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(54) CONTROL KNOB WITH MULTIPLE DEGREES OF FREEDOM AND FORCE FEEDBACK

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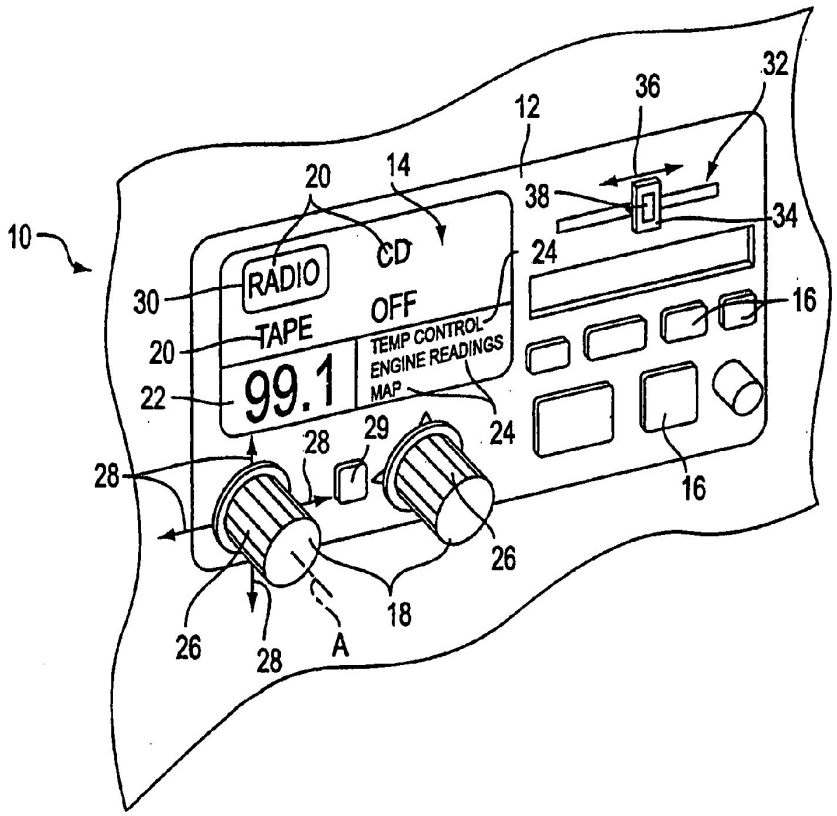
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(57) **ABSTRACT**

The present invention provides a control knob on a device that allows a user to control functions of the device. In one embodiment, the knob is rotatable in a rotary degree of freedom and moveable in at least one transverse direction approximately perpendicular to the axis. An actuator is coupled to the knob to output a force in the rotary degree of freedom about the axis, thus providing force feedback. In a different embodiment, the knob is provided with force feedback in a rotary degree of freedom about an axis and is also moveable in a linear degree of freedom approximately parallel to the axis, allowing the knob to be pushed and/or pulled by the user. The device controlled by the knob can be a variety of types of devices, such as an audio device, video device, etc. The device can also include a display providing an image updated in response to manipulation of the knob. Detent forces can be provided for the knob by overlapping and adjusting ranges of closely-spaced detents in the rotary degree of freedom of the knob.



Valve Exhibit 1006
Valve v. Immersion

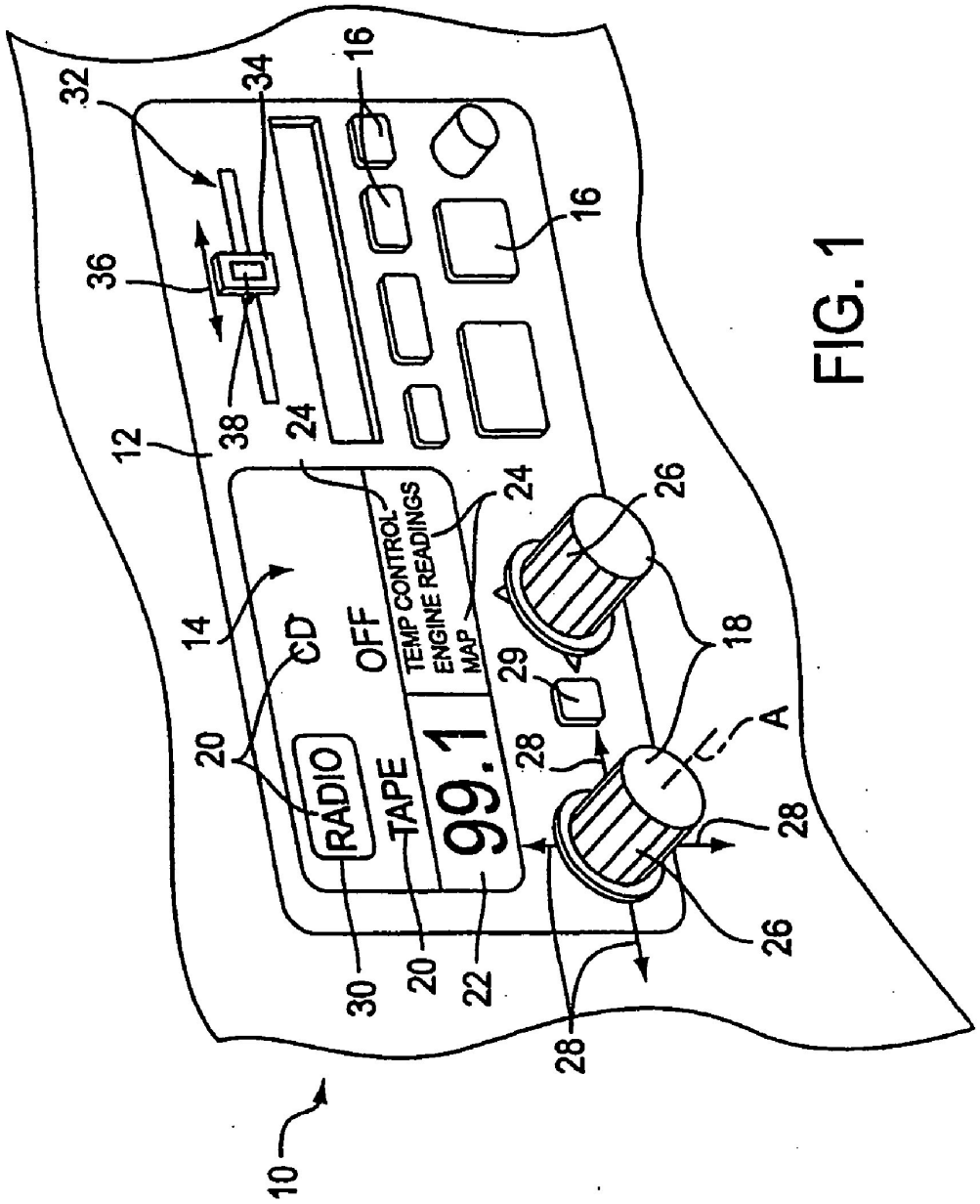

32
34
16
36
16
12
38
24
24
26
14
CD
OFF
TEMP CONTROL
ENGINE READINGS
MAP
29
18
20
RADIO
TAPE
99.1
28
A
28
26
30
20
22
28
10

