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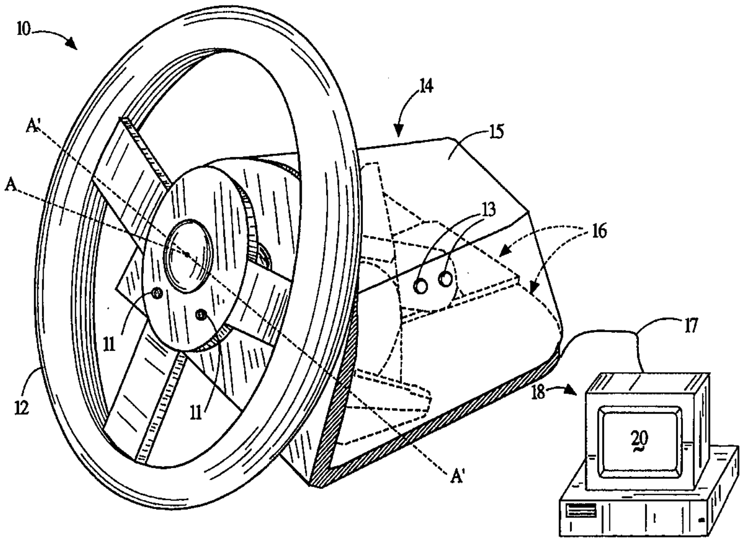

(57) Abstract

Improvements for force feedback transmission mechanisms include a transmission system having multiple stages, including an actuator stage and one or more additional stages, such as an output stage. The actuator stage includes a rotatable capstan pulley and a cylindrical capstan drum coupled to the pulley by a cable. The cable is coupled to the capstan drum at both ends, and causes the capstan drum to rotate for multiple revolutions. A capstan drive mechanism can include a capstan drum that has a curved end over which a cable is routed, the curved end including flanges to substantially prevent cable slippage. The capstan drum can include a tensioning spring member coupled to one or both ends of the cable for tensioning the cable. A different mechanism provides selective engagement of spring members to a user manipulatable object, where the spring members bias the object to a desired center position when the device is unpowered.

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IMPROVEMENTS FOR FORCE FEEDBACK TRANSMISSION MECHANISMS

BACKGROUND OF THE INVENTION

The present invention relates generally to transmission systems for transmitting force and motion in a mechanical system, and more particularly to mechanical force feedback interface devices that interface humans and computers.

Mechanical transmission systems are used in a variety of applications for various purposes. One type of application that uses mechanical transmission systems is human/computer interface devices. Such devices allow a user to input commands or other data to a computer system and thereby interact with an application program executing on the computer. One type of application program displays graphical or visual environments on a display device with which users interact to perform a variety of interfacing activities, such as games or graphical simulations. In many types of games, a graphical or visual environment is displayed on a display device of the computer including one or more graphical representations of objects such as vehicles. For example, one popular type of game is a vehicle simulation game, where the player controls a vehicle such as an automobile, military tank, aircraft, space ship, etc. through a virtual environment. The graphical environment includes other objects and features with which the player's vehicle may interact, such as other vehicles, a side railing on a race track, a missile or other projectile, etc. Simulations are similar to such games except that the realism of the graphical environment and the interaction with such are typically more stressed since the simulation is used for training or learning purposes rather than entertainment. The interface device allows the user to control his or her vehicle in the environment, usually through physical motion in degrees of freedom provided by the interface device.

Users can interact with the displayed environment by inputting commands or data from the interface device. Popular interface devices include joysticks, "joypad" button controllers, mice, trackballs, styluses, tablets, pressure spheres, foot or hand pedals, or the like, that are connected to the computer system controlling the displayed environment. The computer updates the environment in response to the user's manipulation of a moved manipulandum such as a joystick handle or mouse, and provides visual feedback to the user using the display screen.

One popular interface device for use with vehicle simulations and games is a steering wheel controller. The controller simulates the steering wheel in an automobile or other vehicle and typically includes a wheel rotably coupled to a base support to provide a single rotary degree of freedom. As the player turns the wheel, a sensor relays a signal to a connected host computer which controls the display of the simulated vehicle under control and updates the graphical environment accordingly. In addition, other controls may also be provided such as buttons, dials, levers, etc. similar to such controls in a real vehicle in response to which the host computer similarly updates the graphical environment.

Force feedback steering wheel controllers and other interface devices are also known in the prior art. Force feedback provides the user with sensory "haptic" (feel) information about a simulated environment. Thus these devices typically include more elaborate mechanical transmission systems to convey the forces from actuators to the interface object manipulated by the user. For example, recently-available force feedback steering wheels for the home consumer market provide forces to the steering wheel and user by providing a motor coupled to the rotary shaft of the steering wheel. The host computer or other electronic controller can output control signals at appropriate times to provide forces on the steering wheel in conjunction with events in the graphical environment. For example, when the user's vehicle moves off the road onto a rough shoulder, forces can be output on the steering wheel to cause the wheel to jerk in random directions to simulate a bumpy feel and jolts caused by the rough surface. A collision into a railing on the road can cause a large jolt force on the steering wheel in a direction opposite to the direction of travel into the railing.

Force feedback interface devices, and other types of devices, typically use high fidelity mechanical transmission systems to transmit forces to the user object, i.e., transmission systems which transmit forces with little backlash, undesired play, and high bandwidth. Furthermore, the transmission system is often necessary to provide mechanical advantage to increase the magnitude of forces output by a motor, thus allowing smaller sized motors to be used as desired in home consumer interface devices. For example, currently-available force feedback steering wheel controllers use a transmission system to provide mechanical advantage to output the desired strength of forces; otherwise, a large motor must be used to provide the desired force magnitude, which can be expensive and bulky and is thus undesirable. In the prior art, transmission systems such as a pulley system provide the mechanical advantage, where, for example, one pulley is coupled to another through highly-tensioned belts. A large pulley ratio (gear ratio) is typically not desirable since too much friction is generated, leading to distortion of output forces. However, even if small pulley ratio is used, side loads on the steering wheel or other user object can be created by the highly-tensioned belts on the pulleys. These side loads may also distort forces unless high-quality bearings on the pulleys and other high-quality rotatable parts are used, which can greatly increase the expense of manufacturing the steering wheel controller. Such a result is not desirable in the competitive, low-cost consumer market. In other interface device embodiments, capstan drives are used, in which a cable rather than a belt is used between the pulley and drum. However, the capstan drive movement range of the prior art is limited, thus providing inherent limitations to the amount of mechanical advantage provided.

Other types of force feedback devices include joysticks. Commercially available force feedback devices include the ForceFX joystick from CH Products, Inc. and Immersion Corporation, and the Sidewinder Force Feedback Pro from Microsoft Corporation. One problem occurring in the commercially available force feedback devices is the free movement of the manipulandum, such as a joystick handle, when the device is not powered. For example, standard joysticks without force feedback capability typically include physical springs coupled between the joystick handle and the joystick base which provides a spring force on the handle and permanently functions to center the joystick handle in its degrees of freedom, causing the handle to be biased toward a straight and upright position and assisting in playing games. Force feedback joysticks, however, do not include such physical springs. This is because the forces provided by physical springs can interfere with the forces generated by the actuators of the force feedback device, which can greatly reduce the fidelity of generated forces. For example, if a vibration is to be output on the joystick, the force designer may not want a spring force from physical springs to be felt which would interfere with the vibration. However, a problem caused by the lack of physical springs in force feedback joysticks is that the joystick handles are not centered in an upright or other desired position. Although simulated spring forces can be output by the actuators to perform this centering function during normal joystick operation, it remains a problem when the joystick is not powered. For example, store owners or other vendors often display demonstration force feedback joysticks on shelves for users to test the way the handle grip feels. The demonstration joysticks are typically not powered, and since no physical springs are included, the joystick handles are tilted to one side, giving the undesired appearance of a faulty or broken joystick. In addition, spring forces on normal demonstration joystick models give the user an indication of how the joystick feels during normal operation when spring forces are present, which is not possible with unpowered force feedback joysticks. In other situations, the user may not be powering a force feedback joystick for some reason while playing a game, and the normal centering spring forces would not be present on the handle, thus inhibiting game play.

A different problem occurs in force feedback peripherals having a force transmission mechanism such as a cable drive. In some cable drive systems, an actuator transmits forces to a manipulandum by rotating a cable attached to a capstan drum, where the drum is coupled to the manipulandum. The cable typically rides along the end of the drum as the drum is rotated by the actuator. However, if the capstan drum is rotated too far, the cable can move off the end or side of the drum, causing the transmission system to become inoperative. A different problem with the cable is keeping it correctly tensioned on the drum. When the cable has one or two ends that are rigidly attached to points on the drum, the assembly process for the system can become time consuming and expensive due to the requirements for tensioning the system. In addition, the cable typically requires re-tensioning as it becomes loose over time from use. Other problems occurring in commercially available force feedback devices include inaccuracies involved with sensing the position of the manipulandum and outputting forces on the manipulandum, such inaccuracies often contributed by plastic or other flexible components used in low-cost devices.

SUMMARY OF THE INVENTION

The present invention is directed to improvements for force feedback transmission mechanisms which, in a preferred embodiment, are used in a human-computer interface device connected to a host computer and which provides realistic force feedback to a user of the device. The interface device transmission system includes high bandwidth, low cost components well suited for the home consumer market.

More specifically, a transmission system of the present invention for transmitting motion and force between a driven object and an actuator includes an actuator stage coupled to the actuator and an output stage coupled to the actuator stage. The actuator stage includes a capstan pulley coupled to the actuator that is rotatable about a first axis. A capstan drum is rotatable about a second axis, and a flexible member, such as a cable, couples the capstan pulley to the capstan drum. The flexible member is coupled to the capstan drum at both ends of the flexible member, and the capstan pulley causes the capstan drum to rotate about the second axis for multiple revolutions. The output stage is coupled to the driven object to rotate the driven object. In the preferred embodiment, the output stage includes a second capstan pulley rotatable about the second axis, a second capstan drum rotatable about a third axis and coupled to the driven object, and a second flexible member, such as a cable, coupling the second pulley to the second drum. The capstan drums are preferably cylindrical, and a spring member is preferably coupled between one end of the flexible member and the capstan drum to provide tension in the flexible member. The capstan drum(s) can also include grooves for guiding the flexible member thereon.

Another aspect of the present invention provides an interface device for inputting motion signals to a connected host computer in response to manipulations of the interface by the user, and for providing force feedback to the user. The host computer preferably implements a graphical environment with which the user interacts using the interface device. The interface device includes a user manipulatable object, preferably a steering wheel, joystick, or like object, contacted and manipulated by a user and moveable in a rotary degree of freedom. A sensor detects motion of the user object and an actuator provides forces on the user object as commanded by the host computer. A capstan drive assembly couples the actuator to the user object and includes one or more stages similar to the transmission system described above.

Another aspect of the present invention includes a method and mechanism for providing selective engagement of spring members to a user manipulatable object in a force feedback interface device. A grounded member, a moveable member included in a force feedback mechanism and moveable in a degree of freedom to transmit forces to a user manipulatable object of the force feedback interface device, and a spring member that can be selectively coupled and selectively decoupled between the grounded member and the moveable member are included. The spring member preferably provides a spring force on the moveable member that biases the user manipulatable object to a desired position, such as the center of the degree of freedom. The force feedback interface device, including its mechanism, sensors, and actuators, can take a variety of forms.

A dynamic calibration procedure of the present invention for reducing inaccuracies when sensing the position of the user manipulandum is also preferably employed in a device using, for example, a transmission system such as described herein implemented with semi-flexible materials such as plastic. The dynamic calibration procedure normalizes the sensed position of the user manipulandum based on the range of manipulandum movement sensed up to the current point in time. To prevent detecting a "false" limit caused by an actuator overstressing the transmission system, the calibration procedure preferably only reads new range limits when the actuator is not outputting a force in the direction of that limit.

In a different aspect of the present invention, a force feedback interface device includes a user manipulandum for physical contact by a user, a sensor for detecting a position of the manipulandum, an actuator for applying a force to the manipulandum, and a linkage mechanism providing a degree of freedom and transmitting force from the actuator to the manipulandum. Furthermore, a capstan drive mechanism is coupled between actuator and linkage mechanism and includes a capstan pulley, a moveable capstan drum, and a cable coupling the pulley to the drum. In one aspect of the present invention, the capstan drum includes a curved end over which the cable is routed, the curved end including flanges arranged on sides of the curved end to substantially prevent the cable from slipping off the sides of the end. The curved end is preferably a sector, i.e., a portion of a circumference of a cylinder. In a different aspect of the present invention, the capstan drum includes a tensioning spring member coupled to one or both ends of the cable for tensioning the cable.

The improvements of the present invention provide a transmission system and force feedback interface device that provides high bandwidth, realistic forces to a user of the device. The capstan drive mechanism provides to output forces a mechanical advantage superior to designs in the prior art which use an equivalent-sized motor. The selective spring mechanism provides a mechanical spring bias on the user manipulandum in instances when forces are not output or power is not provided to the device, yet allows high-fidelity forces to be transmitted during normal operation by decoupling the spring bias. The capstan drive improvements allow for a more durable drive transmission that reduces problems that might occur with a cable drive, such as the cable becoming loose or the cable slipping from a capstan drum. The dynamic calibration procedure addresses inaccuracies of a described embodiment of the device. The transmission improvements of the present invention allow low friction, more versatility, more durability, and greater ease of manufacturing and assembly, thus providing a device well suited for the consumer market.

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

Figure 1 is a perspective view of a force feedback interface device and system suitable for use with the present invention;

Figure 2 is a perspective view of the interface device of Figure 1 showing the interface inside the housing of the device;

Figure 3 is a perspective view of the transmission mechanism of the present invention;

Figures 4a-d are top plan, front, side elevational, and perspective views of the mechanism of Figure 3;

Figure 5 is a perspective view of an alternative embodiment of an interface device including a speed reduction device of the present invention;

Figure 6 is a perspective view of a second embodiment of a force feedback interface device and system suitable for use with the present invention;

Figure 7 is a perspective front view of an embodiment of the force feedback interface device of Figure 6;

Figure 8 is a perspective rear view of the embodiment of the force feedback interface device of Figure 7;

Figure 9 is a perspective detailed view of a capstan drive mechanism of the present invention used for two degrees of freedom;

Figures 10a and 10b are perspective views of the force feedback interface device of Figure 7 showing the range of motion of the handle;

Figure 11 is a perspective view of a releasable spring mechanism of the present invention;

Figure 12 is a side elevation view of the releasable spring mechanism in an engaged position;

Figure 13 is a side elevation view of the releasable spring mechanism in a disengaged position; and

Figure 14 is a block diagram of a host computer and the force feedback interface device of the present invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

FIGURE 1 is a perspective view of a first embodiment of a force feedback interface device 10 suitable for use with a transmission system of the present invention. Device 10 is capable of providing input to a host computer based on the user ís manipulation of the device and capable of providing force feedback to the user of the steering wheel based on events occurring in a program implemented by the host computer. An embodiment of the transmission device of the present invention will be described with reference to the interface device 10. However, the transmission system described herein may also be used in other devices or applications that require high bandwidth force, and motion transmission, low backlash, and/or high mechanical advantage, such as radar antennae, satellite dishes, precise measurement systems, or other devices.

Interface device 10 includes a wheel 12, a base or support 14, an interface 16, and a host computer 18. Steering wheel 12 is an object that is preferably grasped or gripped and manipulated by a user. By "grasp," it is meant that users may releasably engage or contact a portion of the object in some fashion, such as by hand, with their fingertips, etc. In the described embodiment, wheel 12 is a tube provided in a roughly circular, toroidal shape so that a user's hands may comfortably grasp the wheel at any point of its circumference and move it in the provided degree of freedom. It should be noted that the term "steering wheel" or "wheel" as used herein, indicates an object or manipulandum 12 generally shaped to be grasped or contacted by a user and moved in a rotary degree of freedom. Thus, a solid or hollow wheel, a half or partial wheel, a cylinder, rectangular-shaped object, flat strip, steering bar or grip having bent ends, or any type of grip that may be rotated by the user can be considered a "steering wheel."

