of the audio effect is decreased, the user perceives a decrease in frequency of the corresponding haptic effect, even where such changes result in variations of haptic effect frequencies, which are undetectable to a user (e.g., within the diminished-sensitivity region).

[0071] It will be appreciated, however, that embodiments of the invention can be in other specific forms without departing from the spirit or essential characteristics thereof. For example, while some embodiments have been described in the context of periodic or magnitude sweep control signals for causing haptic effects, any suitable signal can be used. Also, although control signals have been described as square-waves or PWM signals having square-wave-like shapes, other pulse shapes can be used. Additionally, although a specific reference has been made to devices configured to output periodic haptic effect (e.g., rotating haptic devices such spinning mass motors, etc.), any type of haptic device capable of outputting haptic effects associated with an audio output can be used according to one or more embodiments of the invention.

[0072] The presently disclosed embodiments are, therefore, considered in all respects to be illustrative and not restrictive.

What is claimed is:

**1**. A processor-readable medium comprising code representing instructions to cause a processor to:

send a signal configured to cause a haptic effect and an audio effect to be output substantially concurrently, the haptic effect having a frequency and the audio effect having a frequency different from the frequency of the haptic effect, the signal being further configured to vary at least one of the frequency of the haptic effect and the frequency of the audio effect while maintaining substantially constant an average energy of the haptic effect.

**2**. The processor-readable medium of claim 1, wherein the signal is further configured to cause the frequency of the audio effect to vary while causing the frequency of the haptic effect to remain substantially constant.

**3**. The processor-readable medium of claim 1, wherein the signal includes a plurality of pulses, the signal being configured to cause a frequency of the plurality of pulses to vary while causing a magnitude of the plurality of pulses to vary inversely.

**4**. The processor-readable medium of claim 1, the frequency of the haptic effect being a first frequency of the haptic effect, wherein the audio effect is configured to cause a user to perceive the haptic effect as having a second frequency different from the first frequency of the haptic effect.

**5**. The processor-readable medium of claim 1, the frequency of the haptic effect being a first frequency of the haptic effect, wherein the audio effect is configured to cause a user to perceive the haptic effect as having a second frequency different from the first frequency of the haptic effect, the second frequency being higher than the first frequency.

**6**. The processor-readable medium of claim 1, wherein the frequency of the audio effect is higher than the frequency of the haptic effect.

**7**. The processor-readable medium of claim 1, wherein the haptic effect has a frequency from a frequency range from a plurality of frequency ranges, each frequency range from the plurality of frequency ranges being uniquely associated with a control scheme.

**8**. An apparatus, comprising:

a controller configured to output a control signal, the control signal being configured to cause a haptic effect and an audio effect to be output substantially concurrently, the haptic effect having a frequency and the audio effect having a frequency different from the frequency of the haptic effect, the control signal being further configured to vary at least one of the frequency of the haptic effect and the frequency of the audio effect while maintaining substantially constant an average energy of the haptic effect; and

an interface component coupled to the controller and configured to be coupled to a component external to the controller, the interface component configured to provide a haptic instruction to the component based at least partially on the control signal.

**9**. The apparatus of claim 8, wherein the control signal is further configured to cause the frequency of the audio effect to vary while causing the frequency of the haptic effect to remain substantially constant.

**10**. The apparatus of claim 8, wherein the control signal includes a plurality of pulses, the controller being configured to cause a frequency of the plurality of pulses to vary while causing a magnitude of the plurality of pulses to vary inversely.

**11**. The apparatus of claim 8, wherein the audio effect is configured to cause a user to perceive the haptic effect as having a perceived frequency different from the frequency of the haptic effect.

**12**. The apparatus of claim 8, wherein the audio effect is configured to cause a user to perceive the haptic effect as having a perceived frequency different from the frequency of the haptic effect, the perceived frequency being higher than the frequency of the haptic effect.