FIG. 1

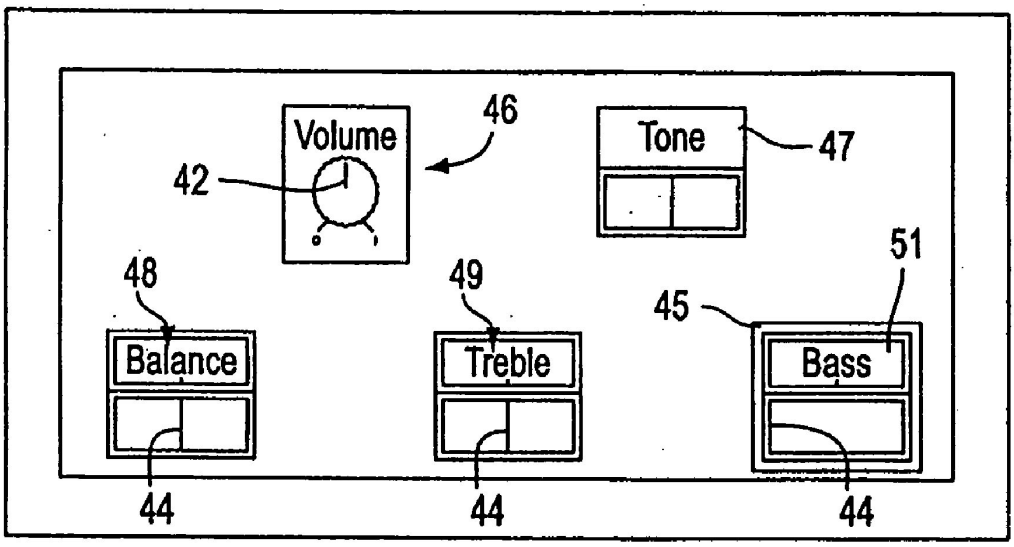


FIG. 2

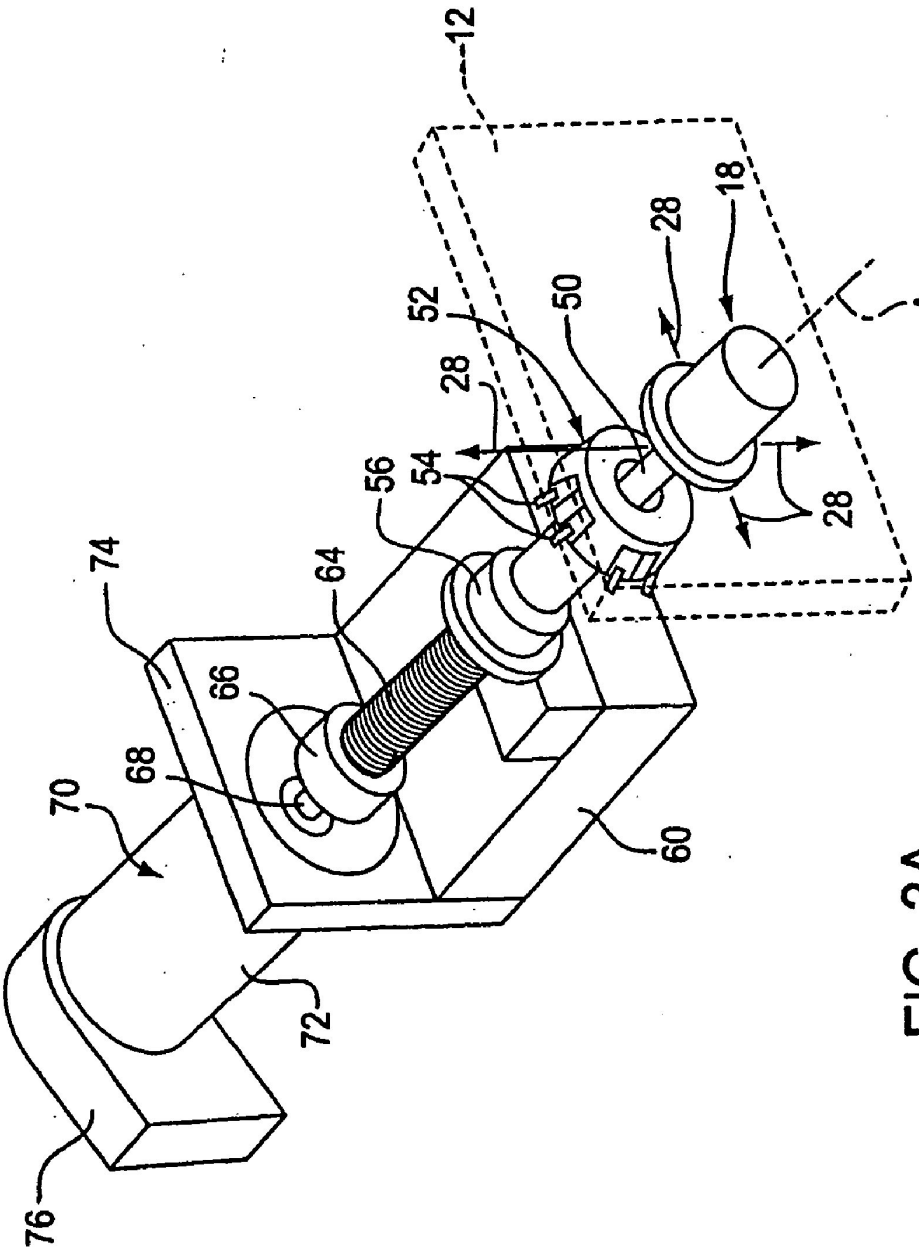


FIG. 3A

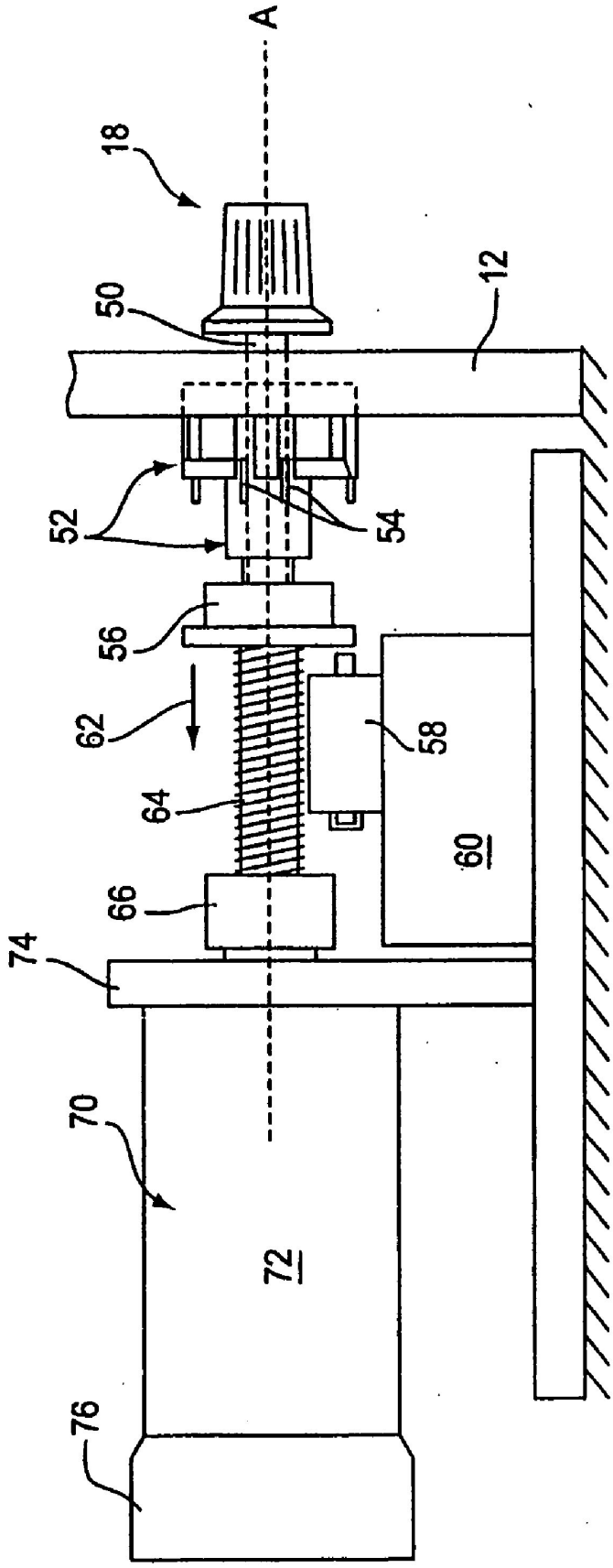


FIG. 3B

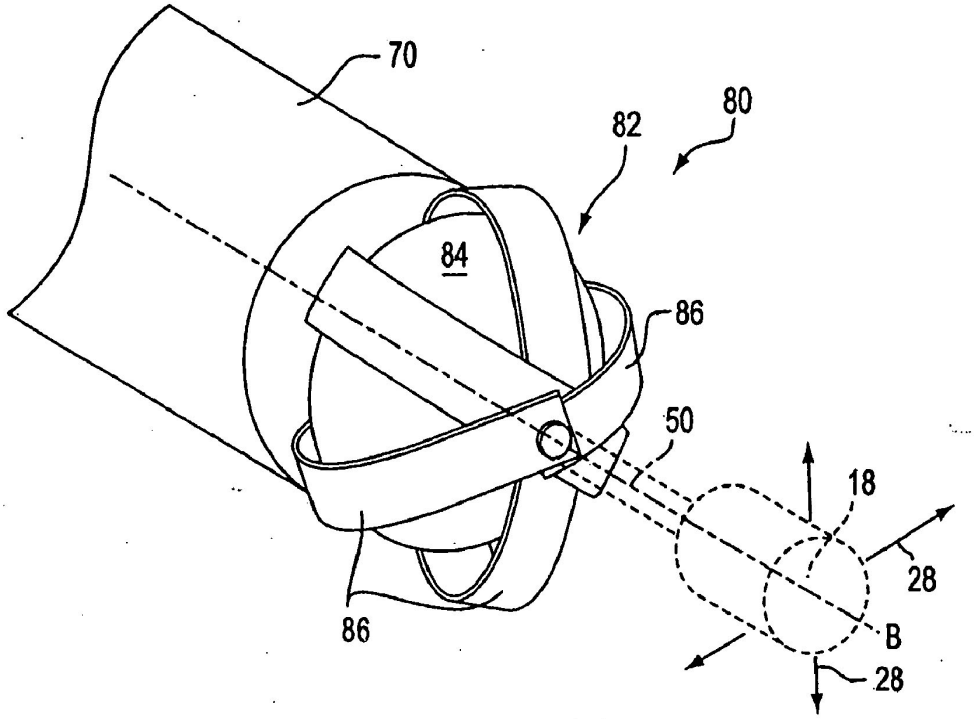


FIG. 4A

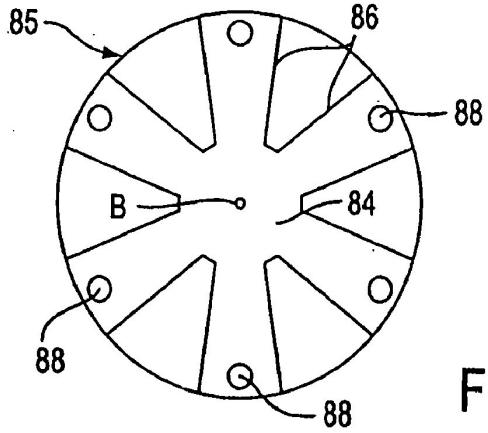


FIG. 4B

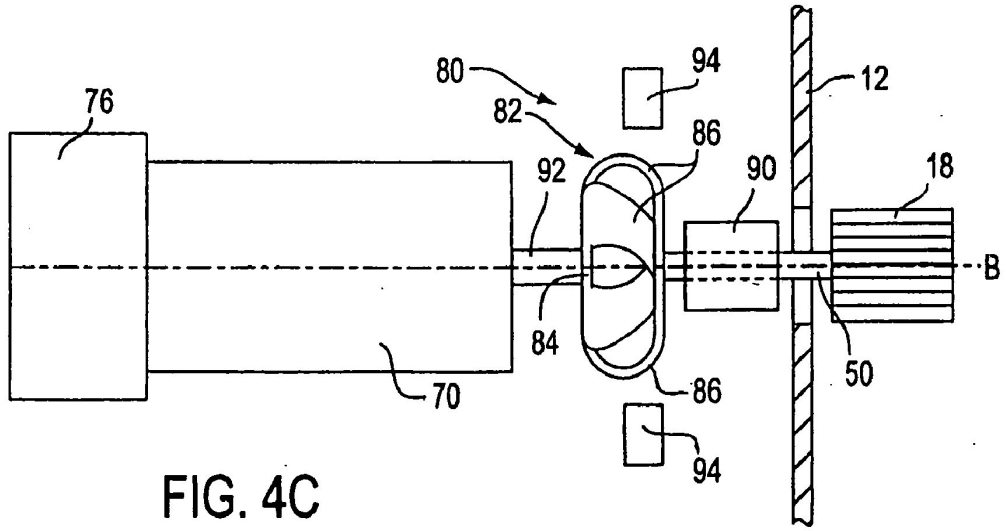


FIG. 4C

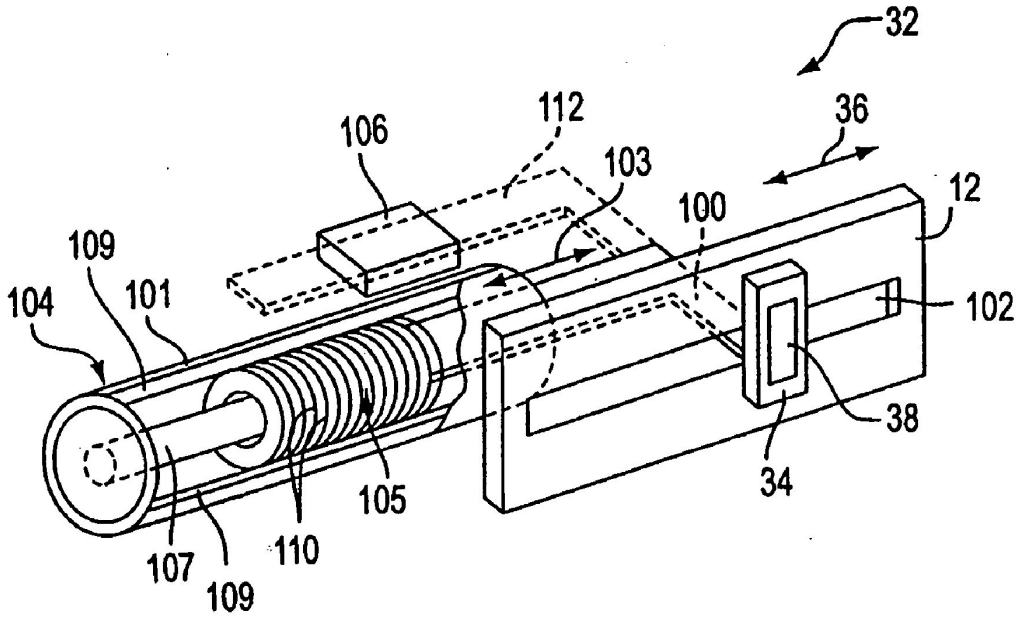


FIG. 5

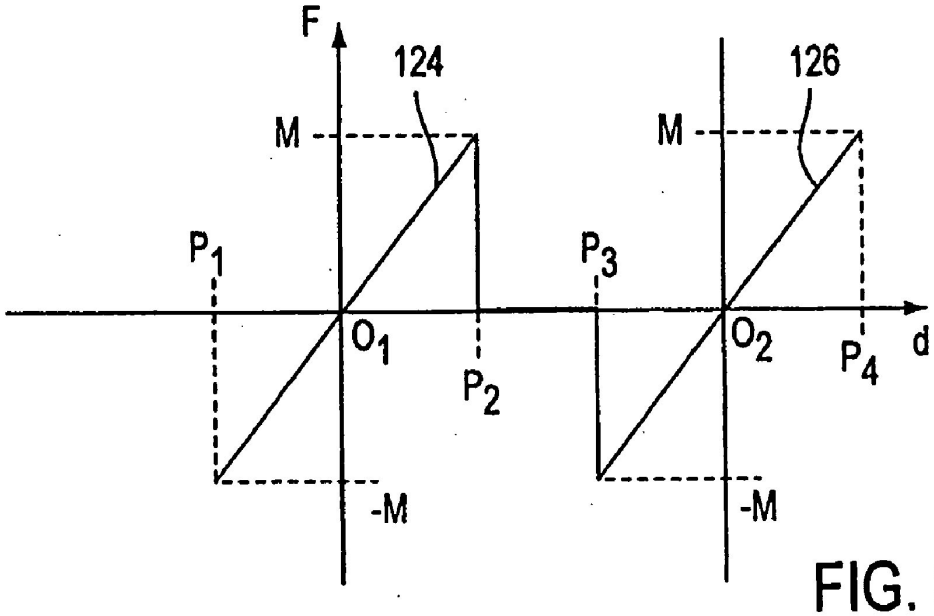

F
124
126
M
M
P1
P3
O1
O2
P2
P4
d
-M
-M

FIG. 6A

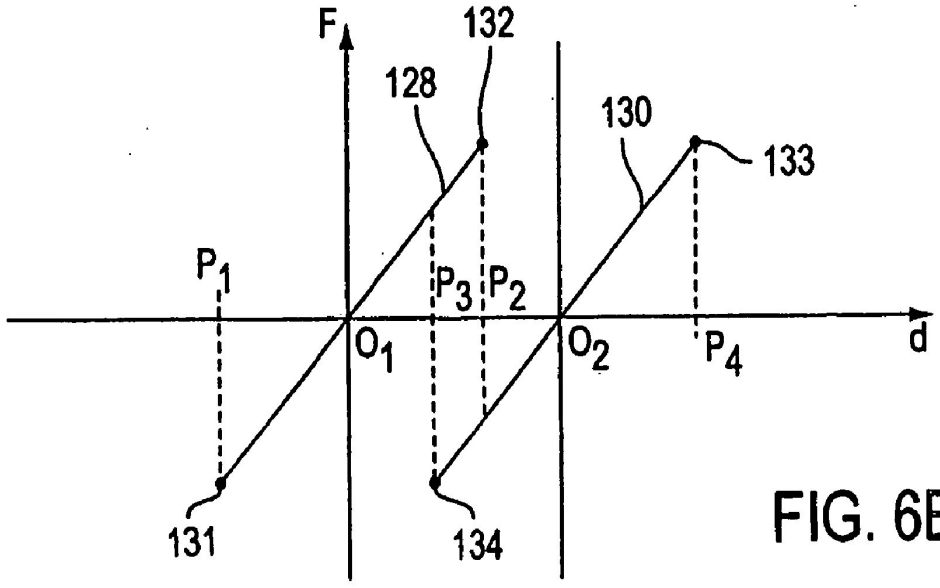

F
132
128
130
133
P1
P3
P2
O1
O2
P4
d
131
134

FIG. 6B

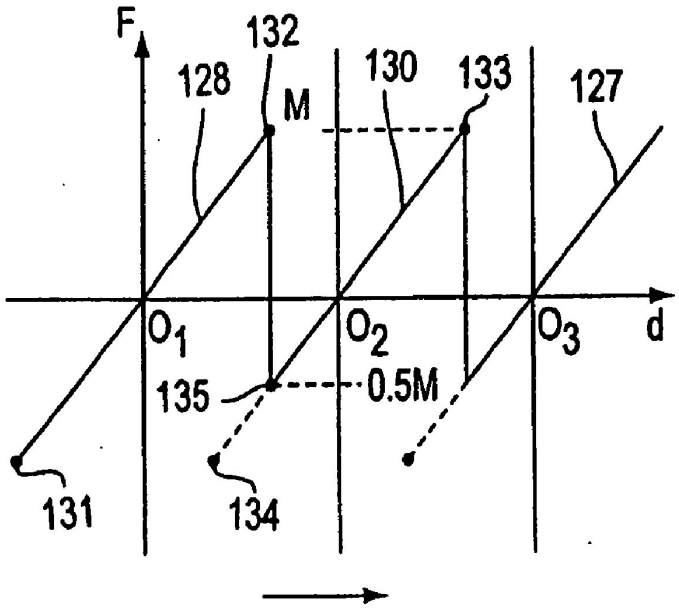

F
132
128
M
130
133
127
O1
O2
O3
d
135
0.5M
131
134

FIG. 6C

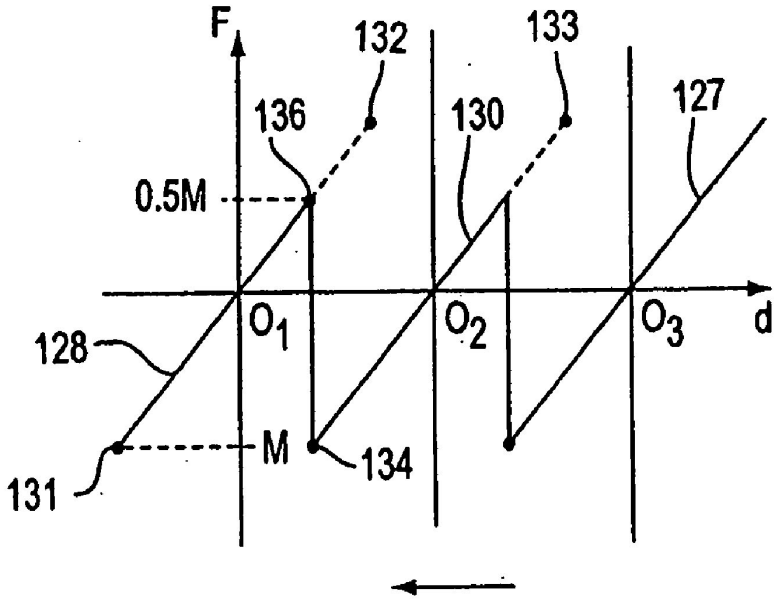

F
132
133
136
130
127
0.5M
O1
O2
O3
d
128
M
131
134

FIG. 6D

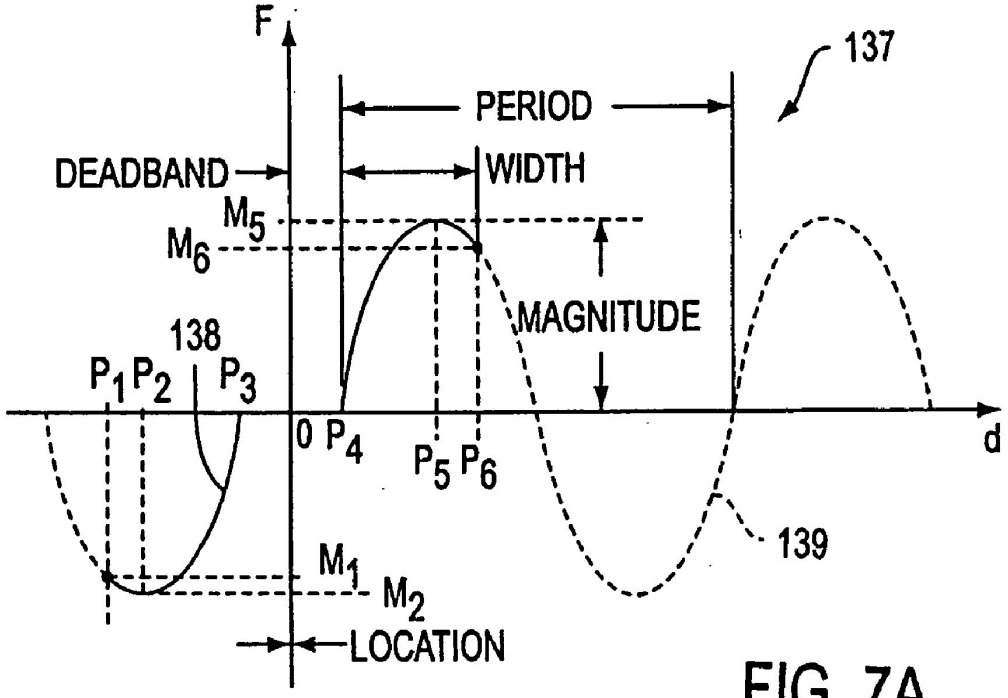

F
137
PERIOD
DEADBAND
WIDTH
M5
M6
MAGNITUDE
138
P1 P2 P3
0 P4
P5 P6
d
139
M1
M2
LOCATION

FIG. 7A

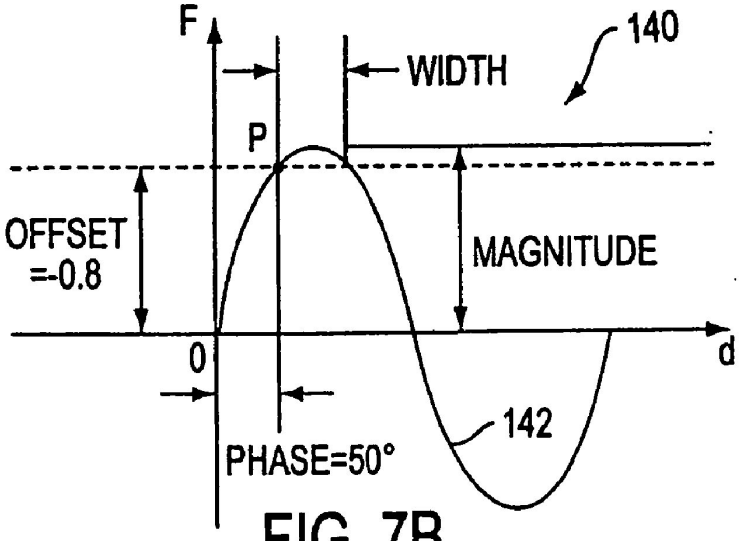

F
140
WIDTH
P
OFFSET
=-0.8
MAGNITUDE
0
d
142
PHASE=50°

FIG. 7B

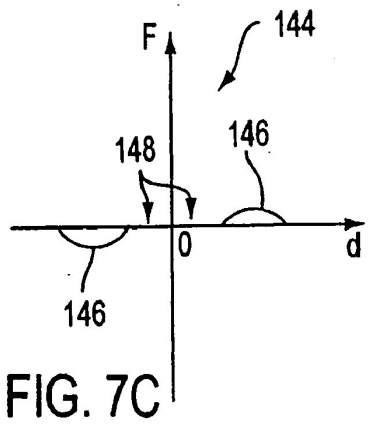


FIG. 7C

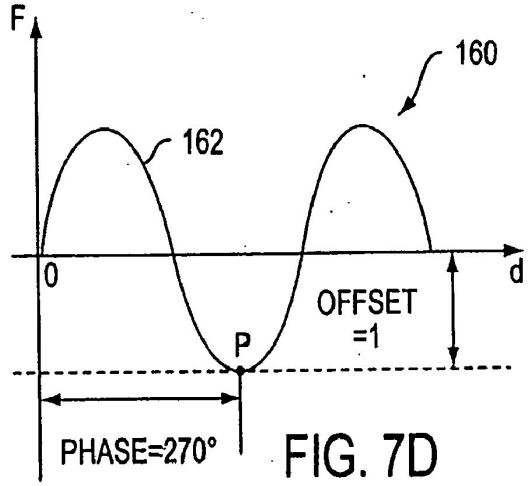


FIG. 7D

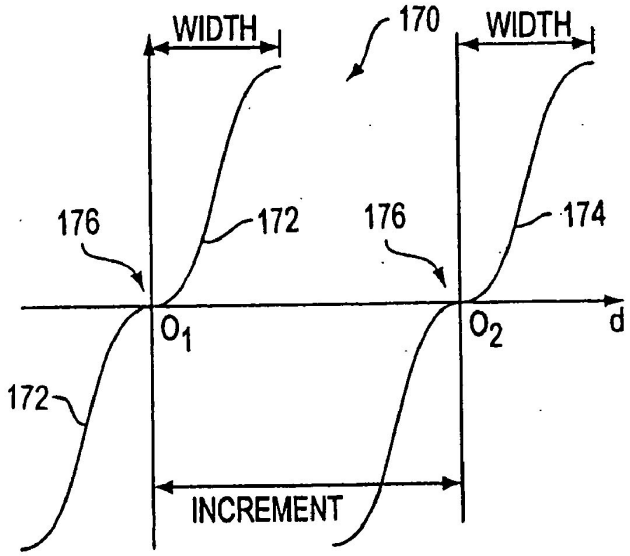


FIG. 7E

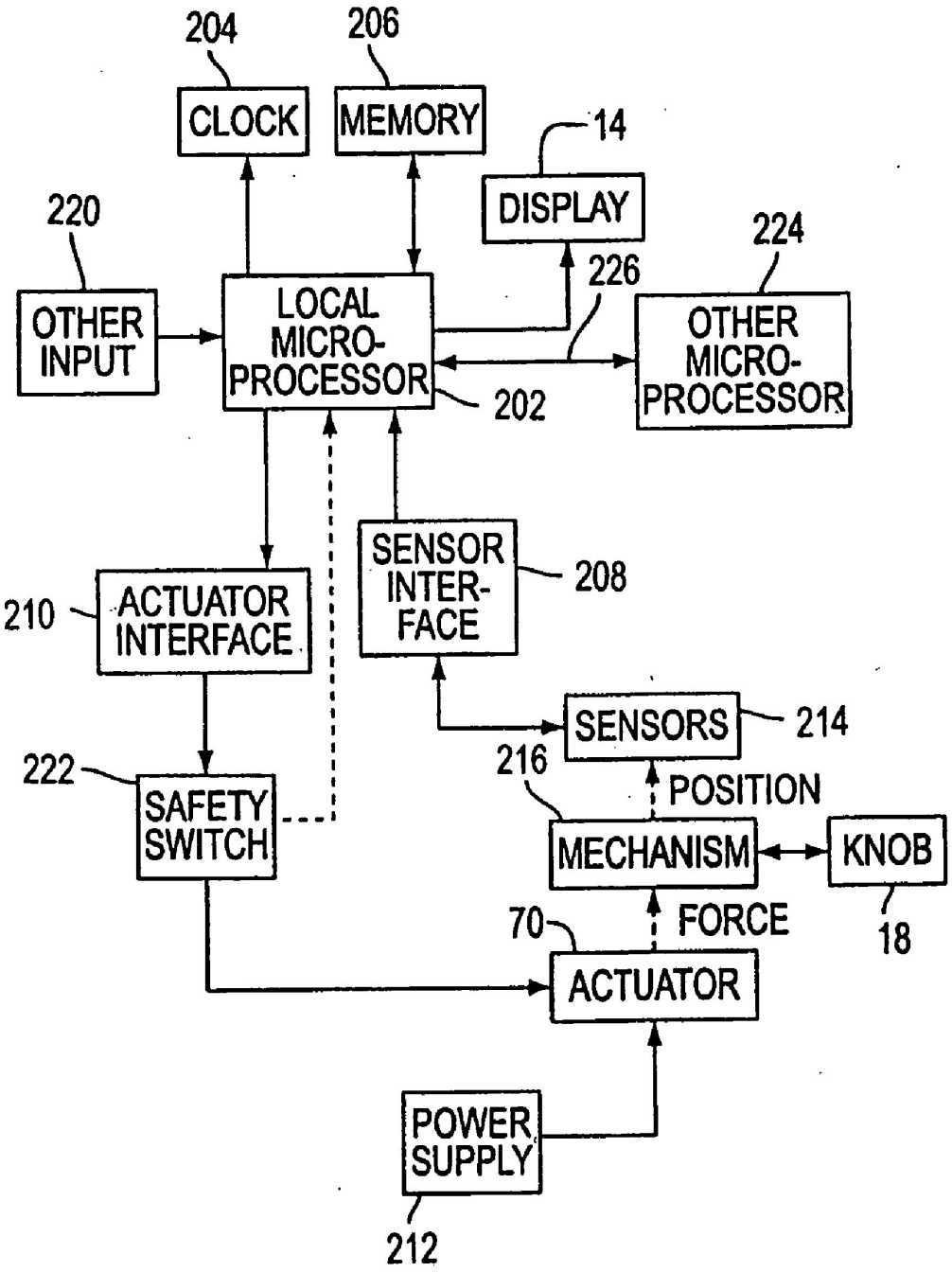

204
206
CLOCK
MEMORY
14
DISPLAY
220
224
226
OTHER INPUT
LOCAL MICRO-PROCESSOR