In other embodiments of interface device 10, a wide variety of other types of user objects 12 can be used. For example, a joystick having one or more degrees of freedom can be provided, as well as a mouse, stylus, medical instrument, sphere, cubical- or other-shaped hand grips, a receptacle for receiving a finger or a stylus, or other objects.

Base 14 supports the steering wheel 12 on a grounded surface, such as a table top, desk surface, floor, etc. Within the housing 15 of base 14 is an interface 16 for interfacing mechanical and electrical input and output between the wheel 12 and host computer 18 implementing the application program, such as a simulation or game environment. Interface 16 preferably includes a mechanical portion and an electrical portion for interfacing motion with electrical signals and vice-versa. The mechanical portion of the interface 16 provides a rotary degree of freedom to wheel 12 about axis A. In other embodiments, additional degrees of freedom can be provided. For example, the wheel 12 might be operative to translate in a linear degree of freedom along axis A, toward or away from the base 14, to control a different function of a simulated vehicle, such as velocity. Or, the wheel or a portion of the wheel (or grip, bar, etc.) might be operative to rotate about another axis, such as axis A'. These additional degrees of freedom can also be sensed and/or actuator similarly to the main rotary degree of freedom, as described below.

Additional input controls can be provided on the wheel 12 or on the base 14. For example, buttons 11 can be provided on the center hub of wheel 12, or the entire central area of the hub can be a button. Also, controls such as buttons 13 can be provided on base 14 and selected by the user while using the wheel 12. In other embodiments, different types of controls can be provided, such as dials, switches, levers, contact or light sensors, etc. Separate controls can also be connected to the device 10 through wires or other transmission means. For example, a separate foot pedal unit coupled to device 10 by a bus or cord can send a signal to device 10 and host 18 to control the acceleration of a simulated vehicle while wheel 12 steers the vehicle.

The electronic portion of interface 16 translates the mechanical motion of the wheel 12 into an electrical form which can be interpreted by host computer 18. The user manipulates wheel 12 and the position of the wheel in its degree of freedom is read by a position sensor of the interface 16. The sensor then provides position information to host computer 18 and any application program implemented by the host. In addition, host computer 18 and/or interface 16 provide force feedback signals or commands to an actuator included in interface 16, and the actuators generate forces on wheel 12 in the rotary degree of freedom. The user experiences the forces generated on the wheel 12 as realistic simulations of force sensations such as jolts, textures, ìbarrierî forces, and the like. The electronic portion of interface 16 is preferably included within the base 14 of the wheel device 10, but can alternatively be included in host computer 18 or as a separate unit with its own housing. In the preferred embodiment, interface 16 includes a local microprocessor distinct and separate from any microprocessors in the host computer 18 to control force feedback on wheel device 10 independently of the host computer, as well as sensor and actuator interfaces that convert electrical signals to appropriate forms usable by the mechanical portion of interface 16 and host computer 18. A suitable embodiment of the electrical portion of interface 16 is described in detail with reference to Figure 6.

The interface 16 can be coupled to the computer 18 by a bus 17, which communicates signals between interface 16 and computer 18. In some embodiments, bus 17 can provide power to the interface 16. In other embodiments, signals can be sent between interface 14 and computer 18 by wireless transmission/reception. The interface 16 can also receive inputs from other input devices or controls that are associated with steering wheel device 10 and can relay those inputs to computer 18. For example, commands sent by the user activating a button, lever, or dial on wheel 12 or base 14 can be relayed to computer 18 by interface 16 to implement a command or cause the computer 18 to output a command to the interface 16. Such input devices are described in greater detail with respect to Figure 6.

Host computer 18 is preferably a personal computer or workstation, such as an IBM-PC compatible computer or Macintosh personal computer, or a SUN, Hewlett-Packard, or Silicon Graphics workstation. For example, the computer 18 can operate under the Windows® or MS-DOS operating system in conformance with an IBM PC standard. Alternatively, host computer system 18 can be one of a variety of home video game systems commonly connected to a television set, such as systems available from Nintendo, Sega, or Sony. In other embodiments, home computer system 18 can be a "set top box" which can be used, for example, to provide interactive television functions to users, or a "network-"or "internet-computer" which allows users to interact with a local or global network using standard connections and protocols such as used for the Internet and World Wide Web. Host computer preferably includes a host microprocessor, 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.

Host computer 18 preferably implements a host application program with which a user is interacting via steering wheel 12 and other peripherals, if appropriate, and which can include force feedback functionality. For example, the host application program can be a simulation, video game, Web page or browser that implements HTML or VRML instructions, scientific analysis program, virtual reality training program or application, or other application program that utilizes input of wheel 12 and outputs force feedback commands to the wheel 12. Herein, for simplicity, operating systems such as Windows™, MS-DOS™, MacOS™, Unix, etc. are also referred to as "application programs." In one preferred embodiment, an application program provides a simulation or game environment with which a user or user-controlled entity interacts. For example, many game application programs include force feedback functionality and may communicate with the force feedback interface device 10 using a standard protocol/drivers such as I-Force available from Immersion Corporation.

Herein, computer 18 may be referred as displaying "graphical objects" or "computer objects." These objects are not physical objects, but are logical software unit collections of data and/or procedures that may be displayed as images by computer 18 on display screen 20, as is well known to those skilled in the art. A displayed cursor or a simulated cockpit of a car or aircraft might be considered a graphical object. The host application program checks for input signals received from the electronics and sensors of interface 16, and outputs force values and/or commands to be converted into forces on wheel 12. Suitable software drivers which interface such simulation software with computer input/output (I/O) devices are available from Immersion Human Interface Corporation of San Jose, California.

Display device 20 can be included in host computer 18 and can be a standard display screen (LCD, CRT, etc.), 3-D goggles, or any other visual output device. Typically, the host application provides images to be displayed on display device 20 and provides other feedback, such as auditory signals. For example, display screen 20 can display images from a game or simulation. Images describing a moving, first person point of view can be displayed, as in a virtual reality game. Or, images describing a third-person perspective of objects, backgrounds, etc. can be displayed. Other types of graphical environments implemented by host computer 18 can be displayed in other embodiments.

FIGURE 2 is a perspective view of the preferred embodiment of the wheel interface device 10 with the cover portion of base housing 15 removed, showing the mechanical portion 22 of interface 16 for providing mechanical input and output in accordance with the present invention. Mechanical portion 22 includes an actuator 24, a capstan drive assembly 26, and a sensor 28. The electronic portion 30 of the interface 16 is also preferably positioned within the base housing 15.

Actuator 24 outputs forces in response to commands from the electronic portion 30 of the interface 16. In the described embodiment, actuator 24 is a rotary DC motor that rotates a shaft coupled to the capstan drive mechanism 26. Due to the mechanical advantage provided by the capstan drive mechanism 26, the actuator 24 need not have a relatively large size to produce realistic forces on wheel 12. Actuator 24 is grounded by securing its housing to a grounded plate 32 that is coupled to base 14, where plate 32 preferably is angled approximately perpendicularly to the axis of rotation A. Actuator 24 also preferably includes a skewed rotor to minimize the magnetic "cogging" effect that can occur with traditional DC motors to distort the fidelity of forces. In other embodiments, other types of actuators may be used to provide forces or resistance to motion of the steering wheel 12. For example, a pneumatic or hydraulic piston or actuator, a voice coil actuator, passive brake, damper element, or other type of actuator can be used.

Capstan drive mechanism 26 is provided to increase the output force from the actuator 24 as applied to the steering wheel 12. Capstan drive mechanism 26 is coupled to the rotating shaft of actuator 24, and is coupled to a shaft of steering wheel 12. In the described embodiment, the mechanism includes capstan drums and capstan pulleys which are rotatably coupled to either grounded plate 32 or to a grounded front panel 34, where the plate 34 and panel 32 are approximately parallel to each other. Thus, the shaft of steering wheel 12 extends through and is rotatably coupled to the front panel 34, and the capstan drums are coupled to front panel 34 or plate 32. Support posts 33, or similar supports, preferably couple the plate 32 to the panel 34 and space plate 32 and panel 34 at the desired distance from each other. In the preferred embodiment, the mechanism 26 preferably includes multiple stages for scaling the output force and provides minimal friction and inexpensive parts. A two stage mechanism is illustrated; thus, a first capstan pulley 36, a first capstan drum 38, and a second capstan pulley 40 are coupled to grounded plate 32, and a second capstan drum 42 is coupled to front panel 34. The components and operation of the capstan drive mechanism 26 is described in greater detail with reference to Figure 3.

A sensor 28 is provided to sense the rotation of the steering wheel 12 and report an electrical signal to the electronic portion 30 of the steering wheel device 10. Sensor 28, in the described embodiment, is coupled to a rotating shaft of the second capstan drum 42, which is coupled to and rotates in accordance with the steering wheel 12. In alternate embodiments, the sensor 28 can be positioned at other rotating positions of the interface device. For example, sensor 28 can be provided on the rotating shaft of first capstan drum 36. In such a position, since the first capstan drum 36 rotates at a different rate than the steering wheel 12, the electronic portion 30 of the interface 16 or host computer 18 can take the different rotational rate into account to determine the actual rotational position of the wheel 12. In the described embodiment, sensor 28 is an analog potentiometer having a body coupled to grounded plate 32, and a rotating shaft coupled to wheel 12 or shaft 57. Alternatively, the sensor 28 can be a lateral effect photo diode; for example, an emitter can be placed on the rotating shaft 57, and a detector can be coupled to plate 32, e.g., a detector sector or ring that detects the beam emitted from the emitter parallel to axis A toward plate 32 as the beam rotates about axis A. A digital encoder (e.g. having an encoder wheel), a magnetic encoder, etc. may also be used as sensor 28. In yet another embodiment, a "light pipe" can be used. In other embodiments, sensor 28 and actuator 24 can be included in a single transducer housing, for example, at the position of actuator 24.

Electronic portion 30 is preferably provided on a bottom support plate 44 of the base 14 and includes electronic components such as amplifiers, microprocessors, other digital circuitry, power supply, and other components as detailed with reference to Figure 6, below.

In other embodiments, additional members or components can be included in interface device 10 to provide the desired degrees of freedom for user object 12. For example, steering wheel 12 may be provided with translational, linear degree of freedom along axis A. Such a linear degree of freedom can be translated into a rotary degree of freedom for use with a capstan drive mechanism 26 using mechanisms well known in the art. For example, a friction roller can be rotated by a linearly-moving member that frictionally engages the roller at a tangential point of the roller. Or, a universal joint such as a ball joint can connect a linearly-moving member to a rotationally-moving member. Other types of user objects may also be used similarly. Additional degrees of freedom can also be provided in interface device 10 which are not coupled to a capstan drive mechanism 26 of the present invention.

FIGURE 3 is a perspective view of the capstan drive mechanism 26 of the present invention used in the steering wheel interface device 10. Capstan drive mechanism 26 includes first capstan pulley 36, first capstan drum 38, second capstan pulley 40, and second capstan drum 42.

The first stage of capstan drive mechanism 26 includes first capstan pulley 36 and firs capstan drum 38. First capstan pulley 36 is rigidly coupled to the rotatable shaft of actuator 24 and thus may rotate about axis B. Preferably, the housing of actuator 24 is coupled to grounded plate 34 (as shown in Figure 2), so that capstan pulley 36 is also grounded and rotationally coupled to actuator 24. Pulley 36 is rotationally fixed to the actuator shaft; in some embodiments, pulley 36 can also be allowed to move along axis B. First capstan pulley 36 is coupled to first capstan drum 38 by a first cable 50. First capstan drum 38 is preferably provided as a circular-shaped (cylindrical) drum that is rigidly coupled to a central shaft 52, where shaft 52 is rotatably coupled to the grounded plate 34 so that drum 38 and shaft 52 are rotatable about axis C. Drum 38, pulley 40, and shaft 52 are rigidly coupled together; thus, drum 38 and pulley 40 rotate together. Drum 38 and pulley 40 need not be translationally fixed; e.g. in an alternative embodiment, pulley 40 can translate with the cable along axis C. Cable 50 is wrapped around both first pulley 36 and first drum 38, thereby coupling the pulley and drum so that drum 38 rotates when pulley 36 is rotated by actuator 24. Cable 50 preferably has an approximately circular cross-section.

Cable 50 is preferably wrapped around pulley 36 and drum 38 multiple times to allow the drum 38 to rotate for multiple revolutions. In the described embodiment, the cable 50 is wrapped around pulley 36 two times, and is wrapped around first drum 38 three and a half times, where one end of the cable 50 is tied to the first drum 38 at a position 54, and the other end of the cable 50 is tied to the first drum 38 at position 56. Preferably, spring tension is provided at position 56, which is described in greater detail below. In other embodiments, the cable 50 can be wrapped around drum 50 and/or pulley 36 for additional (or less) times. For example, the three and a half turns (or "windings") on drum 38 are adequate in the described embodiment to provide about 180 degrees of rotation to the steering wheel 12. Four and a half to five turns about drum 38 can provide about 270 degrees of rotation. Additional turns of the cable about the drum can provide a greater rotation range as desired.

The multiple wraps of cable around drum 38 are advantageous in the present invention since they allow the capstan drum 38 to rotate for multiple revolutions. This allows the capstan drive mechanism 26 to provide mechanical advantage to a much greater range of rotation of user object 12. In the prior art, capstan drives included drums that rotate only a fraction of a complete revolution, thereby severely limiting the rotational range of any member or user object coupled to the capstan drive. In addition, the multiple rotations of the drum allow diameter of the drum 38 to be made smaller, which is desirable for consumer products such as interface device 10. The multiple revolutions of cable 50 on pulley 36 allow a much greater grip of the cable on the pulley, leading to less slipping, less friction, and greater fidelity in transmitted forces. In the preferred embodiment, pulley 36 also includes grooves 48, similar to threads on a screw. Since cable 50 is wrapped multiple times around the pulley, the grooves 48 function to guide the multiple wraps on the pulley as the pulley is rotated. Without the grooves, the cable would tend to migrate to one side of the pulley and slip off the edge of the pulley. In addition, the grooves 48 allow the cable to be routed onto the capstan drive mechanism more easily in a manufacturing environment. In alternate embodiments, the first capstan drum 38 can be provided with grooves in its edge instead of (or in addition to) providing grooves in pulley 36 to guide the multiple wraps of cable 50 on the drum 38. In some embodiments, it may be easier in a manufacturing process to provided grooves in drum 38 rather than pulley 36.

The second illustrated stage of the capstan mechanism includes second capstan pulley 40 and second capstan drum 42. Second capstan pulley 40 is rigidly coupled to drum 38 (or rigidly coupled to shaft 52). Second capstan pulley 40 is thus rotatable about axis C with capstan drum 38. In the described embodiment, the central shaft 52 is rotatably coupled to the front panel 34 at the shaft end not coupled to grounded panel 32 (alternatively, shaft 52 can be coupled at only one end to plate 32 or panel 34). A second capstan drum 42 is rigidly coupled to the wheel shaft 57 of steering wheel 12 at axis A, where the wheel shaft 57 is rotatably coupled to the front panel 34 (shown in Figure 2). Thus, when second drum 42 rotates, the steering wheel 12 rotates in unison. In the described embodiment, second capstan drum 42 is a circular, cylindrical drum. Drum 42 (and drum 38) can be of any convenient diameter, as long as the desired scale ratio is achieved (described below). Second capstan pulley 40 is coupled to second capstan drum 42 by a cable 58, which is preferably wrapped multiple times around pulley 40 and multiple times around drum 42. In the preferred embodiment, cable 58 is wrapped four times around pulley 40 and two times around drum 42. As with the first capstan drum 38 and pulley 36, the cable 58 can be wrapped around pulley 40 and/or drum 42 additional or less times to provide a different rotational range (the cable need only be wrapped around drum 42 1/2 times to allow 180 degrees of travel for steering wheel 12). Cable 58 is preferably of a larger thickness than cable 50 since a greater force must be transmitted between second pulley 40 and second drum 42 than between first pulley 36 and first drum 38 (i.e., the force has been scaled higher when received by the second stage after the first stage). Pulley 40 preferably includes grooves similar to pulley 36, but can be provided without grooves in alternate embodiments.