**13**. The apparatus of claim 8, wherein the control signal is configured to cause a plurality of haptic effects including the haptic effect, each of the plurality of haptic effects having a frequency within at least two frequency ranges from a plurality of frequency ranges, the control signal being configured to cause the haptic effect to be output having a frequency in an intermediate frequency range from the plurality of frequency ranges, the intermediate frequency range being between the at least two frequency ranges.

**14**. The apparatus of claim 8, further comprising:

a haptic device coupled to the controller, the haptic device being configured to receive the control signal and to output the haptic effect and the audio effect.

**15**. The apparatus of claim 8, further comprising:

a haptic device coupled to the controller, the haptic device including an actuator, the haptic device being configured to receive the control signal and to output the haptic effect and the audio effect via the actuator.

**16**. The apparatus of claim 8, further comprising:

a haptic device coupled to the controller, the haptic device including a actuator and an audio output device substantially collocated with the actuator and to receive the control signal, the haptic device being configured to output the haptic effect via the actuator, the haptic device being configured to output the audio effect via the audio output device.

**17**. The apparatus of claim 8, further comprising:

a plurality of controllers including the controller, each controller from the plurality of controllers being associated with a frequency range from a plurality of frequency ranges, each controller from the plurality of controllers being configured to output an associated control signal, the associated control signal output by each controller from the plurality of controllers being configured to cause a haptic effect to be output having a frequency within the frequency range associated with that controller, at least one controller from the plurality of controllers being configured to output the control signal configured to cause the haptic effect and the audio effect to be output substantially concurrently.

**18**. The apparatus of claim 8, further comprising:

a resonant vibrotactile haptic device coupled to the controller, the resonant vibrotactile haptic device being configured to output the haptic effect having a frequency within a pre-determined operational frequency range, the pre-determined operational frequency range having a frequency associated with a resonant mode of the resonant vibrotactile haptic device.

**19**. The apparatus of claim 8, wherein the control signal includes a plurality of pulses, the control signal being configured to cause the haptic effect to be output at a desired output frequency, each pulse from the plurality of pulses having a width associated with the desired output frequency.

**20**. The apparatus of claim 8, further comprising:

a plurality of controllers including the controller, each controller from the plurality of controllers being configured to output a control signal from a plurality of control signals, each control signal from the plurality of control signals being uniquely associated with a frequency range from a plurality of frequency ranges and being configured to cause a haptic effect to be output, a first control signal from the plurality of control signals being output by a first controller, the first control signal being configured to cause the haptic effect to be output substantially concurrently with the audio effect, the audio effect being configured to cause a user to perceive the haptic effect as having a perceived frequency different from the frequency of the haptic effect.

**21**. The apparatus of claim 8, further comprising:

a plurality of controllers including the controller, each controller from the plurality of controllers being configured to output a control signal from a plurality of control signals, each control signal from the plurality of control signals being uniquely associated with a frequency range from a plurality of frequency ranges and being configured to cause a haptic effect to be output, a first control signal from the plurality of control signals being output by a first controller, the first control signal being configured to cause the haptic effect to be output substantially concurrently with the audio effect, the audio effect being configured to cause a user to perceive the haptic effect as having a perceived frequency different from the frequency of the haptic effect; and

a haptic device coupled to the plurality of controllers, the haptic device being configured to output a plurality of haptic effects associated with the plurality of control signals, the plurality of haptic effects including the haptic effect.

**22**. The apparatus of claim 8, further comprising:

a plurality of controllers including the controller, each controller from the plurality of controllers being configured to output a control signal from a plurality of control signals, each control signal from the plurality of control signals being uniquely associated with a frequency range from a plurality of frequency ranges and being configured to cause a haptic effect to be output, a first control signal from the plurality of control signals being output by a first controller, the first control signal being configured to cause the haptic effect to be output substantially concurrently with the audio effect, the audio effect being configured to cause a user to perceive the haptic effect as having a perceived frequency different from the frequency of the haptic effect; and

a plurality of haptic devices, each haptic device from the plurality of haptic devices being uniquely associated with a controller from the plurality of controllers, each haptic device from the plurality of haptic devices being configured to output the haptic effect caused by the control signal output by the associated controller.