OTHER MICRO-PROCESSOR
202
SENSOR INTER-FACE
208
210
ACTUATOR INTERFACE
SENSORS
214
216
222
POSITION
SAFETY SWITCH
MECHANISM
KNOB
18
70
FORCE
ACTUATOR
POWER SUPPLY
212

FIG. 8

CONTROL KNOB WITH MULTIPLE DEGREES OF FREEDOM AND FORCE FEEDBACK

CROSS-REFERENCES TO RELATED APPLICATION

[0001] This application is a continuation of co-pending patent application Ser. No. 10/712,199, filed Nov. 13, 2003, entitled "Control Knob with Multiple Degrees of Freedom and Force Feedback", which is a continuation of co-pending patent application Ser. No. 09/680,408, filed Oct. 2, 2000, entitled "Control Knob with Control Modes and Force Feedback", which is a continuation-in-part of co-pending parent patent application Ser. No. 09/049,155, filed Mar. 26, 1998, entitled, "Force Feedback Mouse Wheel," and Ser. No. 09/087,022, filed May 29, 1998, entitled, "Force Feedback Interface Having Isotonic and Isometric Functionality", which is a divisional application of U.S. Pat. No. 5,825,308, filed Nov. 26, 1996, all assigned to the assignee of the present application, and all of which are incorporated herein by reference.

BACKGROUND

[0002] This invention relates generally to knob control devices, and more particularly to control knob devices including force feedback and additional input functionality.