The pulleys 36 and 40 and drums 38 and 42 need not be provided with grooves or threads for the wraps of cable 58 if only one wrap of cable around the respective component is provided. If multiple wraps are provided on either drum, then grooves on the corresponding pulley (or the drum itself) should be included to prevent the cable from slipping of the edge of the pulley (or if a large pulley is used). Of course, grooves can be provided in pulley 40 and/or drum 42 if desired. Cable 58 preferably is tied at both ends to drum 42, where a first end is coupled at position 60 and the second end is spring tensioned at a position 61, as described in greater detail below. In an alternative embodiment, cable 58 can be wrapped for additional times on drum 42 to relieve tension on the spring coupled at one end of the cable. This can prevent tension on the cable from over-tensioning the spring.

The capstan drive mechanism 26 of the present invention provides substantial advantages over the prior art mechanisms. Two stages of capstan mechanisms are provided in succession, where the first stage includes pulley 36, first drum 38, and cable 50, and where the second stage includes pulley 40, second drum 42, and cable 58. Each stage increases the magnitude of the forces output by the actuator on the wheel 12 by a large factor. It should be noted that more than two stages can be provided in capstan drive mechanism 26 for additional mechanical advantage. Additional stages can be coupled to previous stages similarly as the second stage is coupled to the first stage described above. For example, if additional stages are added, each drum of each stage can be made smaller to achieve the same mechanical advantage since each stage contributes to the overall mechanical advantage.

Each stage should be designed with an appropriate pulley to drum size ratio such that the mechanical advantage of all stages sums to a total desired mechanical advantage. Thus, if the first stage of a two stage mechanism provides a 4:1 mechanical advantage, and the second stage provides a 5:1 mechanical advantage, the total advantage is 20:1. Each stage provides a mechanical advantage based on the relative sizes of pulley and drum in a stage such that the mechanical advantage provided by one stage is the radius of the drum divided by the radium of the pulley. The mechanical advantage of each stage is multiplied together to result in the total mechanical advantage. Thus, a total mechanical advantage of 20 can be provided, for example, by making pulleys 36 and 40 one inch in diameter and making drum 38 four inches in diameter and drum 42 five inches in diameter. For example, using the proportions of drums and pulleys and the distances approximately shown in Figure 3, a scaling of 40:1 can be achieved between the force output by actuator 24 and the force felt by the user on steering wheel 12. With the relatively larger mechanical advantage provided by such a scheme, a much smaller and inexpensive motor 24 can be used to output forces to achieve the same (or better) quality of forces as in the prior art. In addition, since the capstan drives have very little friction, forces are scaled to an even greater extent than the frictional drives of the prior art (such as belt drives). Furthermore, the capstan drive systems provide this mechanical advantage without introducing backlash to the system. In addition, the capstan drive mechanisms provide no large side loads on the pulleys or drums, unlike the highly-tensioned belt drives of the prior art interface devices, such that expensive bearings are not necessary in the present invention to reduce friction. Since each end of the cables 50 and 58 is coupled to a drum 38 or 42 (or alternatively to a pulley), the tension in the cable can be properly and easily adjusted using a spring tension provided by a spring coupled at one end of the cable (described below). Thus there is no need to adjust the highly- tensioned loops of traditional belts provided between pulleys.

A further advantage of the capstan drive mechanism of the present invention is ease of assembly and manufacture. As explained above, the cables are easier to wind on the pulleys than assembling highly-tensioned belts as in the prior art. In addition, the configuration of drums 38 and 42, pulleys 36 and 40, and motor 24 allow easier assembly. For example, the first drum 38, motor 24, and pulley 36 can be initially coupled to plate 32 and the cable 50 can be wrapped between pulley 36 and drum 38. Since drum 42 and panel 34 are not yet placed, there is free access to the first stage for winding cable 50. Second drum 42 can then be installed and aligned with pulley 40, and cable 58 can be wrapped on pulley 40 while access is provided before panel 34 is placed. Panel 34 is then placed over shaft 57 and 42 and fixed to plate 32 by posts 33, followed by the placement of the wheel 12 on the shaft 57.

Many of the above components and configurations can be changed in alternate embodiments. For example, a single stage capstan mechanism can alternatively be provided, where a single capstan pulley is coupled to a single capstan drum by a cable. However, to achieve the desired scaling of force magnitudes using the same size actuator as in Figure 3, the capstan drum would have to be much larger, which in some embodiments is not practical. In other embodiments, one or both of the capstan drums 38 and 42 can be provided as sectors instead of circular disks, i.e. an angular portion of a circle can be used. Alternatively, one or more stages can provide a cylindrical drum, while one or more different stages can provide drums as sectors, e.g., the first stage drum can be cylindrical to allow multiple rotations while the second stage drum is a sector since multiple rotations of that stage may not be required. In yet other embodiments, other flexible members can be used in place of cable 50, such as cord, string, thread, or belt, of various materials. Furthermore, the second stage (or the last stage in a chain of stages) can be a belt drive mechanism using a belt loop on pulleys. Other types of drive mechanisms can be mixed with the capstan stages of the present invention in capstan drive mechanism 26.

In another alternate embodiment, an end of the cable 50 or 58 can be rigidly coupled to first or second capstan pulley 36 or 40, respectively, to prevent slippage of the cable on the pulley. For example, an end of the cable 58 can be secured to one point 43 at the middle of the pulley 40 or pulley 36. However, in such an embodiment, enough wraps around the pulley need be provided so that at least one point on the cable never leaves or moves along the pulley.

Capstan drive mechanism 26 can also be used in other types of interface devices. For example, a joystick that has rotational motion in two degrees of freedom can be provided with a capstan drive mechanism 26 for each degree of freedom. In one example of this, two single stage capstan drives can be used. The multiple stage capstan drives of the present invention can be provided in place of the single stage drives, e.g., actuator 24 can be grounded similarly, and the rotating member can be coupled at the end of the second stage (e.g. to drum 42). The capstan drive mechanism 26 can similarly be used for other types of mechanisms.

Figure 3 also illustrates sensor 28 provided on steering wheel shaft 57. Preferably, one portion of sensor 28 is coupled to ground, such as ground plate 32, and the other portion of the sensor moves with steering wheel 12. As described above, sensor 28 can be a potentiometer, a photo diode sensor, an optical encoder, a magnetic encoder, or other type of sensor. In alternate embodiments, the sensor 28 can be placed on shaft 52 to measure the rotation of the wheel 12. However, it is typically not as desirable in such a location since the shaft 52 rotates multiple times for each rotation of steering wheel 12, unlike the shaft 57. Thus, if sensors senses the rotation of shaft 52, a counter or other device is needed to keep track of the number of revolutions of the shaft 52. Alternatively, a "light pipe" sensor can be provided on shaft 57 or 52. For example, the emitter can be coupled to shaft 57 at one end of the light pipe, and the light pipe can extend out perpendicularly to axis A such that the emitted beam is transmitted onto a detector grounded on plate 32, where the detector is shaped to cover the rotational range of the light pipe. The light pipe can alternatively be positioned on any of the multiple stages of the capstan drive mechanism 26. The light pipe is also quite suitable for smaller ranges of angular motion, such as in a joystick. For example, the light pipe can be used with capstan drive mechanism 26 on a joystick embodiment.

FIGURES 4a-4d are different views of the capstan drive mechanism shown in Figure 3, where Figure 4a is a perspective view, Figure 4b is a top plan view, Figure 4c is a front view, and Figure 4d is a side elevation view. The capstan drums 38 and 42 preferably have much of their interior volume hollowed out as shown so that the drums are lighter and have less rotary inertia. Figures 4a and 4c illustrate the cable end position 56 on capstan drum 38, which in the described embodiment includes a groove 64 in the drum 38. The end of cable 50 is routed into the groove 64 and is coupled to one end of a spring 66. The other end of spring 66 is coupled to the drum 38 at point 56. When the cable 50 is installed, the cable is provided with enough tension so that spring 66 is partially tensioned. The spring 66 thus acts to tension the cable 50 and reduces any slack in the cable that may be introduced through motion and transmission of forces. Cable end position 61 on drum 42 similarly includes a groove 68 in the drum 42, where the end of cable 58 is routed into the groove 68 and is coupled to spring 70, which is coupled to the drum 42 at point 61. Spring 70 tensions cable 58 and reduces slack in cable 58 that may be later introduced.

The cable of the capstan drive mechanism 22 of the present invention is easier to tension than the belt drives of prior art transmissions because cable 50 or 58 is not provided in a continuous loop like the belts of the prior art. Each end of each cable is fixed to a drum 38 or 42, such that the cable is easier to wind and allows a spring to be placed at the end of the cable (such a spring is not easy to place in a continuous loop belt). The springs 66 and 70 provide additional tension in the cables 50 and 58 that reduce the manual tensioning required in the capstan drive mechanism.

The interface device 10 also preferably includes a hard stop to prevent the wheel 12 from rotating outside of a desired angular range. This prevents the cables 50 and 58 from winding off the end of the pulleys 36 and 42, respectively. Thus the hard stop should be engaged by the wheel 12 in either direction of rotation before the cables reach the end of the pulleys. The hard stop can be implemented in a number of ways; for example, a groove (not shown) can be provided in second capstan drum 42 which is blocked at the desired positions of the stops. A pin 76 can be coupled to front panel 34 and extend into the groove in the capstan drum 42. Thus, when the drum 42 rotates in accordance with wheel 12, the pin eventually engages the stops in the groove and blocks the wheel from further rotation. Alternatively, a pin can be provided on drum 42 which rotates within a groove provided in the front panel 34 and which engages stops within the groove. Stops can be placed at other positions on the interface device 10 alternatively or in addition to these stops. For example, a pin or other member can be positioned on shaft 52, shaft 57, or other rotating shafts of the capstan mechanism 26 which engages a grounded stop at a desired position, such as coupled to plate 32 or panel 34.

FIGURE 5 is a perspective view of the steering wheel controller device 10 including a speed reduction element of the present invention. Since capstan drive mechanism 22 provides low friction transmission of forces, the steering wheel or other user object 12 can be easily and freely rotated by the user when no forces are being applied. Likewise, when a force causes the steering wheel 12 to rotate in a particular direction, and/or when the force is removed, the wheel will rotate easily in that direction. For example, the "free wheeling" velocity of the use object 12 is the velocity at which there is equilibrium, i.e., the force on the user object is balanced by the friction and resistance of the wheel. In some cases, a high free wheeling velocity can present a hazard for the user, since the rapidly moving wheel or other user object can cause injury to any portion of the user contacting the user object.

To prevent the user object 12 from achieving a dangerously high rotational velocity, a speed reduction device can be employed in the interface device 10. One embodiment of such a device is shown in Figure 5. Shaft 80 of actuator 24 is rotated by the actuator to cause force on steering wheel 12 as transmitted by capstan drive mechanism 26. Fan blades 82 are rigidly coupled to the shaft 80 and thus rotate when the shaft rotates. The fan blades are operative to catch air as they spin and thus a damping force or resistance is created that resists the spin of the shaft. This damping force slows down the shaft and thus slows down the rotation of the steering wheel that is coupled to the shaft 80. Since the shaft 80 has many rotations in a single rotation of the steering wheel 12 due to the gear ratio provided by the capstan drive mechanism, the fan blades spin very fast compared to the rotation of the steering wheel. This causes the air resistance damping to immediately take effect no matter the rotational velocity of the steering wheel. Thus, the fan blades adjust the maximum velocity of the user object 12 for a given force on the user object, i.e., the maximum velocity is regulated by the fan blades. The size of the fan blades can also be chosen to limit the maximum speed of the user object that the actuator is capable of driving for a given force. For example, it may be desired to keep the speed of a steering wheel below 60 rpm. In alternate embodiments, other equivalent devices to fan blades may be used, such as air veins in a disc, etc.

A further function of the fan blades can be to cool down components in the base 14. Thus, for example, electronic portion 30 of the device 10 can be positioned to receive the air blowing from device 80. Components such as high frequency integrated circuits and amplifiers can benefit from this cooling function.

In FIGURE 6, another embodiment of a force feedback system includes a force feedback interface device 10' and a host computer 18. The illustrated system can used for a virtual reality simulation, video game, training procedure or simulation, computer application program, or other application. In one preferred embodiment, a user manipulatable object 14 is grasped by a user and manipulated. Images are displayed on a display apparatus, such as screen 20, of the computer 18 in response to such manipulations. Computer 18 and display device 20 are described above with reference to Fig. 1.

The interface device 10' as illustrated in Fig. 6 is used to provide an interface to the application running on host computer 18. For example, a user manipulatable object (or "manipulandum") 12 grasped by the user in operating the device 10 may be a joystick handle 92 movable in one or more degrees of freedom, as described in greater detail subsequently. It will be appreciated that a great number of other types of user objects can be used with the method and apparatus of the present invention. In fact, the present invention can be used with any mechanical object where it is desirable to provide a human/computer interface with two to six degrees of freedom. Such objects may include joysticks, styluses, surgical tools used in medical procedures, catheters, hypodermic needles, wires, fiber optic bundles, screw drivers, steering wheels, pool cues, etc.

A housing 93 includes a mechanical apparatus for interfacing mechanical input and output is included in interface device 10'. The mechanical apparatus mechanically provides the degrees of freedom available to the user object 92 and allows sensors to sense movement in those degrees of freedom and actuators to provide forces in those degrees of freedom. The mechanical apparatus is described in greater detail below. The mechanical apparatus is adapted to provide data from which a computer or other computing device such as a microprocessor (see Fig. 14) can ascertain the position and/or orientation of the user object as it moves in space. This information is then translated to an image on a computer display apparatus such as screen 20. The mechanical apparatus may be used, for example, by a user to change the position of a user controlled graphical object on display screen 20 by changing the position and/or orientation of the user object 12, the computer 18 being programmed to change the position of the graphical object in proportion to the change in position and/or orientation of the user object.

An electronic interface is also included in housing 93 of interface device 10'. The electronic interface couples the device 10' to the computer 18. More particularly, the electronic interface is used in preferred embodiments to couple the various actuators and sensors contained in device 10' to computer 18. A suitable electronic interface is described in detail with reference to Fig. 14. The electronic interface is coupled to a mechanical apparatus within the interface device 10' and to the computer 18 by a cable 95. In other embodiments, signals can be transmitted between interface device 10' and computer 18 by wireless transmission and reception.

FIGURES 7 and 8 are perspective views of one embodiment 10' of the mechanical portion and user object 12 of interface device 10' and including features of the present invention, where these figures show orthogonal sides of the device 10'. The described embodiment is a joystick apparatus including two rotary degrees of freedom, where a joystick handle 92 can be moved forward and back in one degree of freedom, and left and right in the other degree of freedom.

Gimbal mechanism 100 couples the user object 12 to a grounded or reference surface 102. All or some of the components of gimbal mechanism 100 (and other components) can be made of metal, or, in a preferred low-cost embodiment, rigid plastic. Gimbal mechanism 100 is preferably a five-member, closed-loop parallel linkage that includes a ground member 104, extension members 106a and 106b, and central members 108a and 108b. Ground member 104 is provided as a base or planar member which provides stability for device 10' on a grounded surface 102, such as a table top, floor, desk top, or other reference surface. Ground member 104 also preferably includes upright members 110 rigidly coupled to the base portion and to which the extension members 106a and 106b are coupled. The members of gimbal mechanism 100 are rotatably coupled to one another through the use of bearings or pivots, wherein extension member 106a is rotatably coupled to ground member 104 and can rotate about an axis D, central member 108a is rotatably coupled to extension member 106a and can rotate about a floating axis G, extension member 106b is rotatably coupled to ground member 104 and can rotate about axis E, central member 108b is rotatably coupled to extension member 106b and can rotate about floating axis H, and central member 108a is rotatably coupled to central member 108b at a center point P at the intersection of axes G and H. A bearing (not shown) connects the two central members 108a and 108b together at the intersection point P. Central drive member 108a is rotatably coupled to an end 109 of extension member 106a and extends at a substantially parallel relation with axis B. Similarly, central link member 108b is rotatably coupled to an end 112 of extension member 106b and extends at a substantially parallel relation to axis D. The axes G and H are "floating" in the sense that they are not fixed in one position as are axes D and E. Axes D and E are substantially mutually perpendicular.