**23**. A method, comprising:

outputting a haptic effect at least partially based on a control instruction; and

outputting an audio effect substantially concurrently with a haptic effect at least partially based on the control instruction, the haptic effect having a frequency, the audio effect having a frequency different from the frequency of the haptic effect, the audio effect and the haptic effect being output by a common device;

varying the frequency of at least one of the frequency of the haptic effect and the frequency of the audio effect while maintaining substantially constant an average energy of the haptic effect.

**24**. The method of claim 23, wherein the frequency of the audio effect is varied while the frequency of the haptic effect is maintained substantially constant.

**25**. The method of claim 23, wherein outputting the haptic effect includes:

varying a frequency of pulses configured to cause the haptic effect to be output while inversely varying a magnitude of the pulses configured to output the haptic effect.

**26**. The method of claim 23, wherein the audio effect is configured to cause a user to perceive the haptic effect as having a perceived frequency different from the frequency of the haptic effect.

**27**. The method of claim 23, wherein the audio effect is configured to cause a user to perceive the haptic effect as having a perceived frequency different from the frequency of the haptic effect, the perceived frequency of the haptic effect being higher than the frequency of the haptic effect.

**28**. The method of claim 23, further comprising:

outputting a plurality of haptic effects, the plurality of haptic effects including the haptic effect, each haptic effect from the plurality of haptic effects having a different corresponding frequency, each corresponding frequency being within a frequency range from a plurality of frequency ranges.

**29**. A method, comprising:

receiving an output instruction; and

outputting a control signal based on the received output instruction, the control signal being configured to cause a haptic effect and an audio effect to be output substantially concurrently, the haptic effect having a frequency and the audio effect having a frequency different from the frequency of the haptic effect, the control signal being configured to vary at least one of the frequency of the haptic effect and the frequency of the audio effect while maintaining substantially constant an average energy of the haptic effect.

**30**. The method of claim 29, wherein the control signal is configured to cause the frequency of the audio effect to vary while causing the frequency of the haptic effect to remain substantially constant.

**31**. The method of claim 29, wherein the control signal includes a plurality of pulses, configured to cause a frequency of the plurality of pulses to vary while causing a magnitude of the plurality of pulses to vary inversely.

**32**. The method of claim 29, wherein the control signal is configured to cause a user to perceive the haptic effect as having a perceived frequency different from the frequency of the haptic effect.

**33**. The method of claim 29, wherein the control signal is configured to cause a user to perceive the haptic effect as having a perceived frequency different from the frequency of the haptic effect, the perceived frequency of the haptic effect being higher than the frequency of the haptic effect.

**34**. The method of claim 29, further comprising:

outputting a plurality of control signals including the control signal, the plurality of control signals being at least partially based on the received output instruction, each control signal from the plurality of control signals being uniquely associated with a frequency range from a plurality of frequency ranges, at least one control signal from the plurality of control signals being configured to cause the haptic effect.

**35**. The method of **29**, wherein the control signal is configured to output the haptic effect and the audio effect via an actuator of a haptic device.

**36**. The method of **29**, wherein the control signal is configured to output the haptic effect via an actuator of a haptic device, the control signal being configured to cause the audio effect to be output by an audio output device of the haptic device, the audio output device being substantially collocated with the actuator.

**37**. A method, comprising:

receiving an output instruction; and

outputting a control signal based on the received output instruction, the control signal being configured to cause a haptic effect and an audio effect to be output substantially concurrently via an actuator of a haptic device, the haptic effect having a frequency and the audio effect having a frequency different from the frequency of the haptic effect, the audio effect being configured to change a perceived frequency of the haptic effect.

* * * * *