[0003] Control knobs are used for a variety of different functions on many different types of devices. Often, rotary control knobs offer a degree of control to a user that is not matched in other forms of control devices, such as button or switch controls. For example, many users prefer to use a rotating control knob to adjust the volume of audio output from a stereo or other sound output device, since the knob allows both fine and coarse adjustment of volume with relative ease, especially compared to button controls. Both rotary and linear (slider) knobs are used on a variety of other types of devices, such as kitchen and other home appliances, video editing/playback devices, remote controls, televisions, etc. Some control knobs have been provided with "force feedback." Force feedback devices can provide physical sensations to the user manipulating the knob. Typically, a motor is coupled to the knob and is connected to a controller such as a microprocessor. The microprocessor receives sensor signals from the knob and sends appropriate force feedback control signals to the motor so that the motor provides forces on the knob. In this manner, a variety of programmable feel sensations can be output on the knob, such as detents, spring forces, or the like.

[0004] One problem occurring in control knobs of the prior art is that the knobs are limited to basic rotary motion. This limits the control options of the user to a simple, one-degree-of-freedom device that does not allow a variety of selection options. In additions if force feedback is provided on the knob, the limited control functionality of the knob limits the user from fully taking advantage of the force feedback to provide more control over desired functions.

SUMMARY

[0005] The present invention provides a knob control interface that allows a user to control functions of a device in a variety of ways. Embodiments of the knob controller include additional degrees of freedom for the knob and force feedback applied to the knob.

[0006] More particularly, in one embodiment a knob controller device of the present invention includes a knob coupled to a grounded surface. The knob is rotatable in a rotary degree of freedom about an axis extending through the knob, and the knob also moveable in a transverse direction approximately perpendicular to the axis. A rotational sensor detects a position of the knob in the rotary degree of freedom, and a transverse sensor detects a position of the knob in the transverse direction. An actuator is coupled to the knob to output a force in the rotary degree of freedom about the axis, thus providing force feedback. In a preferred embodiment, the knob is moveable in multiple transverse directions. For example, the transverse sensor includes a switch that detects when the knob is moved in a transverse direction; the switch can be a hat switch halving multiple individual switches, for example. In one embodiment, the knob is moveable in four transverse directions spaced approximately orthogonal to each other.

[0007] Furthermore, a local microprocessor can be included to control the force feedback on the knob. The microprocessor receives sensor signals from the rotary and transverse sensors and controls a function of a device in response to the sensor signals. The device can be any of a variety of electrical or electronic types of devices. The device can also include a display, wherein an image on said display is changed in response to manipulation of the knob in the transverse direction. A method of the present invention for controlling functions of a device from input provided by a knob similarly uses sensor signals from a rotary sensor and a transverse sensor to control at least one function of a device, such as adjusting a frequency of a radio tuner or updating a displayed image based on at least one of the sensor signals.

[0008] In another aspect of the present invention, a knob is coupled to a grounded surface, where the knob is rotatable in a rotary degree of freedom about an axis extending through the knob. The knob is also moveable in a linear degree of freedom approximately parallel to the axis. A rotational sensor and a linear sensor detect positions of the knob in the respective degrees of freedom. An actuator is also coupled to the knob and operative to output a force in the rotary degree of freedom about the axis, thereby providing force feedback to the knob. The linear degree of freedom of the knob allows it to be pushed and/or pulled by the user, where the push or pull motion is detected by the linear sensor. A spring member is preferably included for biasing the knob to a center position in the linear degree of freedom. The linear sensor can, for example, include a grounded switch that is contacted by a pusher member coupled to the knob when the knob is moved in the linear degree of freedom. Alternatively, the linear sensor can detect a position of the knob within a detectable continuous range of motion of the knob. The transverse degree of freedom of the previous embodiment of the knob can also be included. A microprocessor preferably receives the sensor signals and controls a function of a device in response to the sensor signals, and also sends force feedback signals to the actuator to control forces output by the actuator.

[0009] In a different aspect of the present invention, a method for providing detent forces for a force feedback control includes outputting a first force by an actuator on a user manipulatable object, such as a rotary knob, for a first detent when the user object is moved within a range of the

first detent. The first force assists movement of the user object toward an origin position of the first detent and resists movement away from the origin position. A second force for a second detent is also output on the user object when the user object is moved within a range of the second detent, similar to the first force. A portion of the range of the first detent overlaps a portion of the range of the second detent. The overlapped portions of the ranges preferably modifies the second force such that a force at the beginning point of the second detent range has less magnitude than a force at an endpoint of the second detent range. Preferably, the first force and second force each have a magnitude that increases the further that the user object is positioned from that detent's origin. Preferably, the direction of the knob changes the range endpoint magnitudes Such that if the knob is moved in the opposite direction, the first-encountered point of the first detent range has a lesser magnitude than the last-encountered point.

[0010] In another aspect of the present invention, a method for providing detent forces for a force feedback control includes defining a periodic wave and using at least a portion of the periodic wave to define a detent force curve. The detent force curve defines a force to be output on a user manipulatable object, such as a rotary knob, based on a position of the user manipulatable object in a degree of freedom. The detent force curve is then used to command the force on the user manipulatable object as output by an actuator. The type, period and magnitude can be specified for the periodic wave. The detent force curve can be defined by specifying a portion of said periodic wave to be the width of the detent force curve, specifying a phase and an offset to be applied to said periodic wave to define the detent force curve, and/or specifying an increment distance between successive detents.

[0011] The apparatus and method of the present invention provide a control knob for a device that includes greater control functionality for the user. The lineal and transverse degrees of freedom of the knob allow the user to select functions, settings, modes, or options with much greater case and without having to take his or her hand off the knob. Force feedback may also be added to the knob to provide the user with greater control and to inform the user of options and selections through the sense of touch. Force feedback detent implementations of the present invention provide overlapping detent ranges to allow more accurate control of a knob by a user within closely-spaced detents, and an efficient, convenient method for defining detents from periodic waves.

[0012] These and other advantages of the present invention will become apparent to those skilled in the art upon a reading of the following specification of the invention and a study of the several figures of the drawing.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] FIG. **1** is a perspective view of one embodiment of a device including a control knob of the present invention;

[0014] FIG. **2** is a diagrammatic view of a display allowing the user to use the knob of the present invention to select features of the device;

[0015] FIG. **3***a* is a perspective view of one embodiment of the mechanism for implementing the control knob of the present invention;

[0016] FIG. **3***b* is a side elevational view of the embodiment of FIG. **3***a;*

[0017] FIG. **4***a* is a perspective view of a second embodiment of the mechanism for implementing the control knob of the present invention;

[0018] FIG. **4***b* is a top plan view of a unitary plate used in the embodiment of FIG. **4***a;*

[0019] FIG. **4***c* is a side elevational view of the embodiment of FIG. **4***a;*

[0020] FIG. **5** is a perspective view of a linear slider control of the present invention;

[0021] FIGS. **6***a*-**6***d* illustrate nonoverlapping, overlapping, and hysteresis features of force detent profiles;

[0022] FIGS. **7***a*-**7***e* are graphs illustrating the creation of detent force profiles from periodic waves according to the present invention; and

[0023] FIG. **8** is a block diagram of a control system for the control knob of the present invention.

DETAILED DESCRIPTION

[0024] FIG. **1** is a perspective view of an example of a control panel **12** for a device **10** including a control knob of the present invention. In the described embodiment, device **10** is an audio device that controls the output of sound, such as music or speech, from speakers that are connected to the device **10**. For example, a common embodiment of device **10** is a stereo system that includes the ability to play sound from one or more media or signals, such as cassette tapes, digital audio transmission (DAT) tapes, compact discs (CD's) or other optical discs, or radio signals transmitted through the air from a broadcasting station.

[0025] The device **10** can also include additional or other functionality not related to audio control and output. For example, many vehicles include electronic systems to control the temperature in the vehicle cabin (air conditioning, heat, etc.), as well as systems to provide information on the current operating characteristics of the vehicle, such as current speed, engine temperature, fuel or other fluid levels, whether windows of the vehicle are open, etc. Other systems may include a navigation system that displays a map and the current location of the vehicle with respect to the map, a cellular telephone or other portable telephone control system, and a security/alarm system. Device **10** can include the ability to display information from and/or influence such other systems in a vehicle or other environment, such as a house, office, etc.

[0026] Alternatively, device **10** can be a variety of other electronic or computer devices. For example, device **10** can be a home appliance such as a television set, a microwave oven or other kitchen appliances, a washer or dryer, a home stereo component or system, a home computer, a set top box for a television, a video game console, a remote control for any device, a controller or interface device for a personal computer or console games, a home automation system (to control such devices as lights, garage doors, locks, appliances, etc.), a telephone, photocopier, control device for remotely-controlled devices such as model vehicles, toys, a video or Film editing or playback system, etc. Device **10** can be physically coupled to the control panel **12**, or the panel

12 can be physically remote from the device **10** and communicate with the device using signals transferred through wires, cables, wireless transmitter/receiver, etc.

[**0027**] Device **10** preferably includes a front panel **12**, a display **14**, several control buttons **16**, and one or more control knobs **18** of the present invention. Front panel **12** can be mounted, for example, on the interior of a vehicle, such as on or below the dashboard, or in some other convenient area. Alternatively, the front panel **12** can be the surface of the external housing of the device **10** itself, such as a stereo unit. The device **10** may include several functions, such as playing an audio track, adjusting volume, tone, or balance of an audio output, displaying all image (icons, a map, etc.), or adjusting the temperature or fan speed in a vehicle, which can be changed or set by the user manipulating the controls of the device **10** on front panel **12**.

[**0028**] Display **14** is provided to show information to the user regarding the controlled device or system and/or other systems connected to the device **10**. For example, options **20** can be displayed to indicate which function of the device **10** is currently selected. Such options can include "radio,""tape, ""CD," or power, as shown. Other information, such as the current radio frequency **22** selected for a radio tuner, can also be displayed. Furthermore, any information related to additional functionality of the device **10** can also be displayed. For example, information **24** can be provided to allow the user to select one or more functions not related to the audio operation of the device **10**. In some embodiments, a map or similar graphical display can be shown on display **14** of all device **10** to allow the user to navigate. Some examples of functions displayed by a display **14** are shown with respect to FIG. **2**, below. In other embodiments, display **14** can be a separate monitor displaying a graphical user interface or other graphical environment as controlled by a host computer. Display **14** can be any suitable display device, such as an LED display, LCD display, gas plasma display, CRT, or other device. In some embodiments, display **14** can include a touch-sensitive surface to allow a user to touch displayed images directly on the display **14** to select those images and an associated setting or function.

[**0029**] Control buttons **16** are often provided on device **10** to allow the user to select different functions or settings of the device. For example, on an audio device, buttons **16** can include radio station preset buttons, rewind/fast forward tape functions, power, speaker loudness, etc. Virtually any function of the device can be assigned to buttons **16**. The buttons **16** may also be used in conjunction with the control knobs **18**, as described below.

[**0030**] Control knobs **18** are provided to allow the user a different type of control of functions and settings of device 1I than the buttons **16** allow. Knobs **18**, in the described embodiment, are approximately cylindrical objects engageable by the user. The knobs **18** can alternatively be implemented as a variety of different objects, including conical shapes, spherical shapes, dials, cubical shapes, rods, etc., and may have a variety of different textures on their circumferential surfaces, including bumps, lines, or other gripe, or even projections or members extending from the circumferential surface. In addition, any of variety of differently-sized knobs can be provided; for example, if high-magnitude forces are output, a larger-diameter cylindrical knob is often easier for a user to interface with device **10**. In the described embodiment, each knob **18** rotates in a single rotary degree of freedom about an axis extending out of the knob, such as axis A. The user preferably grips or contacts the circumferential surface **26** of the knob **18** and rotates it a desired amount. Force feedback can be provided in this rotary degree of freedom in some embodiments, as described in greater detail with reference to FIGS. **3***a* and **3***b*.

[**0031**] Furthermore, the control knobs **18** of the present invention allow additional control functionality for the user. The knobs **18** are preferably able to be moved by the user in one or more directions approximately perpendicular to the axis A of rotation, e.g. parallel to the surface of the front panel **12** as shown in FIG. **1** ("transverse motion" or "transverse direction"). This transverse motion is indicated by arrows **28**. For example, the knob **18** can be moved in the four orthogonal directions shown, or may be moveable in less or more directions in other embodiments, e.g. only two of the directions shown, or in eight directions spaced at 45 degree intervals about axis A. In one embodiment, each transverse direction of the knob is spring loaded such that, after being moved in a direction **28** and once the user releases or stops exerting sufficient force on the knob, the knob will move back to its centered rest position. In other embodiments, the knob can be provided without such a spring bias so that the knob **18** stays in any position to which it is moved until the user actively moves it to a new position.

[**0032**] This transverse motion of knob **18** can allow the user to select additional settings or functions of the device **10**. In some embodiments, the additional control options provided by knob **18** allow the number of buttons **16** and other controls to be reduced, since the functions normally assigned to these buttons can be assigned to the knob **18**. For example, the user can move a cursor **30** or other visual indicator on display **14** (e.g. pointer, selection box, arrow, or highlighting of selected text/image) to a desired selection on the display. Thus, the cursor **30** can be moved from the "radio" selection shown to the "tape" selection by moving the knob **28** in the down direction as shown in FIG. **1**. Or, the cursor **30** can be moved to the "CD" selection by moving the knob **28** in the direction to the right. If knob **18** is provided with diagonal directions (e.g. at 45 degree intervals), the user can move the cursor **30** from the "radio" selection directly to the "off" selection. The user can similarly move cursor **30** or a different indicator to the other information settings **24**, to the frequency display **22**, or to any other displayed option, setting, or area/region on the display **14**.

[**0033**] Besides such a cursor positioning mode, the transverse motion of knob **28** can also directly control values or magnitudes of settings. For example, the left motion of knob **18** can decrease the radio station frequency value **22**, where the value can (decrease at a predetermined rate if the user continually holds the knob **18** in the left direction. The right motion of the knob **18** can similarly increase the frequency value **22**. In another example, once one of the information settings **24** is selected, a sub menu can be displayed and the directions **28** of knob **18** can adjust air temperature, a timer, a cursor on a displayed map, etc.