Gimbal mechanism 100 is formed as a five-member ("five-bar") closed chain. Each end of one member is coupled to the end of another member. The five-bar linkage is arranged such that extension member 106a, central member 108a, and central member 108b can be rotated about axis D in a first degree of freedom. The linkage is also arranged such that extension member 106b, central member 108b, and central member 108a can be rotated about axis E in a second degree of freedom.

Joystick handle 92 is coupled to one of the central members 108a or 108b (member 108a in Fig. 7) of gimbal mechanism 100 such that it extends out of the plane defined by axes G and H. Gimbal mechanism 100 provides two degrees of freedom to handle 16 positioned at or near to the center point P of rotation. The handle 92 can be rotated about axis D and E or have a combination of rotational movement about these axes. Joystick handle 92 can be rotated about axis D by rotating extension member 106a, central member 108a, and central member 108b in a first revolute degree of freedom, shown as arrow line 111. Handle 92 can also be rotated about axis E by rotating extension member 106b and the two central members about axis E in a second revolute degree of freedom, shown by arrow line 113. As joystick handle 92 is moved about axis D, floating axis G varies its position, and as joystick handle 92 is moved about axis E, floating axis H varies its position.

In alternate embodiments, additional degrees of freedom can be provided. For example, the joystick handle 92 can be rotated about axis F extending perpendicularly from the plane formed by floating axes G and H. This rotational degree of freedom can be provided with a sensor and/or an actuator to sense motion and apply forces in that degree of freedom. Additionally, a different degree of freedom can be added such that handle 92 can be linearly translated along floating axis F. This degree of freedom can also be sensed and actuated, if desired.

Gimbal mechanism 100 also includes capstan drive mechanisms 114a and 114b. In the described arrangement, a capstan drive mechanism 114 is rigidly coupled to (e.g. formed as part of) each extension member 106a and 106b. Capstan drive mechanisms 114 are included in gimbal mechanism 100 to provide mechanical advantage to the output of actuators 96 without introducing friction and backlash to the system. A capstan drum 116 of each capstan drive mechanism is rigidly coupled to a corresponding extension member 106a or 106b. Capstan drum 116a is, in effect, formed as part of extension member 106a; the portion of drum 116a that extends away from the "L" shaped portion of member 106a is considered the capstan drum portion. Thus, the capstan drum and extension member are rotated about axis D simultaneously. Likewise, extension member 106b is rigidly coupled to the other capstan drum 116b and both are simultaneously rotated about axis E. The capstan drive mechanisms 114 are described in greater detail with respect to Fig. 9.

Also preferably coupled to gimbal mechanism 100 are sensors 98 and actuators 96. Such transducers are preferably coupled at the link points between members of the apparatus and provide input to and output from the electrical system. Transducers that can be used with the present invention are described in greater detail with respect to Fig. 14. In the described embodiment, actuators 96 include two grounded actuators 96a and 96b. The housing of grounded actuator 96a is preferably coupled to ground member 104. A rotational shaft of actuator 96a is coupled to the capstan drive mechanism 114 to apply forces to the joystick handle 92 in the first degree of freedom about axis A. The capstan drive mechanism 114 is described in greater detail with respect to Fig. 9. Grounded actuator 96b preferably corresponds to grounded transducer 96a in function and operation, where actuator 96b is coupled to the ground member 104 and applies forces to the joystick handle 92 in the second revolute degree of freedom about axis B.

Actuators 96, in the described embodiment, are preferably linear current control motors, such as DC servo motors. These motors preferably receive current signals to control the direction and torque (force output) that is produced on a shaft; the control signals for the motor are produced by microprocessor 220 as explained above. The motors may include brakes which allow the rotation of the shaft to be halted in a short span of time. A suitable motor to be used as actuators 96 is HC615L6 manufactured by Johnson Electric. In alternate embodiments, other types of motors can be used, such as a stepper motor controlled with pulse width modulation of an applied voltage, or pneumatic motors, or passive actuators.

Sensors 98 are, in the described embodiment, coupled to the extension members 106a and 106b. One portion of the sensor is grounded by being coupled to ground member 104. A rotary shaft of each sensors is rigidly coupled to an associated extension member. Sensors 98 are preferably relative optical encoders which provide signals to measure the angular rotation of a shaft of the sensor. The electrical outputs of the encoders are routed to microprocessor 220 (or host computer 18) as detailed above. Other types of sensors can also be used, such as potentiometers or other analog or digital sensors as described above. It should be noted that the present invention can utilize both absolute and relative sensors.

The actuators 96 of the described embodiment are advantageously positioned to provide a very low amount of inertia to the joystick handle 92. Actuators 96 are decoupled, meaning that the transducers are both directly coupled to ground member 104 which is coupled to ground surface 102, i.e. the ground surface carries the weight of the actuators, not the joystick handle 92. The weights and inertia of the actuators 96 are thus substantially negligible to a user handling and moving handle 92. This allows more realistic forces to be transmitted to user object 92. The user feels very little compliance or "mushiness" when handling handle 92 due to the high bandwidth.

FIGURE 9 is a perspective view of a capstan drive mechanism 114 shown in greater detail. The drive mechanism 114 is coupled to extension arm 106 as shown in Figures 7 and 8. Each capstan drive mechanism 114a and 114b shown in Figures 7 and 8 is preferably implemented the same way. Capstan drive mechanism 114 includes capstan drum 116, capstan pulley 118, and cable 120. Capstan drum 116 is preferably a wedge- or other-shaped member having a curved end 122, e.g. the end 122 is a portion of the circumference a circular shape about the axis of rotation. Other shapes of drum 116 can also be used. The drum 116 is rigidly coupled to extension member 106, which is pivotally coupled to ground member 104 at axis D or E. Thus, when capstan drum 114 is rotated about axis D or E, the extension member 106 is also rotated. Curved end 122 is preferably formed in an arc centered about the axis D or E, and is preferably positioned about 0.030-0.035 inches away from pulley 118 using a 0.025 inch diameter cable 120 (this distance can vary depending on the diameter of cable 120 used).

Capstan pulley 118 is a cylindrical member positioned near the curved portion 122 of capstan drum 116. The pulley is rigidly coupled to a rotating shaft of actuator 96. In other embodiments, the pulley can be the actual driven shaft of the actuator. Cable 120 is preferably a thin metal cable connected to curved portion 122 of the capstan drum. Other types of flexible members, such as durable cables, cords, wire, thin metal bands, etc. can be used as well. A first end 124 of cable 120 is attached to a spring 126, where the spring 126 is positioned in an aperture 128 provided in the capstan drum 116. The cable is routed from the first end 124, through a guide 130a on the capstan drum, and tautly over a portion of the curved end 122. The cable is then routed a number of times around pulley 118; for example, the cable is wound twice around the pulley in the shown example. The cable is then again drawn tautly against curved end 122, is routed through a guide 130b of the capstan drum, and is attached to the other end of spring 126. In alternate embodiments, the cable 120 can be firmly attached to the capstan drum 116 rather than spring 126; however, certain advantages are obtained by using spring 126, as described below. The spring 126 can be attached to the cable in a variety of assembly methods; for example, the cable can be first routed around the drum 116, and a tool can be used to extend the spring to allow the second end of the cable to be attached to the spring. Or, the cable is routed around its path but not around the drum, the motor is cocked at an angle, the cable is wrapped around the drum, and the motor is straightened to tighten the cable around the drum.

The actuator 96 rotates pulley 118 to move the cable 120 that is tightly wound on the pulley (the tension in cable 120 provides the grip between cable and pulley). As pulley 118 is rotated by an actuator 96 (or as the drum 116 is rotated by the manipulations of the user), a portion of cable 118 wrapped around the pulley travels closer to or further from actuator 96, depending on the direction that pulley 118 rotates. The cable 120 transmits rotational force from the actuator-driven pulley 118 to the capstan drum 116, causing capstan drum 116 to rotate about axis D or E. This provides rotational force on the extension member 106 and the handle 92 in the associated degree of freedom. It should be noted that pulley 118, capstan drum 116 and extension member 106 will only actually rotate in space if the user is not applying the same or greater amount of rotational force to handle 92 in the opposite direction to cancel the rotational movement. In any event, the user will feel the rotational force along the associated degree of freedom on handle 92 as force feedback.

For example, FIGURES 10a and 10b demonstrate the motion of the capstan drums 116a and 116b and the corresponding motion of joystick handle 92. In Figure 10a, the handle 92 has been moved diagonally in one direction (e.g., down-right) to permissible limits. and the capstan drums 116 have correspondingly been rotated toward ground member 104 (note that this movement can be caused by the user moving handle 92 or by actuators 96 rotating pulley 118). A hole or depression 134 can be provided in the surface of ground member 104 under each capstan drum 116a and 116b to allow the capstan drums to move to a desired rotational limit. Such a hole may not be necessary in implementations that position the axis of rotation of the capstan drums at a far enough distance away from the ground member 104. The ground member 104 also acts as a stop in the described embodiment. A fence 105 is coupled to the ground member 104 and is provided as four walls that extend up from the surface of the ground member surrounding an extension (not shown) of handle 92. The extension extends down in the center of the fence 105 so that when the handle 92 is moved in any of the four directions or a combination of directions (e.g. diagonally), the handle extension impacts one side of the fence 105 and prevents further rotation in that direction. The fence 105 thus is a stop that constrains the movement of handle 92 to a desired angular range. This impact with fence 105 occurs before the capstan drums 116a and 116b impact the ground member 104, thus preventing a large load and/or damage to the capstan drums which might occur if the capstan drums were allowed to impact a hard stop.

In Figure 10b, the handle 92 has been moved diagonally to the opposite direction to that shown in Figure 10a, e.g. to the upper-left. The capstan drums 116a and 116b are correspondingly rotated away from the ground member 104. As described above, fence 105 functions as a stop to the movement of the handle 92, so that the handle and capstan drums may not be rotated further than shown in Figure 10b. Thus, the fence 105 constrains the drums to an angular range defined by the dimensions of the fence 105 and the handle extension into the fence. If the handle is to be moved in only one direction (e.g., up or right), then only the capstan drum 116 that corresponds to that axis of rotation is rotated.

The described embodiment of the present invention also is preferably used with an automatic sensor calibration procedure to determine the limits to the range of motion of manipulandum 16, which is used to determine the position of the manipulandum 92 in its degrees of freedom. Although fence 105 provides a hard stop to limit the range of motion of handle 92 and thus provides a sensing range limit for sensors 98, some inaccuracies to the sensed range can still occur, especially based on manufacturing variances between devices. In a preferred embodiment, a dynamic calibration procedure is used, where the sensing range of the device is determined dynamically for a particular device based on the range of motion of the handle sensed up to the current point in time. Thus, the limits (minimum and maximum sensor range values) that have been detected so far in each degree of freedom are considered to be the limits of the motion of the handle, and these limits are increased as the handle is moved closer to the actual physical limits over time (and more extreme sensor values are read). The sensing range eventually extends to the actual physical limits of the sensing range as the handle is moved to its limits during operation of the device as defined by fence 105. At any time, the current sensor range is normalized to a standard range of values that the host computer expects to receive.

A problem can occur in the dynamic calibration of the sensors due to flex or slop in the transmission system or other components of the device, especially if the transmission system includes components made of at least a partially flexible material such as plastic (plastic components are often desirable for high-volume mass market devices). Since actuator forces may often be output in the same direction as the physical stop, the actuator forces can stress the transmission system so that one or more components in the transmission system move an additional amount while handle 92 is stopped by a fence 105 limit. The limits to the sensed range will be then be considered greater than when no forces are output, causing inaccuracies in the sensed position of the manipulandum.

For example, in the present invention, the handle 92 may be stopped by fence 105, but capstan drums 116 may be moved a small distance in their rotatable range past their corresponding limits by the actuator forces while the handle 92 remains stationary, i.e. the capstans are forced to continue to move relative to the handle due to flex in the system. Since, in the described configuration, the sensors 98 sense motion of the capstan drums 116 instead of handle 92 directly, the handle will appear to have moved when only the capstan drums have moved. However, when the handle is moved to a limit while no actuator forces are applied in that direction, the casptan drums are not stressed past their limits and have no extra movement with respect to the handle 92, so that the fence 105 is the sensed limit. Thus, the limits to the sensed range will be greater when actuator forces are output than when no forces are output; and since the dynamic calibration procedure takes the greatest (maximum or minimum) sensed value as the sensor range limit, this limit will present a problem when no actuator forces are applied. The user will move the handle to a limit, but the microprocessor 220 or host computer 18 will not read that position as being at a limit since the dynamic calibration procedure indicated that there is a greater sensing range. This leads to inaccuracies in the sensed position of the handle; for example, the user will not be able to control a graphical object to move to a limit on the screen even though the handle 92 is at a physical limit.

To prevent detecting such a "false" limit caused by an actuator overstressing the transmission system, the calibration procedure used in the present invention preferably only reads new sensor range limits when the actuator is not outputting a force in the direction of that limit. For example, the calibration procedure is preferably performed by instructions implemented by microprocessor 220 (or, alternatively, host computer 18) and is running during the normal operation of the force feedback device. The calibration procedure receives all sensor readings output by the sensors 98. The procedure checks if the sensor reading is greater than the maximum sensor value previously read (as determined from previous sensor readings), or if it is less than the minimum sensor value previously read. If neither is true, the sensor value is ignored by the calibration procedure. If the sensor value is greater than the maximum or less than the minimum, the procedure checks whether the sensor value was read during the output of any component of force by actuators 96 in the direction of the limit applicable to that sensor value. If so, then the calibration procedure ignores the sensor value since the actuator force may have stressed the transmission system past the physical limits provided when no actuator force is output. If no forces were output toward that limit, then that value becomes the new maximum or minimum in the sensed range. Thus, the calibration procedure only includes new maximum or minimum sensor values in the sensor range that are free from the influence of the actuator forces, so that the sensor range never extends past the range provided when no actuator forces are output.

Referring back to Figure 9, the tension in cable 120 should be provided at a level so that the cable 120 adequately grips the pulley 118 without slipping when the pulley is rotated, and also to provide negligible backlash or play between capstan drum 116 and pulley 118. Thus, the cable 120 preferably has a high degree of tension. In the present invention, the cable 120 is tensioned by spring 126, which couples both ends of the cable together. Cable 120 in the present invention is preferably rigidly attached to the capstan drum 116 at anchor points by clamp 132 (preferably provided at either guide 130a or guide 130b). Clamp 132 secures the cable 120 to the drum 116 using friction to prevent the cable 120 from moving or slipping with respect to the drum. Thus, spring 126 pulls both ends of the cable toward each other from opposite directions to tension the cable, while the clamp 132 anchors the cable to the drum.

When the cable 120 is installed, the cable is provided with enough tension so that spring 126 is partially tensioned. In previous systems, the cable was typically attached directly to a capstan drum and tensioned by rotating a screw, pulling more cable through a holding device, or by some other manual adjustment. That procedure significantly added to the production costs of the device, since each cable in each device had to manually adjusted to a proper tension. In addition, as a cable became loose over time in previous systems and introduced slack due to motion and transmission of forces, an operator or user had to manually re-tension the cables. Spring 126, in contrast, is a self-tensioning device that automatically provides the desired tension in the cable without any need for manual adjustment, and does not allow slack to be introduced so that the cable does not become loose over time. Since the ends of the cable are attached to spring 126, the spring force draws the cable tautly together and the tension in the cable is properly maintained. Furthermore, since the ends of the cable are not attached to the drum 116, there is no tendency for the drum material to flex or "creep" over time due to the high cable forces. This advantage is most clear when the drums 116 are made of a material such as plastic, which is most appropriate for high volume, low cost production; since plastic tends to creep over time, the cable being attached to a metal spring 126 rather than the drum 116 is highly advantageous.