[**0034**] Different modes can also be implemented; for example, the default mode allows the user to control cursor **30** using the directions **28** of the knob. Once the cursor is located at a desired setting, such as the frequency value **22**,

the user can switch the mode to allow the directions **28** to control the setting itself, such as adjusting the value **22**. To switch modes, any suitable control can be used. For example, the user can push a button, such as button **29**, to toggle a mode. Alternatively, the user can push or pull the knob **18** to select the mode; this functionality of the present invention is described below. Or, some or all of the directions **28** can be used to select modes; for example, the down direction might switch to "volume" mode to allow the user to rotate the knob to adjust volume; the up direction can switch to "adjust radio frequency" mode, and the left direction can switch to "balance" mode (for adjusting the speaker stereo balance for audio output with rotation of knob **18**).

[**0035**] In addition, the control knobs **18** are preferably able to be pushed and/or pulled in a degree of freedom along axis A (or approximately parallel to axis A). This provides the user with additional ways to select functions or settings without having to remove his or her grip from the knob. For example, in one preferred embodiment, the user can move cursor **30** or other indicator on the display **14** using the directions **28** of the knob **18**; when the cursor has been moved to a desired setting or area on the display, the user can push the knob **18** to select the desired setting, much like a mouse button selects all icon in a graphical user interface of a computer. Or, the push or pull function can be useful to control the modes discussed above, since the user can simply push the knob and rotate or move the knob while it is in the pushed mode, then release or move back the knob to select the other mode. The modes discussed above can also be toggled by pushing or pulling the knob **18**. The push and/or pull functionality of the knob **18** can be provided with a spring return bias, so that the knob returns to its rest position after the use releases the knob. Alternatively, the knob can be implemented to remain at a pushed or pulled position until the user actively moves the knob to a new position.

[**0036**] A slider control **32** of the present invention may also be included in device **10**. Slider control **32** includes a slider knob **34** which is grasped by the user and moved in a linear direction as shown by arrow **36**. In the present invention, slider control **32** preferably includes force feedback functionality. Thus, as the user moves the knob **34**, force sensations such as a spring force, a damping force, jolts, detents, textures, or other forces can be output and felt by the user. Furthermore, the slider knob **34** can include a button **38** which can be pressed by the user similarly to the push knob embodiment discussed above with reference to knob **18**. Alternatively, the knob **34** can be pushed and/or pulled similarly to the knob **18** as described above. Slider control **32** can control any of the various functions, settings, or options of the device **10**. For example, the motion left or right of knob **34** can control the radio frequency **22**, where force detents are output for each station and/or each preset station previously programmed by the user. Or, the cursor **30** can be moved using the slider knob **34**, such that when the cursor reaches a desired setting or selection, the user can push button **38** or push on the knob **34** to select that setting. Other functions such as volume, balance, tone, map functions, temperature functions, or mode selection can also be controlled by the slider control **32**. Slider control is described in greater detail with respect to FIG. **5**.

[**0037**] FIG. **2** is an example showing images which can be displayed on display **14** to assist the user in selecting options with knobs **18** and/or slider control **32**. Display **14** can present icons as shown, in this example for the control of audio output signals from device **10**. Icon **46** is selected to control the volume of the audio output using knob **18**, where the circular pointer **42** can be moved in accordance with the knob **18**. Icon **47** is used to control the frequency of the radio tuner (the current selected frequency can be displayed as well), and the icons **48**, **49**, and **51** are used to control the balance, treble, and bass of the audio, respectively. For example, the indicator **44** can be moved left or right depending on the current setting. Cursor **45** is used to select one of the icons to allow the control of the functions associated with the selected icon. Cursor **45** indicates which of the icons in display **14** are currently selected. The icon can be moved from each icon to the next by rotating the knob **18**. Alternatively, the transverse motion of the knob can move the cursor **45**. A function of the device designed by the selected icon can be selected by pushing the knob **18** in the linear direction. The cursor can be a square or other-shaped box, or the currently-selected icon can be highlighted to indicate the cursor's location.

[**0038**] It should be noted that each of the icons can preferably be set to a position control mode or to a rate control mode as desired by the user. For example, the user may select position control for volume **46** and rate control for the functions of icons **47**, **48**, **49**, and **51**, or any other combination. In position control mode, force detents are preferably output to indicate particular settings or how far the knob **18** has been rotated. In rite control mode, detents can also be output. For example, the user maintains the knob **18** at a rotary position away from the center position in opposition to a spring return force, and a detent force (e.g., jolt) is output to indicate how much a particular value has been changed. For example, a jolt can be output for each 10 MHz of frequency that is increased, or for each particular amount of treble or bass that has been adjusted.

[**0039**] Other icons can be displayed in other embodiments. For example, an for vent location can be selected using cursor **45** to determine which vents in the car provide air flow, where a top vent, a bottom vent, or both top and bottom vents can be selected. A fan speed icon can be selected to choose a fan speed setting for the air flow from the vents in the car. In a preferred force feedback implementation, once the fan speed icon has been selected by pushing in the knob **18**, the user may rotate the knob **18** to select the fan rotation speed in a position control mode. A small vibration can be output on the knob **18** in the rotary degree of freedom, where the frequency (or magnitude) of the vibration forces correlate with the magnitude of fan rotation speed, i.e., a high fan speed provides a fast vibration. Furthermore, detents are preferably output superimposed on the vibration forces so that the user can feel the fan settings at the detents. This allows the user to select fan speed based purely on tactile feel, so that the driver need not look at the display **14**. A temperature icon can be selected to adjust the temperature in the car. The temperature can preferably be adjusted by rotating knob **18**, where force detents indicate each temperature setting. Icons for moving mechanical components, such as seats or mirrors, can be provided, where a rate control force mode is used to control the position of the components.

[**0040**] FIG. **3***a* is a perspective view and FIG. **3***b* is a side elevational view of one implementation of control knob **18** of the present invention. In this implementation, knob **18**

includes the ability to move transversely in four directions, and the knob **18** can also be pushed for additional selection ability.

[**0041**] Knob **18** is rigidly coupled to a rotatable shaft **50** which extends through the grounded front panel **12** (shown in dashed lines). Shaft **50** extends through a four-way switch **52** which detects the transverse motion of the knob **18** in directions **28**. The knob **18** is biased toward the centered rest position within switch **52** by a spring member **64**, described in greater detail below. When the shaft **50** is moved in any of the provided transverse directions, a corresponding micro switch (not shown) included on the interior sidewall of the four-way switch **52** is closed, thus causing a signal to be output on leads **54**. Thus, switch **52** preferably includes individual micro switches, one for each provided transverse direction (four individual switches in the described embodiment). A suitable switch for use as switch **52** is a "hat switch" which is commonly provided for analog joystick controllers for personal computers and allows 4 or 8 directions to a moveable member. For example, joystick hat switches manufactured by such companies as CH Products, Inc. or Logitech can be used. In other embodiments, two-way, eight-way, or other types of switches can be used, depending on how many directions are desired.

[**0042**] A pusher member **56** is rigidly coupled to shaft **50** next to the switch **52**. Since the switch **52** includes an aperture through which the shaft **50** extends, the knob **18**, shift **50** and pusher member **56** are operative to move as a unit along axis A with respect to the front panel (ground) and the switch **52**. A switch **58** (see FIG. **3***b*) is coupled to a grounded member **60** and is provided in the path of the pusher member **56**. Thus, when the knob **18** is pushed by the user, the shaft **50** and the pusher member **56** are moved along axis A in a direction indicated by arrow **62** (see FIG. **3***b*). This causes pusher member **56** to engage the button **64** of the switch **58**, causing the button **64** to be pushed inward and close (or open) the switch. The pushing motion of the knob **18** is thus sensed.

[**0043**] In other embodiments, a sensor can be provided to sense a range of positions of the knob **18** or a continuous motion of the knob **18** linearly along axis A. For example, a Hall effect switch can be provided on pusher member **56** which measures the position of the pusher member **56** relative to a grounded magnet on member **60** (or the Hall effect switch can be placed on the member **60** and the magnet can be placed on the member **56**). Or, an optical sensor (such as a photodiode) or other type of sensor can detect the position of the member **56** and/or knob **18**. In such an embodiment, the position of the knob along axis A can proportionately control a function or setting of the device **10**. For example, such movement can control the volume of audio output of the device, motion of a cursor across a display, or the brightness of lights inside a vehicle.

[**0044**] A pull switch can be implemented similarly to the push switch shown in FIGS. **3***a* and **3***b*. For example, a switch similar to switch **58** can be grounded and provided on the opposite side of pushed member **56** so that when knob **18** is pulled in a direction opposite to direction **62**, a button on this switch is engaged by the pusher member to detect the pulled motion. The pull motion of knob **18** can also be sensed in a continuous range similar to the push embodiments described above. In some embodiments, both push and pull motions of the knob **18** may be provided and sensed.

[**0045**] A spring member **64** is rigidly coupled to the pushing member **56** at one end and is rigidly coupled to a rotatable end member **66** at its other end. Spring member **64** is compressed when the knob **18** and pusher member **56** are moved in the direction of arrow **62**. Spring member **64** thus provides a spring force that biases the knob **18** in the direction opposite to direction **62**. If the knob **18** is not forced in direction **62**, the spring bias moves the knob **18** opposite to direction **62** until the knob reaches its rest position. In those embodiments including a pull motion of the knob **18** in the direction opposite to direction **62**, a spring member can be included on the opposite side of pusher member **56** to spring member **64**, to bias the knob **18** in direction **62** after the user has pulled the knob. In yet other embodiments, no spring member **64** is provided, and the knob **18** remains at any pushed or pulled position until actively moved to a new position by the user.

[**0046**] Spring member **64** also provides the transverse motion of knob **18** in the directions **28**. The flexure of the spring element allows the knob to move in transverse degrees of freedom, while still being relatively torsionally stiff to allow forces to be transmitted effectively from an actuator to the knob **18** about axis A. In other embodiments, other types of couplings can be provided to allow a pivot or translational motion in the directions **28**. For example, flexible disc servo couplings or one-piece flexible shaft disc couplings can be provided; such couplings are available from Renbrandt, Inc. of Boston, Mass. and Helical Products Company, Inc. of Santa Maria, Calif. In other embodiments, bent space frames provided in a square-plate coupling or a rectangular coupling can be used. Furthermore, a different alternate flexible coupling embodiment is described in greater detail with respect to FIGS. **4***a*-**4***c*

[**0047**] End member **66** is coupled to a rotatable shaft **68** of an actuator **70**. The housing **72** of actuator **70** is rigidly coupled to grounded member **74**, and the shaft **68** rotates with respect to the housing **72** and the member **74**. Actuator **72** can be controlled to output force on rotating shaft **68** about axis A, thus driving the shaft and all components rigidly coupled to the shaft about axis A. The shaft **68** thus rotates end member **66**, spring member **64**, pusher member **56**, shaft **50**, and knob **18**. The output force on knob **18** is felt by the user as force feedback. Actuator **70** can be any of a variety of different types of actuators, including a DC motor, voice coil, pneumatic or hydraulic actuator, magnetic particle brake, etc. A sensor **76** has a shaft rigidly coupled to the rotating shaft **68** of the actuator **70** and thus detects the rotation of the shaft **68** and the knob **18** about axis A. Sensor **76** is preferably a digital optical encoder but can alternatively be a different type of sensor, such as an analog potentiometer, a photodiode sensor, a Hall effect sensor, etc.

[**0048**] The force feedback output on knob **18** can include a variety of different force sensations. The force feedback can be integrally implemented with the control functions performed by the knob. A basic force sensation is force detents that are output at particular rotational positions of the knob to inform the user how much the knob has rotated and/or to designate a particular position of the knob. The force detents can be simple jolts or bump forces to indicate

the detent's position, or the detents can include forces that attract the knob to the particular rotational detent position and resist movement of the knob away from that position. The position can correspond to a particular radio station frequency or other station (e.g., television station frequency), thus making selection easier for the user. Such detents can be provided for additional functions, such as volume control for sound speakers, fast forward or rewind of a video cassette recorder or computer-displayed movie (such as a DVD movie), scrolling a displayed document or web page, etc. Force feedback "snap-to" detents can also be provided, for example, for the favorite station frequencies preprogrammed by the user, where a small force biases the knob to the detent position when it is just outside the position.

[0049] Also, the magnitude of the force detents can differ based on the value being controlled. For example, a radio frequency having a higher value might be associated with a stronger force detent, while a lower radio frequency might be associated with a weaker force detent when it is displayed, thus informing the user generally of the radio station being displayed without requiring the user to look at the display **14** (which is particularly useful when operating the device **10** while performing another task, such as driving a vehicle). In some embodiments, the user can also change the magnitude of detents associated with particular values, such as radio stations, to preferred values so as to "mark" favorite settings. Programmability of the location of the detents in the rotary degree of freedom is also convenient since preferred radio frequencies are most likely spaced at irregular intervals in the radio frequency range, and the ability to program the detents at any location in the range allows the user to set detents to those preferred stations. In addition, the knob can be moved by the actuator **70** to select the nearest preprogrammed station or preferred setting. Also, different sets of detent force profiles can be stored in a memory device on the device **30** and a particular set can be provided on the knob **18** by a microprocessor or other controller in the device **30**.

[0050] Another type of force sensation that can be output on knob **18** is a spring force. The spring force can provide resistance to rotational movement of the knob ill either direction to simulate a physical spring on the knob. This can be used, for example, to "snap back" the knob to its rest or center position after the user lets go of the knob, e.g. once the knob is rotated past a particular position, a function is selected, and the user releases the knob to let the knob move back to its original position. A damping force sensation can also be provided on knob **18** to slow down the rotation of the knob, allowing more accurate control by the user. Furthermore, any of these force sensations can be combined together for a single knob **18** to provide multiple simultaneous Force effects.

[0051] The spring return force provided in the rotary degree of freedom of the knob **18** can also be used to implement a rate control paradigm. "Rate control" is the control of a rate of a function, object, or setting based on the displacement of the knob **18** from a designated origin position. The further the knob is moved away from the origin position, the greater the rate of change of controlled input. For example, if a rate control knob **18** with a spring return force is used to control the radio frequency, then the further the knob is moved from the center origin position, the faster the radio frequency will change in the appropriate direction. The frequency stops changing when the knob is returned to the origin position. The spring force is provided so that the further the user moves the knob away from the origin position, the greater the force on the knob in the direction toward the origin position. This feels to the user as if he or she is inputting pressure or force against the spring rather than rotation or displacement, where the magnitude of pressure dictates the magnitude of the rate. However, the amount of rotation of the knob is actually measured and corresponds to the pressure the user is applying against the spring force. The displacement is thus used as an indication of input force.

[0052] This rate control paradigm differs from the standard knob control paradigm, which is known as "position control", i.e. where the input is directly correlated to the position of the knob in the rotary degree of freedom. For example, in the radio frequency example, if the user moves the knob to a particular position, the radio frequency is changed to a particular value corresponding to the rotary position of the knob. Force detents are more appropriate for such a paradigm. In contrast, in the rate control example, moving the knob to a particular position causes the radio frequency to continue changing at a rate designated by the position of the knob.

[0053] Since the spring force and detent forces are programmable and can be output as directed by a microprocessor or other controller, a single knob **18** can provide both rate control and position control over functions or graphical objects. For example, a mode selector, such as a button or the push/pull knob motion, can select whether rate control or position control is used. One example of a force feedback device providing both rate control (isometric input) and position control (isotonic input) is described in greater detail in co-pending patent application Ser. No. 08/756,745, filed Nov. 26, 1996, and incorporated herein by reference. Such rate control and position control can be provided in the rotary degree of freedom of the knob **18**. Also, if knob **18** is provided with force feedback in the transverse degrees of freedom or in the push/pull linear degree of freedom, then the rate control and position control modes can be provided in those degrees of freedom.

[0054] Other force sensations that can be output on knob **18** include forces that simulate ends of travel for the knob **18** or inform the user that the end of travel has been reached. For example, as the user rotates the knob in one direction to adjust the radio frequency **22**, the end of the radio frequency range is reached. There is no hard stop on the knob **18** at this position, but the actuator **70** can be controlled to output an obstruction force to prevent or hinder the user from rotating the knob further in that direction. Alternatively, a jolt force can be output that is stronger in magnitude than normal detents, which informs the user that the end of the frequency range has been reached. The user can then continue to rotate the knob in that direction, where the displayed frequency **22** wraps around to the beginning value in the range.

[0055] In another alternate embodiment, one or more of the transverse motions of knob **18** in directions **28** can be actuated. For example, a greater range of motion can be provided for each transverse direction of the knob than typically allowed by a hat switch, and a linear or rotary actuator can be provided to output forces in the transverse

degree of freedom, in one or both directions (toward the center position and away from the center position of the knob). For example, one or more magnetic actuators or solenoids can be used to provide forces in these transverse directions.

[0056] Furthermore, in other embodiments, the pull and/or push motion of knob **18** along axis A can be actuated. For example, a jolt force can be output on the knob in the linear degree of freedom along axis A as the user pushes the knob. Also, the spring return force provided by spring member **64** can instead be output using an actuator controlled by a microprocessor.

[0057] It should be noted that the embodiment of FIGS. **3***a* and **3***b* is not the only embodiment of the present invention. For example, some embodiments may only include the transverse motion of knob **18** and not the push and/or pull functionality nor the force feedback functionality. Other embodiments may only include the push and/or pull functions. Yet other embodiments may only include force feedback with transverse knob motion, or force feedback with push and/or pull functions.

[0058] FIG. **4***a* is a perspective view of an alternate embodiment **80** of the control knob **18** of the present invention. In embodiment **80**, knob **18** is coupled to shaft **50**, which is rigidly coupled to a flex member **82**. Flex member **82** includes a base plate **84** and a plurality of bent portions **86** extending from the base plate **84**. For example, as shown in FIG. **4***b*, the flex member **82** can be formed by cutting out the circular base plate **84** and the portions **86** from a unitary piece **85** of material, such as spring steel or stainless steel. The unitary piece is preferably provided as a thin sheet. Holes **88** or other apertures can be placed near the ends of the portions **86**. Referring back to FIG. **4***a*, the portions **86** are then bent such that the holes **88** substantially align with the other holes **88**, where the holes **88** are aligned with axis B that extends approximately perpendicular to the surface of the base plate **84**. The base plate **84** is rigidly coupled to the rotating shaft of the actuator **70**.

[0059] FIG. **4***c* is a side elevational view of the embodiment **80** of FIG. **4***a*. In the described embodiment, knob **18** is coupled to shaft **50**, which extends through a switch **90** and is coupled to the bent portions **86** of the flex member **82**. The switch **90** is preferably similar to the switch **52** described above with reference to FIGS. **3***a* and **3***b*. For example, a microswitch can be provided on the inside surface of the housing of switch **90** for each transverse direction of knob **18** that is to be sensed. The base plate **84** of the flex member **82** is rigidly coupled to shaft **92** of actuator **70**. The shaft **92** is rigidly coupled to a shaft (not shown) of sensor **76**, which has a grounded housing that is coupled to the grounded housing of actuator **70**.

[0060] Alternatively, a plurality of sensors can be positioned external to the flex member **82** instead of using switch **90**. For example, switches **94** can be positioned on two or more sides around the flex member **82**, depending on how many directions are to be sensed. Switches **94** can be contact switches that each detect when the portions **86** move to engage the contact switch, thus indicating movement of knob **18** in a particular transverse direction. Alternatively, members can be positioned on shaft **50** which extend to the sides of the shaft and which engage electrical contacts or other sensors. In other embodiments, other switches or sensors can be used, as described above in the embodiment of FIG. **3***a*. A spring (not shown) can also be coupled to the shaft **50**, flex member **82**, or knob **18** to provide linear motion along the axis B and allow the knob **18** to be pushed and/or pulled by the user, as described in the embodiment of FIG. **3***a*. Some types of flexible couplings that allow transverse motion of the knob **18** may also allow linear motion along axis B, such as flexible disc servo couplings, in which case such as spring may not be needed.

[0061] In operation, the transverse motion of knob **18** in embodiment **80** operates as follows. The knob **18** is moved by the user approximately in a transverse direction **28**, which causes the shaft **50** to move with the knob by pivoting approximately about the end of the shaft **50** where it is coupled to the portions **86**. Shaft **50** is allowed such movement due to the flexibility in portions **86**. In some embodiments, the knob **18** is also allowed to translate in a transverse direction **28** as well as or in addition to pivoting approximately in directions **28**. When the knob **18** is rotated about axis B (by the user or the actuator), the shaft **50** rotates about its lengthwise axis, causing the flex member **82** to rotate about axis B. Since the portions **86** are stiff in the rotational direction about axis B, torque output on the shaft **50** and on the flex member **82** is transmitted accurately from actuator **70** to knob **18** and from knob **18** to sensor **76**. Thus, the rotation on flex member **92** causes the shaft **92** to rotate, which is sensed by sensor **76**. The rotational force about axis B output by actuator **70** is similarly transmitted from shaft **92**, through flex member **82**, to shaft **50** and knob **18**.

[0062] FIG. **5** is a perspective view of an exemplary embodiment for the slider control **32** as shown in FIG. **1**. Slider control **32** includes slider knob **34** which may move in a linear degree of freedom as indicated by arrow **36**. In the described embodiment, a transmission member **100** is rigidly coupled to the knob **34** and extends through a slit or opening **102** in the front panel **12** or other grounded member. Transmission member **100** can be coupled to an actuator, such as linear voice coil actuator **104**

[0063] The member **100** can move in and out of a housing **101** of actuator **104** as indicated by arrow **103**. The housing **101** preferably includes a central core **107** and a number of elongated magnets **109**. An armature **105** includes a hollow, cylindrical member having an inner surface which slidingly engages the core **107**. Wrapped around the armature **105** are coils **110** that are electrically coupled to actuator and/or sensor interfaces. The armature **105** is coupled to the transmission member **100** so that the armature **105** and member **100** can move in a linear fashion as indicated at arrow **103**. Other voice coil configurations can also be used, such as differently shaped cores, different coil layouts, etc. Voice coil actuator **104** can serve both as a sensor and an actuator. Alternatively, the voice coil can be used only as an actuator, and a separate sensor **106** can be used. Separate sensor **106** can be a linear sensor that senses the motion or position of an extension **112** that is coupled to the transmission member **100** and moves linearly when the transmission member moves. Voice coil actuators such as actuator **104** are described in greater detail in U.S. Pat. No. 5,805,140, the disclosure of which is incorporated herein by reference. In particular, the operation of the voice coils as actuators and/or sensors is described therein.

[0064] Other types of actuators **104** and transmissions can also be used in slider control **32**. For example, a capstan

drive and cable transmission can provide linear forces on the knob **34**. Other types of actuators suitable for use with the slider include active actuators, such as linear current control motors, stepper motors, pneumatic/hydraulic active actuators, a torquer, etc. Passive actuators may also be used, such as magnetic particle brakes, friction brakes, fluid controlled passive actuators, or other actuators which generate a damping resistance or friction in a degree of motion.

[**0065**] Slider knob **34** can also include a button **38** which is used to provide input to the device **10**. In yet other embodiments, the slider knob **34** can be pushed and/or pulled in a linear degree of freedom approximately perpendicularly to the surface of front panel **12**. In such an embodiment, a moveable contact switch can be provided between the knob **34** and the transmission member **100**. A spring member can also be provided similarly to the embodiment of FIGS. **3***a*-**3***b* and **4***a*-**4***c* to bias the knob **34** to a neutral rest position.

[**0066**] The force sensations and modes described above for the rotary knob in FIGS. **3***a*-**3***b* and **4***a*-**4***c* may also be used for the slider control **32** in a linear degree of freedom. For example, force detents can be applied in a position control paradigm as the knob **34** is moved in its linear degree of freedom. In a rate control paradigm, a spring return force can bias the knob **34** toward a center origin position, for example the center of the range of motion of the knob. The further the user moves the knob from the origin position, the greater the spring force opposing that motion and the greater the rate of the controlled value changes (increases or decreases). Other force effects include damping forces, texture forces, jolts, obstruction forces, assistive forces, periodic forces such as vibration forces, and end-of-travel forces.

[**0067**] FIGS. **6***a* and **6***b* are diagrammatic illustrations illustrating detent force profiles suitable for use with the knobs of device **10**. Detent force profiles can be implemented by a microprocessor or other controller based on instructions stored in a computer readable medium, such as a memory circuit, magnetic disk, optical disk, etc. In FIG. **6***a,* a detent force profile is shown. The vertical axis F represents the magnitude of force output, where a positive F value indicates force in one direction, and a negative F value indicates force in the opposite direction. The horizontal axis d represents the distance or position of the moved user object (knob) in a degree of freedom, where the origin position O indicates the position of the detent, a positive d is a position past the origin of the detent in one direction, and a negative d is a position past the origin of the detent in the opposite direction. The curve **124** represents the force output for a single detent over a position range for the detent. Thus, for example, if the user moves the knob clockwise toward the detent origin O**1**, the motion may be from the left toward the origin O**1** on the axis d. A force toward the origin is output at position P**1** at a magnitude −M to assist the user in moving the knob clockwise toward the origin. As the user continues to move the knob clockwise toward the origin O**1**, the assisting force is decreased in magnitude until no force is output when the knob is positioned at the origin position. If the user moves the knob counterclockwise from the origin position O**1** (from right to left), the force will resist such motion in an increasing manner until the knob has been moved to position P**1**, after which the force magnitude drops to zero. Similarly, on the positive side of the d axis, if the user rotates the knob clockwise away from the detent origin position O**1** (corresponding to movement from left to right), an increasing magnitude of force is output until the knob reaches the position P**2**, at which point the force magnitude drops from its maximum at M to zero. If the user moves the knob counterclockwise from position P**2** toward the origin O**1**, the user initially feels a large magnitude force assisting that movement, after which the assisting force gradually decreases until it is zero at the origin O**1**. Preferably, point P**1** is at an equal distance from origin O**1** as point P**2**.

[**0068**] Additional detents may be positioned in the degree of freedom of the knob in successive positions, represented along axis d. For example, curve **126** represents another detent that is encountered shortly after leaving the previous detent curve **124** when turning the knob in a particular direction.

[**0069**] A problem occurring with closely spaced detents is that often the user moves the knob from a first detent to a second detent but unintentionally moves the knob past the second detent due to the assistive detent forces of the second detent. This is because the force from the user required to move the knob past the resistive force of the first detent curve is combined with the assistive force of the second detent curve, causing the knob to unintentionally move past the second origin and past the endpoint of the second detent curve. Furthermore, the same problem occurs when the user moves the knob in the opposite direction, from the second detent to the first detent. The user must exert force to overcome the resistance at the last point of the second detent curve, which causes the knob to quickly move past the first point of the first detent curve, where the assistive force is added to the motion to cause the knob to unintentionally move past the last encountered point of the first detent.

[**0070**] FIG. **6***b* shows a detent force profile of the present invention in which the detent forces of two successive detents are partially overlapped due to the detents, and provide a hysteresis-like force effect. The two detent curves **128** and **130** are identical, thus allowing a single force command to create the multiple detents if desired. Endpoint **131** of curve **128** is positioned at position P**1** and endpoint **132** of curve **128** is positioned at position P**2**, where P**2** is about the same distance from origin O**1** as P**1**. Similarly, endpoint **134** of curve **130** is positioned at position P**3** and endpoint **133** of curve **130** is positioned at position P**4**, where P**4** is about the same distance from origin O**2** as P**3**. Detent curve **128** ends at endpoint **132** on the right side of origin O**1** and within the range of forces of detent curve **130**. Preferably, the end point **132** of curve **128** is positioned well after the endpoint **134** of curve **130**, such that the point **132** has a position in the middle of the range between point **134** and the origin O**2**. The overlapped zone is between positions P**3** and P**2**. In addition, the end point **132** of the first detent preferably does not extend past the origin O**2** of the second detent into the positive side of the second detent. If another detent is positioned further on the d axis after curve **130**, the end point **133** of curve **130** preferably is positioned well after the starting endpoint of the next detent curve and not past the origin of the next detent curve. Similar positioning can be provided for curves before curve **128** on axis d.