In other embodiments, such as that of Figs. 1-5 above, only one end of the cable is attached to the spring 126, while the other end is securely anchored to the capstan drum 116. However, unlike the above embodiment having two ends attached to the spring, this embodiment has the disadvantage that the material of the drum may flex or creep at the cable end directly attached to the drum, especially when plastic or other softer materials are used for drum 116.

A different improvement of the present invention to the capstan drive mechanism is the provision of flanges 136 on the curved end 122 of capstan drums 116. Flanges 136 are small raised portions at the lengthwise edges of the curved end 122 which function to prevent the cable 120 from slipping off the end 122 of the drum as the capstan drum is rotated. This can be helpful in preventing a major mechanical malfunction of the device if the capstan should happen to rotate too far, where the cable may tend to migrate off one side of the drum and pulley; the flanges can prevent this by prevent cable motion to the sides of the drum and to prevent the cable from escaping between the drum and the pulley. In addition, the flanges 136 ease the assembly process when wrapping the cable on the capstan drum and capstan pulley, since the cable is less likely to slip off the drum during the assembly or winding process. The curved end of the capstan drum 116 can also be grooved in alternate embodiments to further help in guiding the cable and preventing the cable from slipping off the capstan drum.

The capstan mechanism 114 provides a mechanical advantage to the output forces of actuators 96 so that the force output of the actuators is increased. The ratio of the diameter of pulley 118 to the diameter of capstan drum 116 (i.e. double the distance from associated axis of rotation to the curved end of capstan drum 116) dictates the amount of mechanical advantage, similar to a gear system. In the preferred embodiment, the ratio of drum to pulley is equal to 17:1, although other ratios can be used in other embodiments.

Alternatively, the pulley 118 can include guides, such as threads similar to a screw. The threads can function to help guide the cable along the pulley as the pulley rotates and to provide cable 120 with a better grip on pulley 118. Cable 120 can be positioned between the threads.

In the present embodiment, the sensors 98 are only indirectly coupled to the capstan drive mechanism 114 since the rotation of extension members 116 is directly sensed. However, in an alternate embodiment, each sensor can be coupled to a pulley 118 to measure the rotation of the pulleys. Cable 120 would then also transmit rotational motion from drum 116, as initiated by a user on handle 92, to the pulley 118 and sensor 98. Such an embodiment has the advantage of increasing sensor accuracy since the pulley rotates a greater number of times for each rotation of the extension member, and a greater resolution is achieved. Since little or no backlash is present using the capstan drive mechanism, this sensing is also quite accurate.

Capstan drive mechanism 114 is advantageously used in the present invention to provide transmission of forces and mechanical advantage between actuators 96 and joystick handle 92 without introducing substantial compliance, friction, or backlash to the system. A capstan drive provides increased stiffness, so that forces are transmitted with negligible stretch and compression of the components. The amount of friction is also reduced with a capstan drive mechanism so that substantially "noiseless" forces can be provided to the user. In addition, the amount of backlash contributed by a capstan drive is also negligible. "Backlash" is the amount of play that occurs between two coupled rotating objects in a gear or pulley system. Two gears, belts, or other types of drive mechanisms could also be used in place of capstan drive mechanism 114 in alternate embodiments to transmit forces between an actuator 96 and extension member 106. However, gears and the like typically introduce some backlash in the system, and a user might be able to feel the interlocking and grinding of gear teeth during rotation of gears when manipulating handle 92.

FIGURE 11 is a perspective view of a releasable spring mechanism of the present invention. This mechanism allows physical springs to be selectively coupled to the rotating members of gimbal mechanism 100 to bias the members about their rotational axes of motion to a desired position when the user is not exerting force on handle 92, such as to place the joystick handle 92 in a central upright position. When the interface device is desired to be powered and forces applied, the physical springs can be disconnected from the gimbal mechanism to allow the forces to be applied without interference. A spring mechanism 150 is preferably provided for both degrees of freedom of interface device 10' in which forces are applied (only one spring mechanism, for axis D, is shown in Figures 7 and 8).

Releasable spring mechanism 150 includes a moveable catch member 152, a grounded catch member 154, and a spring 156. Moveable catch member 152 (also shown between extension member 106a and grounded upright member 110 in Figure 8) is moved by the user to connect or disconnect the spring 156 from the gimbal mechanism. In the described embodiment, an aperture is provided in ground member 104 so that a grip portion 158 of the member 152 may extend through the bottom of the interface device 10' to allow a user to move the member 152. The catch member 152 is moved by a user to engage or disengage grounded catch member 154, which in the described embodiment is a peg or similar member coupled to grounded upright member 110. A latch 160 of the catch member 152 may receive catch member 154 when the user moves the catch member 152 in the appropriate fashion, as described below.

Spring 156 is coupled at one end 162 to grounded upright member 110 (which is part of grounded member 104) and is coupled at its other end 157 to moveable catch member 152 (shown in Figs. 12 and 13). Spring 156 functions, when coupled to the extension member, to apply a spring force to the gimbal mechanism and center the joystick handle about the axis associated with the extension member 116 to which the mechanism 150 is coupled (axis D in Fig. 11). Spring 156 does not apply any spring force to the gimbal mechanism when the spring is disengaged, as described below.

In the preferred embodiment, the releasable spring mechanism 150 provides a preload condition that ensures the handle 92 is biased in a completely upright position when the springs are engaged. The springs 156 are preloaded by stretching them so that a spring force is applied to the handle even when in an upright center position. This causes a higher spring return force to be applied to the handle 92 even after only a small deflection from the upright center position (or other desired position). This preload condition prevents the handle 92 from resting at slightly off-center positions caused by a weak spring force at small handle deflections.

FIGURE 12 is a side elevation view of releasable spring mechanism 150 in its engaged position, i.e., where spring 156 is engaged with the gimbal mechanism to provide a centering spring force on the joystick handle 92 in the associated axis of motion. In this position, the latch 160 has not been engaged with catch member 154. This allows the catch member 152 to be pulled in the direction of arrow 164 toward the grounded catch member 162 because of the spring force in that direction contributed by spring 156.

Moveable catch member 152 preferably includes a central aperture 166 through which the bearing portion 168 extends. Catch member 152 includes a central receptacle 169 on the edge of the aperture 166 and shaped so that the catch member 152 has clearance from the bearing portion 168. Furthermore, the extension member 106 includes pegs 170 which are rigidly coupled to the extension member 106 and which extend into the aperture 166 of the catch member 152. Catch member 152 includes receptacles 172 on the edge of aperture 166 which are shaped to receive the pegs 170. Furthermore, grounded member 110 includes grounded pegs 174 which also extend into the central aperture 166 of the catch member 152. Catch member 152 includes receptacles 176 on the edge of aperture 166 and shaped to receive the pegs 174.

In the engaged position, the catch member 152 is pulled toward catch member 162, which causes the receptacles 176 to engage grounded pegs 174 in the direction of arrow 164 and prevents the catch member 152 from moving further towards catch member 162. In this position, when extension member 106 is horizontally oriented along axis y, the pegs 170 coupled to extension member 106 are substantially engaged with receptacles 172. When the extension member 106 (and capstan drum 116) is moved in a direction about axis A shown by arrow 180, as shown in Fig. 12, then the peg 170a is forced against the receptacle 172a and the peg 170b is moved away from receptacle 172b. This causes the catch member 152 to move in a direction approximately opposite to arrow 164, which is against the direction of spring force. Thus, the extension member 106 is biased with the spring to return to its horizontal position. Similarly, when the extension member 106 is moved (not shown) in a direction about axis D shown by arrow 182, then the peg 170b is forced against the receptacle 172b and the peg 170a is moved away from receptacle 172a. This again causes the catch member 152 to move in a direction approximately opposite to arrow 164, providing a spring force on extension member 106 and biasing the extension member to return to its horizontal position.

The weight of the capstan drums 116 and extension members 106 may cause the spring return force to be asymmetric, i.e., if the same spring force is used to force the member 106/drum 116 down to the center position as is used to force the member 106/drum 116 up to the center position, the member/drum will not be forced by the same amount since the spring force up has to overcome the weight of the member/drum (gravity) while the spring force down is assisted by the weight of the member/drum. This asymmetry can be compensated for by repositioning the pins 170 about axis D so that a greater amount of spring deflection is provided when the member/drum rotates down, thereby providing a greater spring force when the member/drum is returned up to the center position in comparison to the spring force provided when moving the member/drum down to the center position. This can be accomplished, for example, by positioning pin 170b further from axis D than pin 170a.

In sum, the engaged mode of the mechanism 150 provides a spring force on extension member 106 in both of its directions about axis D that biases the extension member and thus the joystick handle 92 to a predetermined position. In the described embodiment, the predetermined position is approximately the center position of the degree of freedom. In other embodiments, the spring force can bias the handle 92 to a different desired predetermined position (e.g. an upright position of handle 92 may not be the center of a degree of freedom in some embodiments). This spring force prevents the joystick handle from leaning to one side when forces are not being exerted by the actuators 96 and when no external forces (such as from the user) are applied to the handle. This can be useful in situations where the joystick is being displayed and/or tested (e.g. by prospective consumers) when the joystick is not powered. For example, many stores wish to provide joystick demonstration models for consumers to try out, determine how the joystick handle feels, etc. The demonstration models typically are not powered, and without power the joystick handles tilt to one side, giving the undesired appearance of a faulty or broken joystick. The springs 156 center the handle 16 in its workspace so that the handle is in an upright position (or other desired position) to prevent this undesired appearance. In addition, when trying an unpowered demonstration force feedback joystick or other force feedback interface device, the user does not get any sense of how the device feels when powered. The springs mechanism 150 of the present invention provides an approximation of a centering force that provides the user with at least an indication of how the joystick feels when it is in normal operation with centering forces applied.

FIGURE 13 is a side elevation view of releasable spring mechanism 150 in a disengaged position, i.e., where the springs 156 have been disengaged from the members of the gimbal mechanism to allow free movement of the joystick handle 92. In this position, the user has pushed the moveable catch member 152 to be engaged with grounded catch member 154. Preferably, the user pushes on grip 158 in the directions indicated by arrows 186 to engage these catch members 154 and 160. In other embodiments, different mechanisms can be provided that allow the user to move mechanism 150 into the disengaged position, such as a button or lever which performs the same engagement, or an automatic system that allows the host computer or microprocessor 220 to put the device in the engaged or disengaged position (using a solenoid or other actuator, for example).

In the disengaged position of Fig. 13, the moveable catch member 152 has been forced in a direction indicated by arrow 188 to the position shown in Fig. 13; the member 152 is locked in this position by the latch 160. This position stretches spring 156 and causes the central aperture 166 of catch member 152 to move in direction 188 relative to pegs 170 and pegs 174. Thus, the receptacles 172 and 176 are provided in a position some distance away from pegs 170 and 174, i.e. the pegs 170 and 174 are now in a more central position within aperture 166. This allows the member 106 to move freely within the space of aperture 166, i.e. when the member 106 moves in a direction 180 or 182, the pegs 170a and 170b are able to move within aperture 166 without engaging receptacles 172a and 172b. No spring bias is therefore placed on the member 106 as it moves. The handle 92 (and thus the capstan drum 116) preferably encounters a hard stop in its motion before any of the pegs 170 engage the catch member 152.

Having no mechanical spring forces present on the members of the gimbal mechanism is important when outputting forces on the gimbal mechanism 100. When interface device 10' is powered, actuators 62 may apply forces to members 106 to cause any of a variety of force sensations to the user grasping joystick handle 92, as explained above. Any forces applied by physical springs 156 would greatly interfere with forces generated by actuators 96, thus decreasing the fidelity and realism of any generated force sensations. In addition, forces from physical springs 156 are not needed to center handle 92 when the joystick is powered because the microprocessor 220 can control actuators 96 to output simulated spring forces on the members 106 to center the joystick in its workspace. Thus, even if the user does not want forces generated on the joystick, the actuators 96 can be used to apply centering spring forces equivalent to those normally provided by physical springs in non-force feedback joysticks.

FIGURE 14 is a block diagram illustrating interface device 10 or 10' and host computer 18 suitable for use with the present invention. Interface device 10 and 10' includes an electronic interface 200, mechanical apparatus 202, and user object 12, which in the described embodiments is preferably a steering wheel or a joystick handle.

As explained with reference to Fig. 1, computer 18 is preferably a personal computer, workstation, video game console, or other computing or display device. Host computer system 18 commonly includes a host microprocessor 204, random access memory (RAM) 206, read-only memory (ROM) 208, input/output (I/O) electronics 210, a clock 212, a display device 20, and an audio output device 214. Host microprocessor 204 can include a variety of available microprocessors from Intel, AMD, Motorola, or other manufacturers. Microprocessor 204 can be single microprocessor chip, or can include multiple primary and/or co-processors and preferably retrieves and stores instructions and other necessary data from RAM 206 and ROM 208 as is well known to those skilled in the art. In the described embodiment, host computer system 18 can receive sensor data or a sensor signal via a bus 216 from sensors of device 10 or 10' and other information. Microprocessor 204 can receive data from bus 216 using I/O electronics 210, and can use I/O electronics to control other peripheral devices. Host computer system 18 can also output commands to interface device 10 or 10' via bus 216 to cause force feedback for the interface device.

Clock 212 is a standard clock crystal or equivalent component used by host computer 18 to provide timing to electrical signals used by host microprocessor 204 and other components of the computer system 18 and can be used to provide timing information that may be necessary in determining force, velocity, position, or acceleration values. Display device 20 is described with reference to Figure 1. Audio output device 214, such as speakers, can be coupled to host microprocessor 204 via amplifiers, filters, and other circuitry well known to those skilled in the art. Host processor 204 outputs signals to speakers 214 to provide sound output to the user when an "audio event" occurs during the implementation of the host application program. Other types of peripherals can also be coupled to host processor 204, such as storage devices (hard disk drive, CD ROM drive, floppy disk drive, etc.), printers, and other input and output devices.

Electronic interface 200 is coupled to host computer system 18 by a bi-directional bus 216. The bi-directional bus sends signals in either direction between host computer system 18 and the interface device 10 or 10'. Bus 216 can be a serial interface bus, such as USB, RS-232, or Firewire (IEEE 1392), providing data according to a serial communication protocol, a parallel bus using a parallel protocol, or other types of buses. An interface port of host computer system 18, such as a USB or RS232 serial interface port, connects bus 216 to host computer system 18. In another embodiment, an additional bus can be included to communicate between host computer system 18 and interface device 10 or 10'. The second bus can be coupled to a second port of the host computer system to provide greater communication bandwidth.

Electronic interface 200 includes a local microprocessor 220, local clock 222, local memory 224, sensor interface 226, and actuator interface 228. Interface 200 may also include additional electronic components for communicating via standard protocols on bus 216. In various embodiments, electronic interface 200 can be included in mechanical apparatus 202, in host computer 18, or in its own separate housing. Different components of interface 200 can be included in device 10 or 10' or host computer 18 if desired.

Local microprocessor 220 preferably coupled to bus 216 and may be closely linked to mechanical apparatus 202 to allow quick communication with other components of the interface device. Processor 220 is considered "local" to interface device 10 or 10', where "local" herein refers to processor 220 being a separate microprocessor from any processors 204 in host computer 18. "Local" also preferably refers to processor 220 being dedicated to force feedback and sensor I/O of the interface device 10 or 10', and being closely coupled to sensors and actuators of the device, such as within the housing of or in a housing coupled closely to the device. Microprocessor 220 can be provided with software instructions to wait for commands or requests from computer host 18, parse/decode the command or request, and handle/control input and output signals according to the command or request. In addition, processor 220 preferably operates independently of host computer 18 by reading sensor signals and calculating appropriate forces from those sensor signals, time signals, and force processes selected in accordance with a host command, and outputs appropriate control signals to the actuators. Suitable microprocessors for use as local microprocessor 220 include the 8X930AX by Intel, the MC68HC711E9 by Motorola or the PIC16C74 by Microchip, for example. Microprocessor 220 can include one microprocessor chip, or multiple processors and/or co-processor chips. In other embodiments, microprocessor 220 can include digital signal processor (DSP) functionality.