[**0071**] To solve the problem of unintentionally moving past a successive detent, the range of the second or successive detent is adjusted such that a lesser magnitude is

preferably output at the beginning of the successive detent than would normally be output if the entire curve of the successive detent were used. Furthermore, the force detent curve used to output force is preferably different depending on the direction of the knob, similar to a hysteresis effect. As shown in FIG. **6***c,* when moving the knob so the knob position changes from left to right, the force at the beginning of the range of detent curve **130** is at point **135** having a magnitude of 0.5M, which is one-half the magnitude M of the force at the other endpoint **133** of the range of curve **130** (ignoring the signs or direction of the forces). Of course, in other embodiments point **135** can have a magnitude of other fractions of M, such as one-third or three-fourths of M. Additional curve **127** can be similarly positioned and provide a similar overlap with curve **130**, and additional curves may be added before curve **128** and/or after curve **127**.

[**0072**] As shown in FIG. **6***d,* when moving the knob in the other direction so the knob position changes from right to left, the endpoints of the curve **130** reverse in magnitude with respect to the endpoints shown in FIG. **6***c*. In FIG. **6***d,* starting from origin O**2**, the force at the beginning of the range of detent curve **128** is at point **136** having a magnitude of 0.5M, which is one-half the magnitude M of the force at the other endpoint **131** of curve **128** (other fractions of M can be provided for endpoint **136** in other embodiments). Any additional curves, such as curve **127**, can be provided with a similar overlap. The force output on the knob thus changes depending on the direction of the knob. In a digital sensing system (e.g. using a digital encoder), the direction can be determined from a history of sensed values. For example, one or more sensed position values can be stored and compared to a current sensed position to determine the knob direction.

[**0073**] The use of a lesser magnitude at the beginning of the second detent reduces the tendency of the user to unintentionally skip past a second detent after moving the knob over a first detent closely spaced to the second detent. For example, when moving the knob left to right (e.g., clockwise) from position P**1**, a first detent (curve **128**) ends at point **132** of curve **128**, after which the force magnitude of point **135** on curve **130** begins assisting the knob's movement. This magnitude is less than the magnitude of the "original" beginning point **134**, i.e. the beginning point of the full curve **130**. Thus, less force is assisting the user to move toward the origin O**2** of curve **130** than if the force magnitude for beginning point **134** of the curve **130** were in effect. With less force assisting motion toward origin O**2**, the user has an easier time slowing down the knob and preventing the knob from unintentionally overshooting the origin O**2**. Furthermore, the changing of endpoints of the detent curve, as dependent on direction, provides a hysteresis-like effect the reduces the unintentional skip in both directions. Thus, when moving the knob from right to left (e.g., counterclockwise) starting at origin O**2**, a first detent (curve **130**) ends at point **134** of curve **130**, after which a magnitude of point **136** on curve **128** begins assisting the knob's movement. This magnitude is less than the magnitude of the "original" beginning point **134**. Thus, less force is assisting the user to move toward the origin O**1** of curve **128** than if the force magnitude for beginning point **132** of the curve **128** were in effect. With less force assisting motion toward origin O**1**, the user has an easier time slowing down the knob and preventing the knob from unintentionally overshooting the origin O**1**.

[**0074**] The same overlapping and hysteresis feature can be provided for differently-shaped detents as well, such as curved detents of FIGS. **7***a*-**7***e,* detents having deadbands around the origin O, and/or other-shaped force profiles. In embodiments having detent endpoints that are spaced further apart, or which have very gradually-sloping curves, the overlap and hysteresis may not be needed since there may be enough space in the degree of freedom for the user to control the knob from unintentionally moving past the next detent.

[**0075**] FIG. **7***a* is a graph illustration **137** of a periodic wave **139** that can be used to provide a variety of detent force sensations for use with the knob control device of the present invention. The periodic wave represents force exerted on the knob (axis F) vs. the position or displacement (axis d) of the knob, similar to the force detent profile shown in FIGS. **6***a* and **6***b*. The wave **139** is a periodic function, such as a sine wave, triangle wave, square wave, etc. In FIG. **7***a,* a sine wave shape is shown. In the present invention, a portion of the wave may be used to provide detent and other force sensations for the knob **18** or **34**. Various parameters of the sine wave are shown in FIG. **7***a,* including period and magnitude.

[**0076**] Curve **138** (solid line) represents a detent force effect that has been created based on the sine wave **139**. Curve **138** has a width, which is the amount of the wave **139** along axis d used for the force detent. The location of the detent is the position in the degree of freedom at which the detent force is centered, i.e. the location of the origin position O of the detent. A deadband can be defined to be a distance from the origin O to a specified point, a region in which zero forces are output on the knob. Thus, the curve **138** shown in FIG. **7***a* shows a detent force starting at a magnitude M**1** at location P**1** and, when the knob is moved toward the origin O, the force increases to the maximum point M**2** at location P**2** and then decreases until point P**3**, where the deadband is reached (zero magnitude). Similarly, at point P**14** on the other side of the origin O, the force increases from zero to a maximum magnitude M**5** at location P**5**, after which the force drops a short distance to magnitude M**6** at location P**6**. The force then drops to zero for increasing d, until another detent effect is encountered. The small decreases in force magnitude from the maximum magnitude at the end points of the curve **138** are useful in some detent embodiments to provide a less extreme assistive or resistive force to the user when entering or exiting the detent range, e.g., to gradually lead the user into the detent range before outputting the maximum force. This can provide a smoother-feeling and, in some cases, a more easily-selected detent (i.e., it can be easier to position the knob at the detent's origin).

[**0077**] The detent curve **138** can thus be defined using the parameters shown in FIG. **7***a*. For example, a force command protocol can provide a number of different commands that can cause the output of different force sensations to the user. The commands can each include a command identifier followed by one or more command parameters that define and characterize the desired force sensation. An example of a command defining a detent curve **138** is as follows:

[**0078**] DETENT (TYPE, PERIOD, MAGNITUDE, LOCATION, DEADBAND, FLAG, WIDTH, PHASE, OFFSET, LOCATION, INCREMENT, ARRAY POINTER)

[**0079**] The DETENT identifier indicates the type of force sensation. The TYPE parameter indicates a type of periodic

wave from which to base the force detent curve, such as a sine wave, triangle wave, square wave, ramp, etc. The PERIOD and MAGNITUDE parameters define those characteristics of the periodic wave. The LOCATION parameter defines the location of the origin position for the detent in the degree of freedom of the knob. The DEADBAND parameter indicates the size of the deadband around the origin position. The FLAG parameter is a flag that indicates whether the detent is provided on the positive side, the negative side, or both sides around the location (origin position). The WIDTH parameter defines the amount of the wave **139** used for the detent curve, i.e. the extent of the wave used starting from the PHASE position. The PHASE parameter indicates the starting position of the detent curve **138** on the wave **139** (and is described in greater detail below). The OFFSET parameter indicates the amount of magnitude offset that curve **138** includes from the d axis, and is described in greater detail below. The INCREMENT parameter indicates the distance in the degree of freedom of the knob between successive detent locations. The optional LOCATION ARRAY POINTER parameter indicates a location in a separate array that has been previously programmed with the particular positions in the degree of freedom of the knob at which the detents are located and (optionally) the total number of detents; the array can be provided in memory, such as RAM, or other writable storage device. For example, the array can be preprogrammed with three detents, at locations of 45 degrees, 78 degrees, and 131 degrees in the rotation of the knob. The array can be accessed is necessary to retrieve these locations at which detent forces are to be output. This can be useful when the detent locations are not evenly or regularly spaced in the degree of freedom, and/or when a particular number of detents are desired to be output.

[**0080**] Furthermore, in other embodiments, a periodic wave can be additionally "shaped" to form a particular detent curve. For example, an "envelope" can be applied to a periodic wave to shape the wave in a particular way. One method of shaping a wave is to define a first magnitude and a settle width, which is the distance required for the wave to settle to a second, lesser magnitude from the first magnitude. This settle width thus provides a ramping shape to the upper and/or lower portions of the periodic wave about axis d. Although such shaping is performed in a spatial domain, it is similar to the force signal shaping in the time domain described in co-pending U.S. patent application Ser. No. 08/747,841, incorporated herein by reference. Such shaping is also described in co-pending U.S. patent application Ser. Nos. 08/846,011 and 08/877,114, incorporated herein by reference. The shaping can be specified by parameters in a commands, such as a settled width parameter, magnitude parameters, etc.

[**0081**] The detent command can be sent by a supervisory microprocessor to a lower-level local microprocessor to decode and interpret the commands to control procedures provided in device **10** in firmware or other storage medium, as described with reference to FIG. **8** below. If a host computer and local microprocessor are used, the host computer can send the command to the local microprocessor, which parses/decodes and interprets the command and causes appropriate forces to be output. Commands and protocols for use in force feedback are described in greater detail in U.S. Pat. No. 5,734,373, incorporated by reference herein. Such commands can also be retrieved from a storage device such as memory and then parsed and interpreted by a local microprocessor.

[**0082**] The ability to define a force detent (in the spatial domain) in terms of a periodic waveform can be useful in force feedback implementations in which periodic force effects in the time domain are also provided. For example, vibration force sensations can be provided by outputting a periodic sine wave or square wave for the magnitude of the force over time. If such time-based effects can be output on knob **18** or **34**, then it is convenient to use the same periodic wave definitions and data for defining force vs. position profiles for detents as shown in FIGS. **7***a*-**7***e*.

[**0083**] FIG. **7***b* is a graph illustration **140** showing particular parameters of the detent command described above which are applied to a periodic wave. Sine wave **142** has a magnitude and period as shown. A specified phase of the desired detent curve causes the detent curve to start at a position on wave **142** in accordance with the phase. For example, in FIG. **7***b*, a phase of 50 degrees is specified. This will cause the resulting detent curve to start at point P on the wave **142**. A width parameter specifics the amount of the wave from the phase location to be used as the detent curve. Furthermore, an offset of −0.8 is indicated. This causes the resulting detent curve to be shifted down by 80% from the wave **142**. Furthermore, a deadband is also specified (not shown in FIG. **7***b*.).

[**0084**] FIG. **7***c* is a graph **144** showing the resulting detent curve **146** obtained from the application of the parameters to the wave **142** described with reference to FIG. **7***b*. The portion of the wave **142** starting at the phase and positioned above the offset line in FIG. **7***b* is used in the detent curve **146**. Furthermore, a deadband **148** has been added to the curve. The flag in the detent command has caused the positive side of the curve **146** to be mirrored on the negative side of the origin O. This detent curve **146** causes a detent force that is similar to the detent force described with reference to FIG. **7***a*, only smaller in magnitude and in position range over the degree of freedom of the knob.

[**0085**] FIG. **7***d* is a graph **160** showing a periodic wave and parameters to be applied to the wave. Sine wave **162** is provided as described above, having a particular period and magnitude. An offset is specified for the resulting detent curve; in the example of FIG. **7***d*, the offset is 1, thus causing the detent curve to be shifted upward by its entire magnitude. A phase of 270 degrees is also indicated, so that the detent curve starts at the lowest magnitude of the wave **172** at point P. Furthermore, an increment is also specified as a parameter (not shown). FIG. **7***e* is a graph **170** illustrating the detent curves **172** and **174** resulting from the wave **162** and parameters described with reference to FIG. **7***d*. The portion of the wave **162** past point P and ending at a point defined by a width parameter is provided both on the positive side and the negative side of origin O**1** of graph **170** for curve **172** (the positive and negative sides are designated by the flag parameter). A second curve **174** is also shown, where the origin O**2** of the second curve is positioned at a distance from the origin O**1** as specified by the increment parameter. Additional curves similar to curves **172** and **174** are provided at further distances at same increment from each other. The detent curves **172** and **174** provide a much steeper, less gradual detent force over the detent range than

the other detent forces shown in FIGS. **7***a* and **7***c*. Furthermore, no actual deadband is specified, although the shape or each half of the curve **172** provides a small zone **176** where zero force is output, similar to a deadband.

[**0086**] FIG. **8** is a block diagram illustrating an electromechanical system **200** for the device **10** of FIG. **1** suitable for use with the present invention. A force feedback system including many of the below components is described in detail in co-pending patent application Ser. No. 09/049,155, filed Mar. 26, 1998, and U.S. Pat. No. 5,734,373, which are both incorporated by reference herein in their entirety.

[**0087**] In one embodiment, device **10** includes an electronic portion having a local microprocessor **202**, local clock **204**, local memory **206**, sensor interface **208**, and actuator interface **210**.

[**0088**] Local microprocessor **202** is considered "local" to device **10**, where "local" herein refers to processor **202** being a separate microprocessor from any other microprocessors, such as in a controlling host computer (see below), and refers to processor **202** being dedicated to force feedback and/or sensor I/O for the knob **18** of the interface device **10**. In force feedback embodiments, the microprocessor **202** reads sensor signals and can calculate appropriate forces from those sensor signals, time signals, and force processes selected in accordance with a host command, and output appropriate control signals to the actuator. Suitable microprocessors for use as local microprocessor **202** include the 8X930AX by Intel, the MC68HC711E9 by Motorola and the PIC16C74 by Microchip, for example. Microprocessor **202** can include one microprocessor chip, or multiple processors and/or co-processor chips, and can include digital signal processor (DSP) functionality. Also, "haptic accelerator" chips can be provided which are dedicated to calculating velocity, acceleration, and/or other force-related data. Alternatively, fixed digital logic and/or state machines can be used to provide similar functionality.