For example, in one host-controlled embodiment that utilizes microprocessor 220, host computer 18 can provide low-level force commands over bus 216, which microprocessor 220 directly transmits to the actuators. In a different local control embodiment, host computer system 18 provides high level supervisory commands to microprocessor 220 over bus 216, and microprocessor 220 manages low level force control loops to sensors and actuators in accordance with the high level commands and independently of the host computer 18. In the local control embodiment, the microprocessor 220 can process inputted sensor signals to determine appropriate output actuator signals by following the instructions of a "force process" that may be stored in local memory 224 and includes calculation instructions, formulas, force magnitudes, or other data. The force process can command distinct force sensations, such as vibrations, textures, jolts, or even simulated interactions between displayed objects. For example, a computer-controlled object is generated on computer screen 20 and a computer object or entity controlled by the user collides with the computer controlled object. High-level host commands can be used to provide the various forces associated with the collision in real time. Also, the local control mode microprocessor 220 can be helpful in increasing the response time for forces applied to the user object, which is essential in creating realistic and accurate force feedback. The microprocessor 220 can read the sensors of the device 10, provide the sensor data to the host, and execute an appropriate force process when the host indicates a collision takes place, thus freeing the host computer for other tasks. The host could implement program functions (such as displaying images) when appropriate, and synchronization commands can be communicated between processor 220 and host 18 to correlate the microprocessor and host processes. The host can also send the local processor 220 a spatial layout of objects in the graphical environment so that the microprocessor has a mapping of locations of graphical objects and can determine force interactions locally.

Sensor signals used by microprocessor 220 are also reported to host computer system 18, which updates a host application program and outputs force control signals as appropriate. In an alternate embodiment, no local microprocessor 220 is included in interface device 10 or 10', and host computer 18 directly controls and processes all signals to and from the interface device.

A local clock 222 can be coupled to the microprocessor 220 to provide timing data, similar to system clock 212 of host computer 18; the timing data might be required, for example, to compute forces output by actuators 234 (e.g., forces dependent on calculated velocities or other time dependent factors). Local memory 224, such as RAM and/or ROM, is preferably coupled to microprocessor 220 in interface 200 to store instructions for microprocessor 220 and store temporary and other data. Microprocessor 220 may also store calibration parameters and the state of the force feedback device in a local memory 224. Memory 224 may be used to store the state of the force feedback device, including a reference position, current control mode or configuration, etc.

Sensor interface 226 may optionally be included in electronic interface 200 to convert sensor signals to signals that can be interpreted by the microprocessor 220 and/or host computer system 18. For example, sensor interface 226 can receive and convert signals from a digital sensor such as an encoder or from an analog sensor using an analog to digital converter (ADC). Such circuits, or equivalent circuits, are well known to those skilled in the art. Alternately, microprocessor 220 can perform these interface functions or sensor signals from the sensors can be provided directly to host computer system 18 without the need for a separate sensor interface. Actuator interface 228 can be optionally connected between the actuators of device 10 and microprocessor 220 to convert signals from microprocessor 220 into signals appropriate to drive the actuators. Interface 228 can include power amplifiers, switches, digital to analog controllers (DACs), and other components well known to those skilled in the art. In alternate embodiments, interface 228 circuitry can be provided within microprocessor 220 or in the actuators..

Power supply 230 can be included within the housing of interface device 10 or 10', or can be provided as a separate component, for example, connected by an electrical power cord.

Alternatively, if the USB or a similar communication protocol is used, actuators and other components can draw power from the USB from the host computer. Active actuators, rather than passive actuators, tend to require more power than can be drawn from USB, but this restriction can be overcome in a number of ways. One way is to configure interface device 10 or 10' to appear as more than one peripheral to host computer 18; for example, each provided degree of freedom of user object 12 can be configured as a different peripheral and receive its own allocation of power. Alternatively, power from the USB can be stored and regulated by interface device 10 or 10' and thus used when needed to drive actuators 234. For example, power can be stored over time and then immediately dissipated to provide a jolt force to the user object. A capacitor circuit or battery, for example, can store the energy and dissipate the energy when enough power has been stored. This power storage embodiment can also be used in non-USB embodiments to allow a smaller power supply 230 to be used.

Mechanical apparatus 202 is coupled to electronic interface 200 and preferably includes sensors 232, actuators 234, and mechanism 236. Sensors 232 can be any of the sensors 28 or 98 of the embodiments herein and sense the position, motion, and/or other characteristics of user object 12 along one or more degrees of freedom and provide signals to microprocessor 220 including information representative of those characteristics. Typically, a sensor 232 is provided for each degree of freedom along which object 12 can be moved, or, a single compound sensor can be used for multiple degrees of freedom. Example of sensors suitable for embodiments described herein are digital rotary optical encoders, which sense the change in position of an object about a rotational axis and provide digital signals indicative of the relative change in position. Linear optical encoders may similarly sense the change in position of object 14 along a linear degree of freedom. A suitable optical encoder is the "Softpot" from U.S. Digital of Vancouver, Washington. Alternatively, analog sensors such as potentiometers can be used. It is also possible to use non-contact sensors at different positions relative to mechanical apparatus 202, such as Polhemus (magnetic) or Hall effect sensors for detecting magnetic fields from objects, or an optical sensor such as a lateral effect photo diode having an emitter/detector pair. In addition, velocity sensors (e.g., tachometers) and/or acceleration sensors (e.g., accelerometers) can be used. Furthermore, either relative or absolute sensors can be employed.

Actuators 234 may be any of the actuators 24 or 96 described above and transmit forces to user object 12 in one or more directions along one or more degrees of freedom in response to signals output by microprocessor 220 and/or host computer 18, i.e., they are "computer controlled." Typically, an actuator 234 is provided for each degree of freedom along which forces are desired to be transmitted. Actuators 234 can include two types: active actuators and passive actuators. Active actuators include linear current control motors, stepper motors, pneumatic/hydraulic active actuators, a torquer (motor with limited angular range), a voice coil actuator, and other types of actuators that transmit a force to an object. Passive actuators can also be used for actuators 234, such as 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 232 and actuators 234 can be included together as a sensor/actuator pair transducer.

Mechanism 236 can be one of several types of mechanisms as shown in Figures 3-4 and 7-8. Other mechanisms may also be used. User object 12 can be a wheel, joystick, or other device or article coupled to mechanism 236, as described above.

Other input devices 238 can optionally be included in interface device 10 and send input signals to microprocessor 220 and/or host computer 18. Such input devices can include buttons, such as buttons on user object 12 or the housing of the interface device, used to supplement the input from the user to a game, simulation, GUI, etc. Also, dials, switches, voice recognition hardware (with software implemented by host 18), or other input mechanisms can be used.

Safety or "deadman" switch 240 is preferably included in interface device to provide a mechanism to allow a user to override and deactivate actuators 234, or require a user to activate actuators 234, for safety reasons. For example, the user must continually activate or close safety switch 240 during manipulation of user object 12 to activate the actuators 234. The safety switch can be provided on the wheel 12 or joystick handle 92 at a location where the user grasps the user object. If, at any time, the safety switch is deactivated (opened), power from power supply 230 is cut to actuators 234 (or the actuators are otherwise deactivated) as long as the safety switch is opened. Embodiments of safety switch 240 include an optical safety switch, electrostatic contact switch, hand weight safety switch, etc. The safety switch can be provided between the actuator interface 228 and actuator 234 as shown in Fig. 14; or, the switch can be placed elsewhere. The state of the safety switch can be provided to the microprocessor 130 and/or to the host 18.

In some embodiments, multiple interface devices 10 or 10' can be coupled to a single host computer system 18 through bus 216 (or multiple buses 216) so that multiple users can simultaneously interface with the host application program (in a multi-player game or simulation, for example). In addition, multiple players can interact in the host application program with multiple interface devices 10 using networked host computers 18, as is well known to those skilled in the art.

While this invention has been described in terms of several preferred embodiments, it is contemplated that alterations, permutations and equivalents thereof will become apparent to those skilled in the art upon a reading of the specification and study of the drawings. For example, other types of mechanical linkages and drive assemblies can be provided between the user object 12 and the electronic portion of the interface device. The mechanical portion of the interface can take a variety of forms, including the closed loop linkage described herein, a mechanism having linearly-moving members, a slotted bail mechanism, or other mechanisms.

Different types of stages can be mixed with the capstan stages of the present invention, such as a belt drive or gear drive. Likewise, other types of mechanisms can be provided for disengaging and engaging the physical springs of the interface device with the moving mechanical members. In addition, other types of actuators, sensors, and user objects can be used in other embodiments. 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 all such alterations, permutations, and equivalents as fall within the true spirit and scope of the present invention.

What is claimed is:

CLAIMS

1. A transmission system for transmitting motion and force between a driven object and an actuator, the transmission system comprising:

an actuator stage coupled to said actuator, said actuator stage including:

a capstan pulley coupled to said actuator, said capstan pulley rotatable about a first axis by said actuator;

a capstan drum rotatable about a second axis; and

a flexible member coupling said capstan pulley to said capstan drum, wherein said flexible member is coupled to said capstan drum at both ends of said flexible member, and wherein said capstan pulley causes said capstan drum to rotate about said second axis for multiple revolutions; and

an output stage coupled to said actuator stage, said output stage coupled to said driven object to rotate said driven object.

2. A transmission system as recited in claim 1 wherein said capstan pulley is a first capstan pulley, said capstan drum is a first capstan drum, and said flexible member is a first flexible member, and wherein said output stage includes:

a second capstan pulley rigidly coupled to said first capstan drum and rotatable about said second axis;

a second capstan drum coupled to said driven object, said second capstan drum rotatable about a third axis; and

a second flexible member coupling said second capstan pulley to said second capstan drum, wherein said second flexible member is coupled to said second capstan drum at both ends of said second flexible member.

3. A transmission system as recited in claim 2 wherein said first, second and third axes are approximately parallel to each other.

4. A transmission system as recited in claim 1 wherein said flexible member is a cable.

5. A transmission system as recited in claim 2 further comprising an intermediate stage coupled between said actuator stage and said output stage, said intermediate stage including a third capstan drum and a third capstan pulley coupled together by a third flexible member.

6. A transmission system as recited in claim 2 wherein said first capstan drum is cylindrical.

7. A transmission system as recited in claim 1 further comprising a spring member coupled between one end of said flexible member and said capstan drum, said spring member providing tension in said flexible member.

8. A transmission system as recited in claim 1 wherein said capstan drum includes grooves for guiding said flexible member thereon.

9. A transmission system as recited in claim 1 wherein said driven object is rotatable about a third axis and is a user object manipulatable by a user about said third axis.

10. A transmission system as recited in claim 9 wherein said user object is a steering wheel.

11. A transmission system as recited in claim 9 wherein said user object is a joystick.

12. An interface device coupled to a host computer and inputting motion signals to said host computer in response to manipulations of said interface device by a user. said interface device providing force feedback to said user. said interface device comprising:

a user manipulatable object contacted and manipulated by a user and moveable in a degree of freedom;

a sensor coupled to said user manipulatable object that detects motion of said user manipulatable object, wherein said sensor provides a sensor signal including information describing said motion of said user manipulatable object in said degree of freedom;

an actuator that provides forces in said degree of freedom of said user manipulatable object, wherein said actuators are controlled from commands output by said host computer; and

a capstan drive assembly coupling said actuator to said user manipulatable object, said capstan drive assembly including an actuator stage and an output stage, wherein said actuator stage includes a capstan pulley coupled to a cylindrical capstan drum by a flexible member, said cylindrical drum having rotatable range over 360 degrees, and wherein a ratio of a diameter of said drum to a diameter of said pulley in said actuator stage increases a magnitude of forces output on said user manipulatable object from said actuator.

13. An interface device as recited in claim 12 wherein both ends of said flexible member are coupled to said drum.

14. An interface device as recited in claim 13 wherein said capstan pulley is a first capstan pulley, said capstan drum is a first capstan drum, and said flexible member is a first flexible member, said output stage includes a second capstan pulley coupled to a second capstan drum by a second flexible member, said second capstan drum being coupled to said user manipulatable object, wherein both ends of said second flexible member are coupled to said second drum, and wherein a ratio of a diameter of said second pulley to a diameter of said second drum in said output stage increases a magnitude of forces output on said user manipulatable object from said actuator.

15. An interface device as recited in claim 14 wherein said user manipulatable object is rotatable about an axis.

16. An interface device as recited in claim 15 wherein said user manipulatable object is a steering wheel.

17. An interface device as recited in claim 15 wherein said flexible member of each of said stages of said capstan drive assembly is a cable having an approximately circular cross section.

18. An interface device as recited in claim 15 wherein said capstan drive assembly scales forces output by said actuator in a ratio of about 40:1.

19. An interface device as recited in claim 13 wherein said capstan drum includes grooves for guiding said flexible member thereon.

20. An interface device for as recited in claim 13 wherein said pulley includes grooves for guiding said flexible member thereon.

21. An interface device as recited in claim 14 wherein said first pulley is rotatable about a first axis, said first drum and said second pulley are rotatable about a second axis, and said second drum and said user manipulatable object are rotatable about a third axis.

22. An interface device as recited in claim 14 wherein said second flexible member is of greater thickness and is capable of transmitting forces of greater magnitude than said first flexible member.

23. An interface device as recited in claim 13 wherein said flexible member is wrapped a plurality of times around said capstan pulley and a plurality of times around said capstan drum.

24. An interface device as recited in claim 13 wherein said flexible member is coupled to said drum at one end, and further comprising a spring coupled between said end of said flexible member and said drum to provide a spring tension in said flexible member.

25. An interface device as recited in claim 15 wherein said sensors are lateral effect photo diodes including an emitter and a detector.

26. An interface device as recited in claim 25 wherien said sensor includes a light pipe for guiding light emitted by said emitter to said detector.

27. An interface device as recited in claim 15 further comprising a stop mechanism for limiting movement of said user manipulatable object to a desired angular range.

28. An interface device as recited in claim 15 further comprising a local microprocessor, separate from said host computer system and coupled to said host computer system by a communication bus, said microprocessor receiving sensor signals from said sensors and sending output control signals to said actuators to control a level of force output by said actuators.

29. An interface device as recited in claim 15 further comprising a speed reduction device coupled to said actuator for limiting a top rotational speed of said user manipulatable object, thereby increasing the safety of said interface device.

30. A method for transmitting forces from an actuator to a driven object, the method comprising:

causing said actuator to output a force on a first capstan pulley coupled to a shaft of said actuator and causing said first capstan pulley to rotate;

rotating a first capstan drum in conjunction with said first capstan pulley, wherein said first capstan drum is coupled to said first capstan pulley by a first cable, said first cable being coupled to said first capstan drum at each end of said first cable, and wherein said first capstan drum rotates for multiple revolutions;

rotating a second capstan pulley in conjunction with said first capstan drum, said second capstan pulley rigidly coupled to said first capstan drum; and

rotating a second capstan drum in conjunction with said second capstan pulley, wherein said second capstan drum is coupled to said second capstan pulley by a second cable, wherein said second capstan drum is coupled to said driven object.

31. A method as recited in claim 30 wherein said first capstan drum includes grooves for guiding said first cable on said first capstan drum and wherein said first capstan drum is cylindrical in shape.

32. A method as recited in claim 30 further comprising rotating a third capstan pulley and a second capstan drum in conjunction with said second capstan drum, wherein said third capstan pulley and said third capstan drum are coupled between said second capstan drum and said driven object.

33. A method as recited in claim 30 further comprising a spring member coupled between one end of said first cable and said first capstan drum.

34. A method as recited in claim 30 wherein said second cable is coupled at both ends of said second cable to said second capstan drum.

35. A method as recited in claim 30 wherein said driven object is a user manipulatable object provided in a force feedback interface device coupled to a host computer.

36. A method for interfacing a graphical simulation implemented by a host computer with a user using an interface device including a mechanical transmission system, the method comprising:

providing a user manipulatable object graspable by a user and rotatable in a rotary degree of freedom;

sensing motion of said user manipulatable object and providing signals indicating of said motion to said host computer;

outputting a force from an actuator on said user manipulatable object in said rotary degree of freedom; and providing mechanical advantage for said force such that said force is increased in magnitude before being output on said user object, said mechanical advantage being provided from a capstan drive mechanism having a plurality of stages, each stage of said capstan drive mechanism including a pulley coupled to a cylindrical drum by a flexible member.

37. A method as recited in claim 36 wherein a cylindrical drum of a first stage of said capstan drive mechanism rotates for multiple revolutions.

38. A method as recited in claim 37 wherein said plurality of stages of said capstan drive mechanism are provided such that a first stage scales a force output by said actuator, and a second stage scales a force output by said first stage, wherein a force output by said second stage is output on said user manipulatable object.

39. A method as recited in claim 37 further comprising stopping said rotation of said user manipulatable object when said user manipulatable object is moved to a limit of a desired angular range.

40. A method as recited in claim 37 further comprising providing a spring tension in at least one of said flexible members using a spring member coupled to said at least one flexible member.

41. A method as recited in claim 37 wherein one of said flexible members is wrapped a plurality of times around said first capstan pulley and a plurality of times around said first capstan drum.

42. A method as recited in claim 36 further comprising reducing a top rotational speed of said user manipulatable object to a maximum desired rotation speed.

43. A method as recited in claim 37 further comprising sending control signals to said host computer from an input device selected by said user and separate from said motion of said user manipulable object.

44. A mechanism for providing selective engagement of spring members to a user manipulatable object in a force feedback interface device coupled to a host computer, the mechanism comprising:

a grounded member coupled to a ground;

a moveable member included in a force feedback mechanism, said moveable member moveable in a degree of freedom by an actuator and transmitting forces to said user manipulatable object of said force feedback interface device; and a spring member operative to be selectively coupled and selectively decoupled between said grounded member and said moveable member.

45. A mechanism as recited in claim 44 wherein said spring member provides a spring force on said moveable member that biases said user manipulatable object to a predetermined position in said degree of freedom.

46. A mechanism as recited in claim 45 wherein said spring force approximately centers said user manipulatable object in said degree of freedom.

47. A mechanism as recited in claim 44 further comprising a catch mechanism coupled to said spring member, said catch mechanism including a first catch member and a second catch member, wherein said first catch member may be selectively engaged and selectively disengaged with said second catch member.

48. A mechanism as recited in claim 47 wherein said first catch member is coupled to one end of said spring member, and said second catch member is grounded and coupled to another end of said spring member.

49. A mechanism as recited in claim 48 wherein said first catch member includes at least one receptacle for receiving at least one peg coupled to said moveable member, wherein when said spring member is engaged with said force feedback mechanism, said peg engages said receptacle when said moveable member is moved and is biased by said spring member, and when said spring member is disengaged with said force feedback mechanism, said peg does not engage said receptacle when said moveable member is moved.

50. A mechanism as recited in claim 47 wherein said first catch member is moveable by a user of said interface device to selectively engage said spring members with said force feedback mechanism.

51. A mechanism as recited in claim 50 wherein a portion of said first catch member extends through an opening in a housing of said force feedback interface device for access by said user.

52. A mechanism as recited in claim 48 wherein said moveable member is rotatable about an axis of rotation.

53. A mechanism as recited in claim 52 wherein said first catch member includes an aperture and wherein said moveable member includes two pegs, wherein each of said pegs extends through said aperture on opposite sides of said axis of rotation, and wherein one of said

pegs engages said first catch member when said moveable member is rotated, thereby exerting a spring force from said spring member on said moveable member.

54. A mechanism as recited in claim 53 wherein when said spring member is decoupled between said grounded member and said moveable member, neither of said pegs engages said first catch member when said moveable member is moved.

55. A mechanism as recited in claim 54 wherein said first catch member includes a latch for engaging said second catch member, thereby locking said first catch member in a position such that neither of said pegs engages said first catch member when said moveable member is moved.

56. A mechanism as recited in claim 45 wherein said spring member is preloaded when said user manipulatable object is positioned at said predetermined position.

57. A force feedback interface device for providing forces on a user manipulating said interface device when coupled to a host computer, said force feedback interface device comprising:

a user manipulandum for physical contact by a user;

a sensor for detecting a position of said user manipulandum in a degree of freedom;

an actuator coupled to said user manipulandum for applying a force to said user manipulandum;

a linkage mechanism coupled between said actuator and said user manipulandum, said linkage mechanism providing said degree of freedom and transmitting said force from said actuator to said user manipulandum; and

a spring selection mechanism coupled to said linkage mechanism selectively allowing a physical spring to be coupled to said linkage mechanism to provide a spring force on said user manipulandum.

58. A force feedback interface device as recited in claim 57 wherein said spring selection mechanism includes said physical spring, wherein said spring is coupled between a moveable member of said linkage mechanism and a grounded surface.

59. A force feedback interface device as recited in claim 58 wherein said spring selection mechanism includes a catch member coupled between said spring and said moveable member of said linkage mechanism.

60. A force feedback interface device as recited in claim 59 wherein said catch member includes a latch for engaging a grounded catch mechanism, wherein when said latch is engaged, said spring member is decoupled from said linkage mechanism, and when said latch is disengaged, said spring member is coupled to said linkage mechanism.

61. A force feedback interface device as recited in claim 60 wherein said spring force approximately centers said user manipulandum in said degree of freedom.

62. A force feedback interface device as recited in claim 61 wherein said actuator is a first actuator, and further comprising a second actuator, wherein a first member of said linkage mechanism is coupled between said first actuator and said user manipulandum and a second member of said linkage mechanism is coupled between said second actuator and said user manipulandum.

63. A force feedback interface device as recited in claim 62 wherein said spring selection mechanism is a first spring selection mechanism coupled to said first member, and further comprising a second spring selection mechanism coupled to said second member.

64. A force feedback interface device as recited in claim 57 further comprising a capstan drive mechanism coupled between said actuator and said linkage mechanism, wherein said capstan drive mechanism includes a capstan pulley coupled to said actuator, a capstan drum coupled to said linkage mechanism, and a cable coupling said capstan pulley to said capstan drum.

65. A force feedback interface device as recited in claim 64 wherein said capstan drum includes a tensioning spring member coupled to both ends of said cable for tensioning said cable.

66. A force feedback interface device as recited in claim 64 wherein said capstan drum includes a curved end over which said cable is routed, and wherein said curved end includes flanges arranged on sides of said curved end to substantially prevent said cable from slipping of said sides of said curved end.

67. A force feedback interface device as recited in claim 57 wherein said user manipulandum is a joystick handle.

68. A force feedback interface device as recited in claim 57 wherein said linkage mechanism is a closed loop five-member linkage.

69. A force feedback interface device as recited in claim 57 wherein said spring selection mechanism includes a catch member coupled between said spring and said linkage mechanism, wherein said catch member operates as a switch and is moveable by said user.

70. A force feedback interface device as recited in claim 64 further comprising a stop coupled to a ground, said stop preventing motion of said user manipulandum in a direction past a predetermined range, wherein said user manipulandum impacts said stop before said capstan drum reaches a limit to movement.

71. A force feedback interface device as recited in claim 57 wherein a sensing range for said force feedback interface device is dynamically determined, wherein said sensing range does not include positions of said user manipulandum sensed during said force application by said actuators in a direction towards a range limit corresponding with said positions.

72. A method for selectively providing a spring force in a force feedback interface device using a physical spring, the method comprising:

providing a spring member between a user manipulandum and a linkage mechanism, said user manipulandum to be physically contacted by a user to feel forces output on said user manipulandum;

selectively decoupling said spring from said user manipulandum when an actuator of said interface device is to output said forces on said user manipulandum; and

selectively coupling said spring member to said user manipulandum when said actuator is not to output forces on said user manipulandum.

73. A method as recited in claim 72 wherein said spring member provides a centering spring force on said user manipulandum when coupled to said user manipulandum for centering said user manipulandum a degree of freedom.

74. A method as recited in claim 72 wherein said selectively decoupling and selectively coupling are accomplished using a spring selection mechanism coupled to said linkage mechanism.

75. A method as recited in claim 72 wherein said selectively coupling said spring member is performed when said force feedback interface device is not powered.

76. A force feedback interface device coupled to a host computer and providing forces to a user manipulating said interface device, the interface device comprising:

a user manipulandum for physical contact by a user;

a sensor for detecting a position of said user manipulandum in a degree of freedom;

an actuator coupled to said user manipulandum for applying a force to said user manipulandum;

a linkage mechanism coupled between said actuator and said user manipulandum, said linkage mechanism providing said degree of freedom and transmitting said force from said actuator to said user manipulandum; and

a capstan drive mechanism coupled between said actuator and said linkage mechanism, wherein said capstan mechanism includes a pulley coupled to said actuator, a moveable capstan drum coupled to said linkage mechanism, and a cable coupling said pulley to said capstan drum, and wherein said capstan drum includes a curved end over which said cable is routed, said curved end including flanges arranged on sides of said curved end to substantially prevent said cable from slipping off said sides of said curved end.

77. An interface device as recited in claim 76 wherein said degree of freedom is a rotary degree of freedom and wherein said capstan drum is coupled to a member of said linkage mechanism and rotates about an axis of rotation.

78. An interface device as recited in claim 76 wherein said curved end is approximately a portion of a circumference of a cylinder.

79. An interface device as recited in claim 76 wherein said capstan drum includes a tensioning spring member coupled to both ends of said cable for tensioning said cable.

80. An interface device as recited in claim 76 further comprising a spring selection mechanism coupled to said linkage mechanism and selectively allowing a physical spring to be coupled to said linkage mechanism to provide a spring force on said user manipulandum.

81. An interface device as recited in claim 76 wherein a sensing range for said sensor is dynamically determined, and wherein said sensing range is not based on positions of said user manipulandum sensed during said force application by said actuators in a direction towards a range limit corresponding with said positions.

82. A force feedback interface device coupled to a host computer and providing forces to a user manipulating said interface device, the interface device comprising:

a user manipulandum for physical contact by a user;

a sensor for detecting a position of said user manipulandum in a degree of freedom;

an actuator coupled to said user manipulandum for applying a force to said user manipulandum;

a linkage mechanism coupled between said actuator and said user manipulandum, said linkage mechanism providing said degree of freedom and transmitting said force from said actuator to said user manipulandum; and

a capstan drive mechanism coupled between said actuator and said linkage mechanism, wherein said capstan mechanism includes a pulley coupled to said actuator, a moveable capstan drum coupled to said linkage mechanism, and a cable coupling said pulley to said capstan drum, and wherein said capstan drum includes a tensioning spring member coupled to at least one end of said cable for tensioning said cable.

83. A force feedback interface device as recited in claim 82 wherein said tensioning spring cable is coupled to both ends of said cable.

84. A force feedback interface device as recited in claim 83 further comprising an anchoring device coupled between said capstan drum and said cable, said anchoring device coupling said cable to said capstan drum to substantially prevent slippage of said cable with respect to said drum.