[**0089**] A local clock **204** can be coupled to the microprocessor **202** to provide tilling data, for example, to compute forces to be output by actuator **70**. In alternate embodiments using the USB communication interface, timing data for microprocessor **202** can be retrieved from the USB interface. Local memory **206**, such as RAM and/or ROM, is preferably coupled to microprocessor **202** in interface device **10** to store instructions for microprocessor **202**, temporary and other data, calibration parameters, adjustments to compensate for sensor variations can be included, and/or the state of the device **10**. Display **14** can be coupled to local microprocessor **202** in some embodiments. Alternatively, a different microprocessor or other controller can control output to the display **14**.

[**0090**] Sensor interface **208** may optionally be included in device **10** to convert sensors signals to signals that can be interpreted by the microprocessor **202**. For example, sensor interface **208** can receive signals from a digital sensor such as an encoder and convert the signals into a digital binary number. An analog to digital converter (ADC) can also be used. Such circuits, or equivalent circuits, are well known to those skilled in the art. Alternately, microprocessor **202** can perform these interface functions. Actuator interface **210** can be optionally connected between the actuator **70** and microprocessor **202** to convert signals from microprocessor **202** into signals appropriate to drive the actuators. Actuator interface **210** can include power amplifiers, switches, digital to analog controllers (DACs), and other components, as well known to those skilled in the art. In alternate embodiments, actuator interface **210** circuitry can be provided within microprocessor **202** or in the actuator **70**.

[**0091**] A power supply **212** can be coupled to actuator **70** and/or actuator interface **210** to provide electrical power. In a different embodiment, power can be supplied to the actuator **70** and any other components (as required) by an interface bus. Power can also be stored and regulated by device **10** and thus used when needed to drive actuator **70**.

[**0092**] A mechanical portion is included in device **10**, an example of which is shown above in FIGS. **3***a*-**3***b* and **4***a*-**4***c*. The mechanical portion can include some or all of the components needed for rotational motion of knob **18**, transverse motion of knob **18**, the push and/or pull motion of knob **18**, and force feedback in any or all of these degrees of freedom of the knob.

[**0093**] Mechanical portion **200** preferably includes sensors **214**, actuator **70**, and mechanism **216**. Sensors **214** sense the position, motion, and/or other characteristics of knob **18** along one or more degrees of freedom and provide signals to microprocessor **202** including information representative of those characteristics. Typically, a sensor **214** is provided for each degree of freedom along which knob **18** can be moved, or, a single compound sensor can be used for multiple degrees of freedom. Sensors **214** can include sensor **76**, switch **52**, and switch **58** as shown in FIGS. **3***a*-**3***b*. For example, one switch **52** of FIGS. **3***a*-**3***b* or switch **90** of FIG. **4***c* can include a sensor switch for each transverse direction **28** that the knob **18** can be moved. Examples of sensors suitable for rotary sensor **70** of FIGS. **3***a*-**3***b* and **4***a*-**4***c* include optical encoders, analog sensors such as potentiometers, Hall effect magnetic sensors, optical sensors such as a lateral effect photo diodes, tachometers, and accelerometers. Furthermore, both absolute and relative sensors may be used.

[**0094**] In those embodiments including force feedback, actuator **70** transmits forces to knob **18** in one or more directions in a rotary degree of freedom in response to signals output by microprocessor **202** or other electronic logic or device, i.e., it is "electronically-controlled." The actuator **70** produces electronically modulated forces which means that microprocessor **202** or other electronic device controls the application of the forces. Typically, an actuator **70** is provided for each knob **18** that includes force feedback functionality. In some embodiments, additional actuators can also be provided for the other degrees of freedom of knob **18**, such as the transverse motion of the knob **18** and/or the push or pull motion of the knob. The actuators, such as actuator **70**, can include active actuators, such as linear current control motors, stepper motors, pneumatic/hydraulic active actuators, a torquer (motor with limited angular range), voice coil actuators, etc. Passive actuators can also be used, including magnetic particle brakes, friction brakes, or pneumatic/hydraulic passive actuators, and generate a damping resistance or friction in a degree of motion. In some embodiments, all or some of sensors **214** and actuator **70** can be included together as a sensor/actuator pair transducer, as shown in FIGS. **3***a*-**3***b* for actuator **70** and sensor **76**.

[**0095**] Mechanism **216** is used to translate motion of knob **18** to a form that can be read by sensors **214**, and, in those

embodiments including force feedback, to transmit forces from actuator **70** to knob **18**. Examples of mechanism **216** are shown with respect to FIGS. **3***a*-**3***h* and **4***a*-**4***c*. Other types of mechanisms can also be used, as disclosed in U.S. Pat. Nos. 5,767,839, 5,721,566, 5,805,140, and co-pending patent application Ser. Nos. 08/664,086, 08/709,012, and 08/736,161, all incorporated by reference herein.

[**0096**] Also, a drive mechanism such as a capstan drive mechanism can be used to provide mechanical advantage to the forces output by actuator **70**. Some examples of capstan drive mechanisms are described in U.S. Pat. No. 5,731,804 and co-pending patent application Ser. Nos. 08/961,790, 08/736,161, all incorporated by reference herein. Alternatively, a belt drive system, gear system, or other mechanical amplification/transmission system can be used.

[**0097**] Other input devices **220** can be included in interface device **10** and send input signals to microprocessor **202**. Such input devices can include buttons, such as buttons **16** on front panel **12** as shown in FIG. **1**, used to supplement the input from the knob to the device **10**. Also, dials, switches, voice recognition hardware (e.g. a microphone, with software implemented by microprocessor **202**), or other input mechanisms can be used, can also be included to send a signal (or cease sending a signal) to microprocessor **202** or to the actuator **70** or actuator interface **210**, indicating that the user is not gripping the knob **18**, at which point all output forces are ceased for safety purposes. Such safety switches are described in U.S. Pat. No. 5,691,898 incorporated by reference herein.

[**0098**] Furthermore, a safety or "deadman" switch **222** can optionally be included for the knob **18** in those implementations providing force feedback on the knob. The safety switch prevents forces from being output on the knob when the user is not contacting or using it, and to prevent the knob from spinning on its own when the user is not touching it. In one embodiment, the safety switch detects contact of a user's digit (finger, thumb, etc.) with the knob **18**. Such a switch can be implemented as a capacitive sensor or resistive sensor, the operation of which is well known to those skilled in the art. In a different embodiment, a switch or sensor that detects pressure on the knob **18** from the user can be used. For example, a switch can be sensitive to a predetermined amount of pressure, which will close the switch. Alternatively, a pressure magnitude sensor can be used as the safety switch, where forces are output on the knob only when a pressure magnitude over a minimum threshold is sensed. A pressure requirement for safety switch **222** has the advantage of ensuring good contact between finger and knob before forces are Output; output forces are enabled only when the user is moving or actively using the knob. Thus, if the user simply rests his or her finger lightly on the knob without intending to use it, no forces will be output to surprise the user.

[**0099**] Other microprocessor **224** can be included in some embodiments to communicate with local microprocessor **202**. Microprocessors **202** and **224** are preferably coupled together by a bi-directional bus **226**. Additional electronic components may also be included for communicating via standard protocols on bus **226**. These components can be included in device **10** or another connected device. Bus **226** can be any of a variety of different communication busses. For example, a bi-directional serial or parallel bus, a wireless link, a network architecture (such as Canbus), or a uni-directional bus can be provided between microprocessors **224** and **202**.

[**0100**] Other microprocessor **224** can be a separate microprocessor in a different device or system that coordinates operations or functions with the device **10**. For example, other microprocessor **224** can be provided in a separate control subsystem in a vehicle or house, where the other microprocessor controls the temperature system in the car or house, or the position of mechanical components (car mirrors, seats, garage door, etc.), or a central display device that displays information from various systems. Or, the other microprocessor **224** can be a centralized controller for many systems including device **10**. The two microprocessors **202** and **224** can exchange information as needed to facilitate control of various systems, output event notifications to the user, etc. For example, if other microprocessor **224** has determined that the vehicle is overheating, the other microprocessor **224** can communicate this information to the local microprocessor **202**, which then can output a particular indicator on display **14** to warn the user. Or, if the knob **18** is allowed different modes of control, the other microprocessor **224** can control a different mode. Thus, if the knob **18** is able to control both audio stereo output as well as perform temperature control, the local microprocessor **202** can handle audio functions but can pass all knob sensor data to other microprocessor **224** to control temperature system adjustments when the device **10** is in temperature control mode.

[**0101**] In other embodiments, other microprocessor **224** can be a microprocessor in a host computer, for example, that commands the local microprocessor **202** to output force sensations by sending host commands to the local microprocessor. The host computer can be a personal computer, workstation, video game console, or other computing or display device, set top box, "network-computer", etc. Besides microprocessor **224**, the host computer preferably includes random access memory (RAM), read only memory (ROM), input/output (I/O) circuitry, and other components of computers well-known to those skilled in the art. The host computer can implement a host application program with which a user interacts using knob **18** and/or other controls and peripherals. The host application program can be responsive to signals from knob **18** such as the transverse motion of the knob, the push or pull motion, and the rotation of the knob (e.g., the knob **18** can be provided on a game controller or interface device such as a game pad, joystick, steering wheel, or mouse that is connected to the host computer). In force feedback embodiments, the host application program can output force feedback commands to the local microprocessor **202** and to the knob **18**. In a host computer embodiment or other similar embodiment, microprocessor **202** can be provided with software instructions to wait for commands or requests from the host computer, parse/decode the command or request, and handle/control input and output signals according to the command or request.

[**0102**] For example, in one force feedback embodiment, host microprocessor **224** can provide low-level force commands over bus **226**, which microprocessor **202** directly transmits to the actuators. In a different force feedback local control embodiment, host microprocessor **224** provides high level supervisory commands to microprocessor **202** over bus

226, and microprocessor **202** manages low level force control loops to sensors and actuators in accordance with the high level commands and independently of the host computer. In the local control embodiment, the microprocessor **202** can independently process sensor signals to determine appropriate output actuator signals by following the instructions of a "force process" that may be stored in local memory **206** and independently calculation instructions, formulas, force magnitudes (force profiles), and/or other data. The force process can command distinct force sensations, such as vibrations, textures, jolts, or even simulated interactions between displayed objects. Such operation of local microprocessor in force feedback applications is described in greater detail in U.S. Pat. No. 5,734,373, previously incorporated herein by reference.

[**0103**] In an alternate embodiment, no local microprocessor **202** is included in interface device **10**, and a remote microprocessor, such as microprocessor **224**, controls and processes all signals to and from the components of interface device **10**. Or, hardwired digital logic can perform any input/output functions to the knob **18**.

[**0104**] While this invention has been described in terms of several preferred embodiments, there are alterations, modifications, and permutations thereof which fall within the scope of this invention. It should also be noted that the embodiments described above can be combined in various ways in a particular implementation. Furthermore, certain terminology has been used for the purposes of descriptive clarity, and not to limit the present invention. It is therefore intended that the following appended claims include such alterations, modifications, and permutations as fall within the true spirit and scope of the present invention.

That which is claimed is:

1. A device comprising:

a manipulandum configured to be displaced in a degree of freedom;

a means for sensing a displacement of said manipulandum in said degree of freedom;

a means for selecting a mode associated with said displacement of said manipulandum in said degree of freedom, said mode comprising at least one of a position control mode and a rate control mode;

an actuator configured to output a processor-controlled force sensation to said manipulandum, said force sensation associated with said mode; and

a processor configured to receive a sensing signal from said sensing means and to output to the actuator a control signal associated with the sensing signal, the control signal configured to cause said actuator to output the processor-controlled force sensation.

2. The device of claim 1, wherein said degree of freedom comprises a first degree of freedom and a second degree of freedom.

3. The device of claim 2, wherein the first degree of freedom comprises a rotary degree of freedom, and the second degree of freedom comprises a translatory degree of freedom, and wherein the translatory degree of freedom is co-axial with the axis of rotation of the rotary degree of freedom.

4. A method comprising:

providing a manipulandum configured to be displaced in a first degree of freedom and a second degree of freedom;

providing a means for sensing a position of said manipulandum in the first degree of freedom;

providing a means for selecting a mode associated with the position of said manipulandum, said mode comprising at least one of a position control mode and a rate control mode;

providing an actuator configured to output a processor-controlled force sensation to said manipulandum, said force sensation associated with said mode; and

providing a processor configured to control said force sensation output from said actuator and to receive a signal from said sensing means, said first microprocessor configured to associate a value with a position of said manipulandum in said position control mode and to control a rate of change of said value in said rate control mode.

5. The device of claim 4, wherein the first degree of freedom comprises a rotary degree of freedom, and the second degree of freedom comprises a translatory degree of freedom, and wherein the translatory degree of freedom is co-axial with the axis of rotation of the rotary degree of freedom.

6. A device comprising:

a manipulandum coupled to a grounded surface, the manipulandum moveable in a rotary degree of freedom and a transverse degree of freedom;

a first sensor configured to sense a rotary position of the manipulandum and transmit a first sensor signal to a processor;

a second sensor configured to detect a transverse position of the manipulandum and transmit a second sensor signal to a processor;

a processor configured to receive the first and second sensor signals and to transmit an actuator signal to the actuator, the actuator signal configured to cause an actuator to output a force in the rotary degree of freedom.

7. The device of claim 6, wherein the second sensor signal is based at least in part on the transverse position, and is configured to select a mode of operation of the manipulandum.

8. The device of claim 7, wherein the mode of operation comprises a first mode of operation and a second mode of operation.

9. The device of claim 8, wherein the force comprises a first force and a second force, and wherein the first force is configured to be output during the first mode of operation, and the second force is configured to be output during the second mode of operation.

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