85. A force feedback interface device as recited in claim 83 wherein said anchoring device includes a clamp.

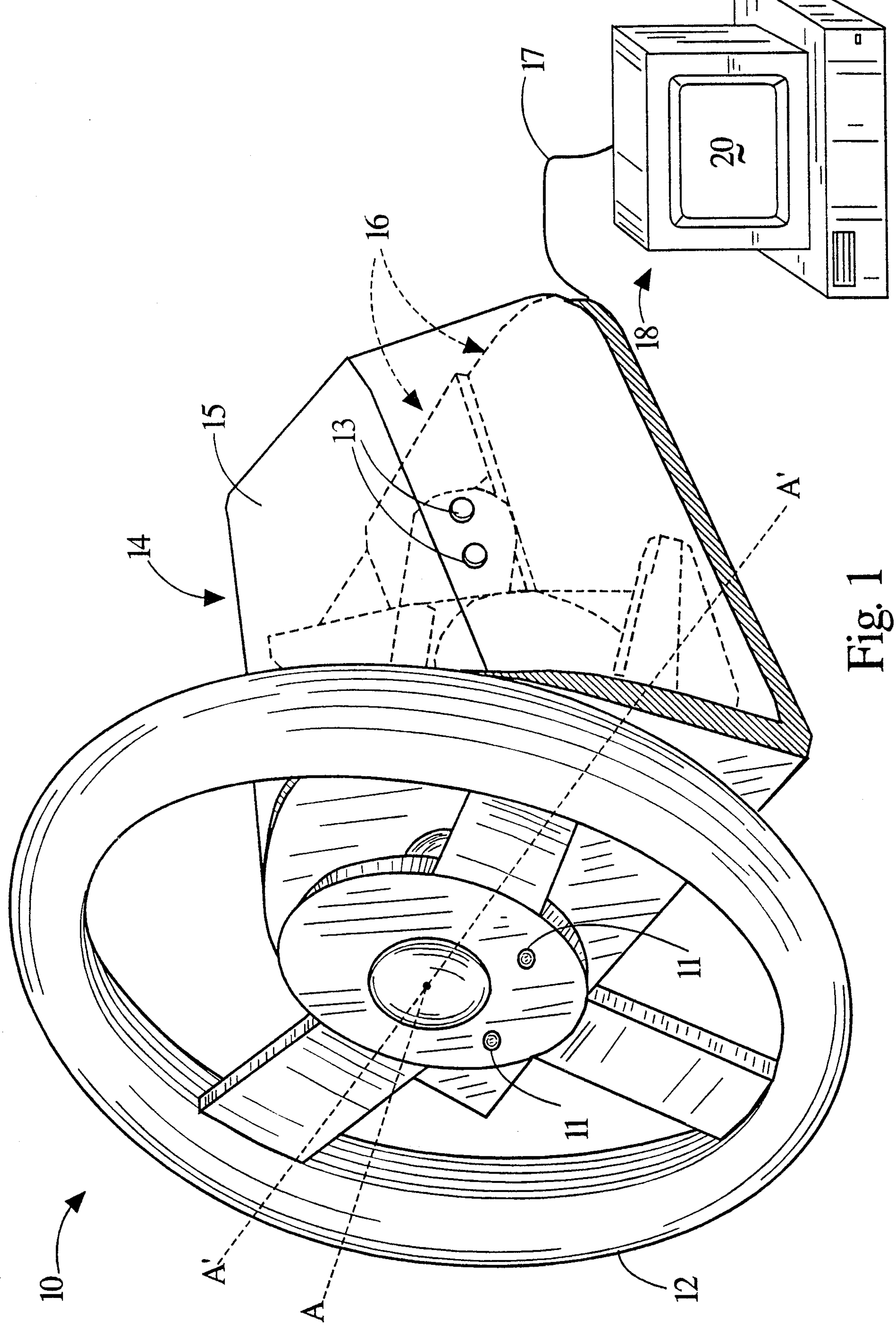

Fig. 1

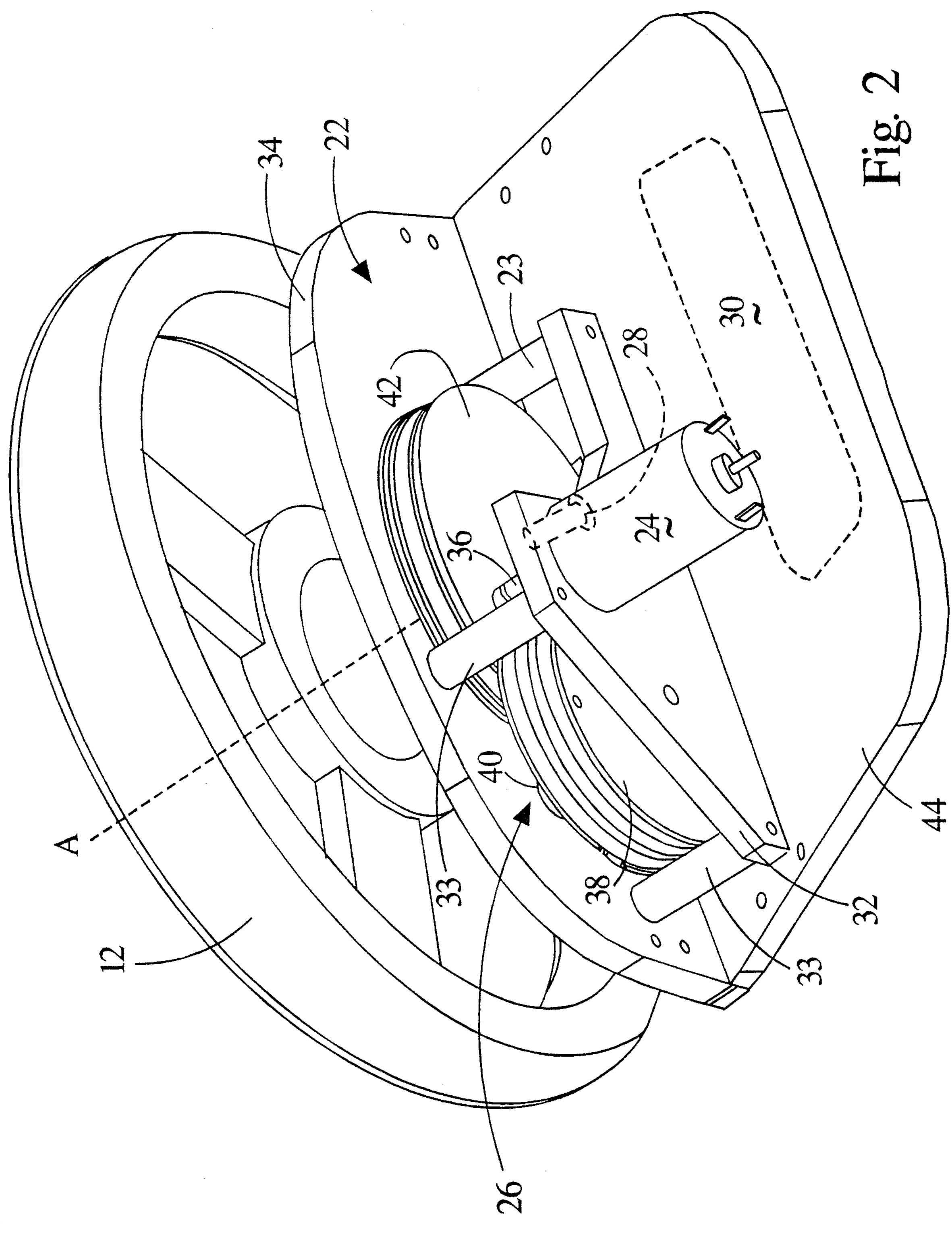

Fig. 2

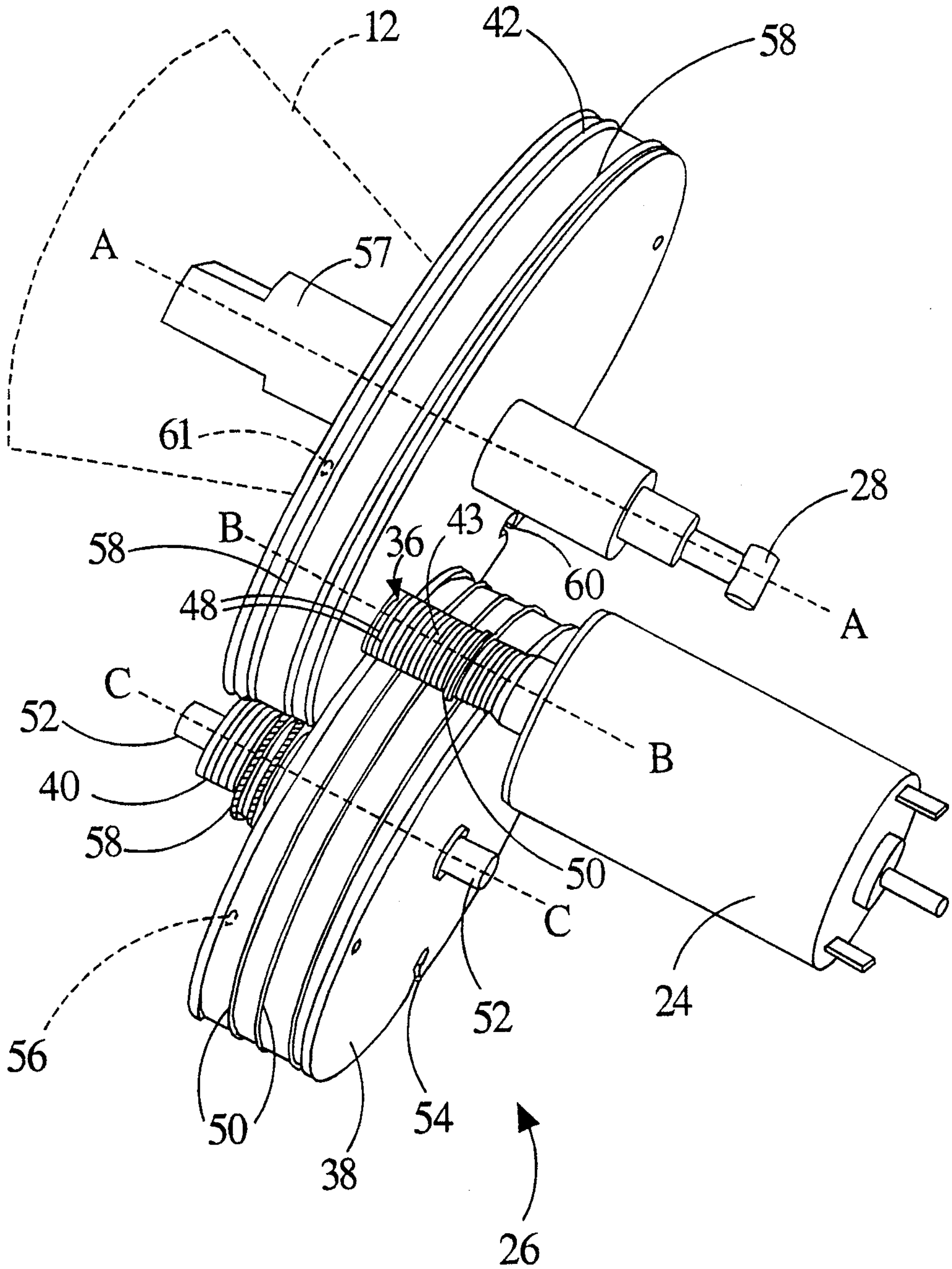
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Fig. 3

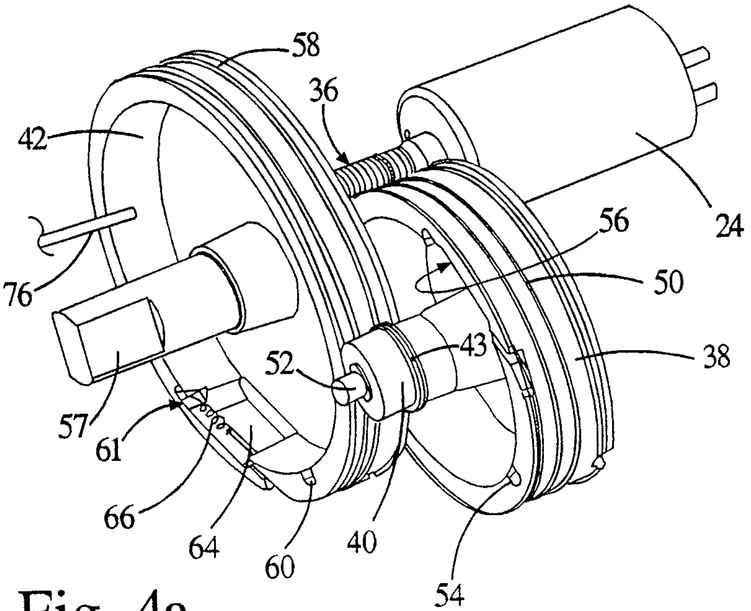

Fig. 4a

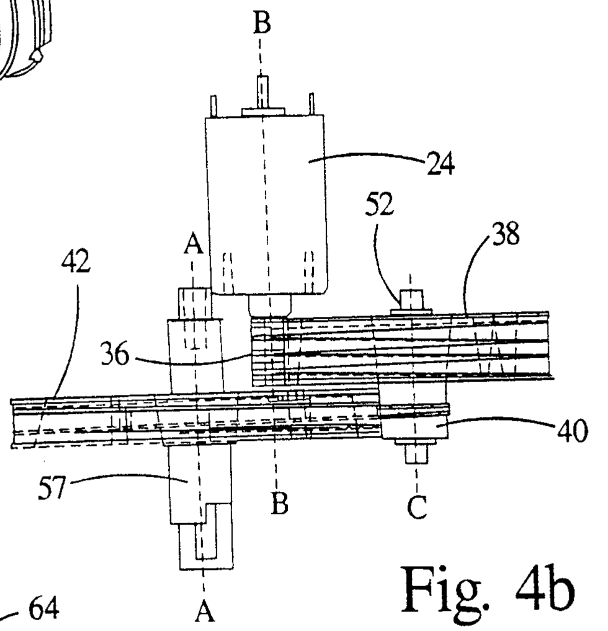

Fig. 4b

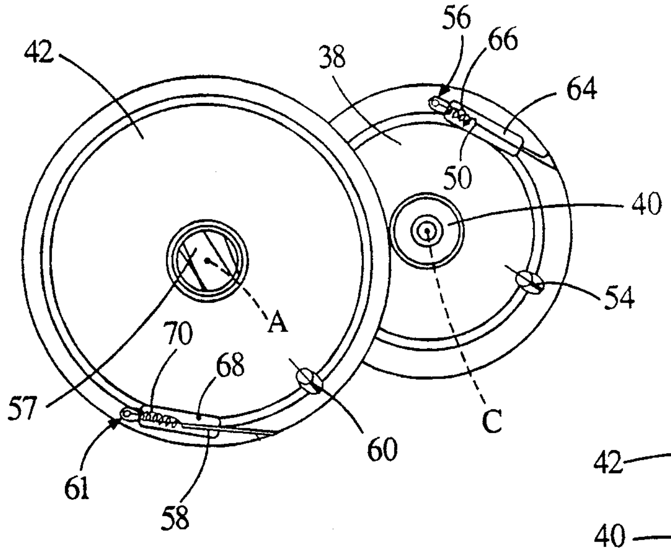

Fig. 4c

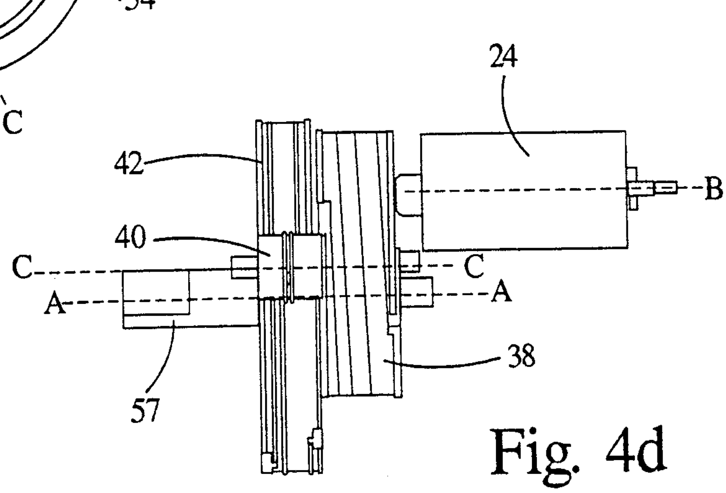

Fig. 4d

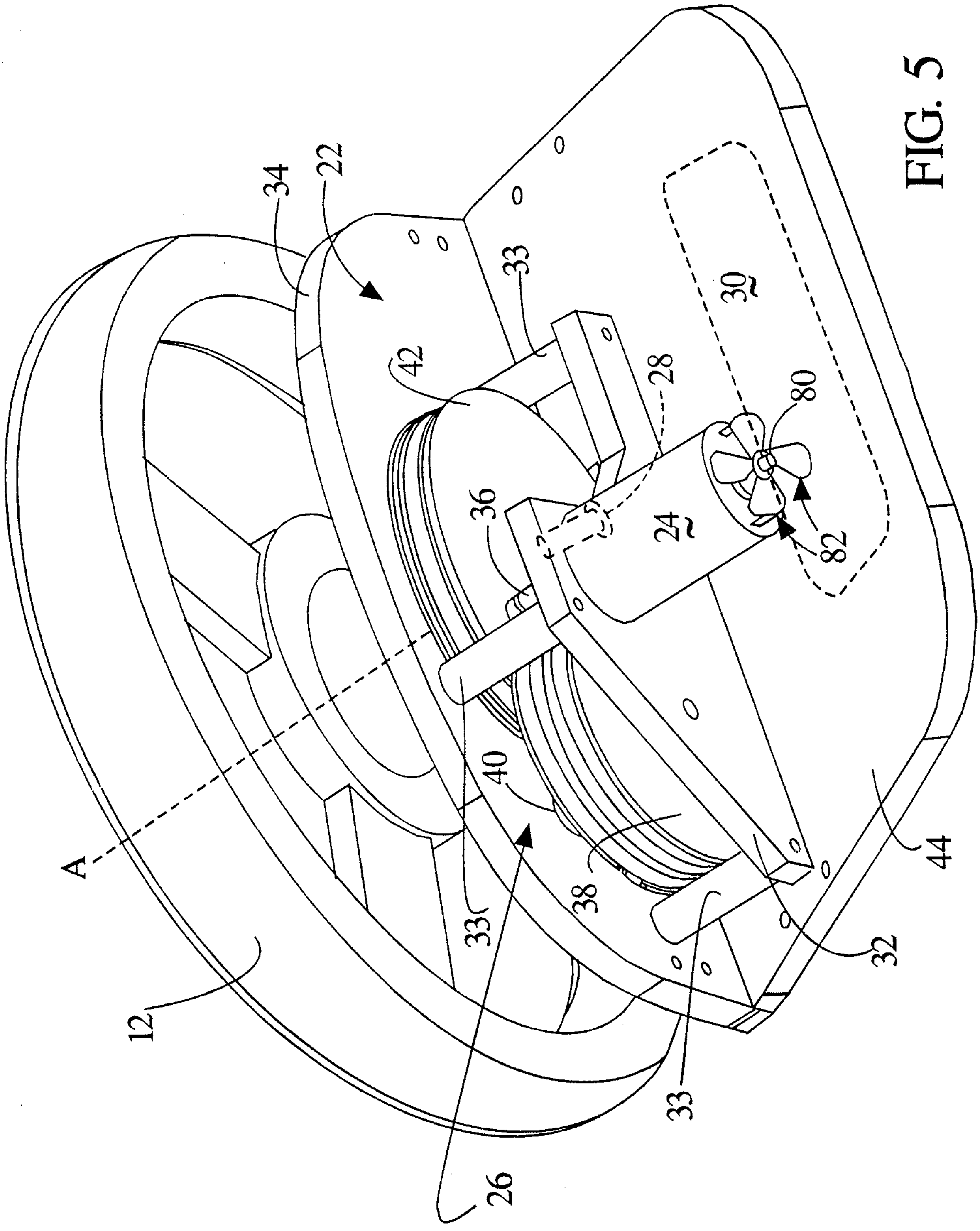

FIG. 5

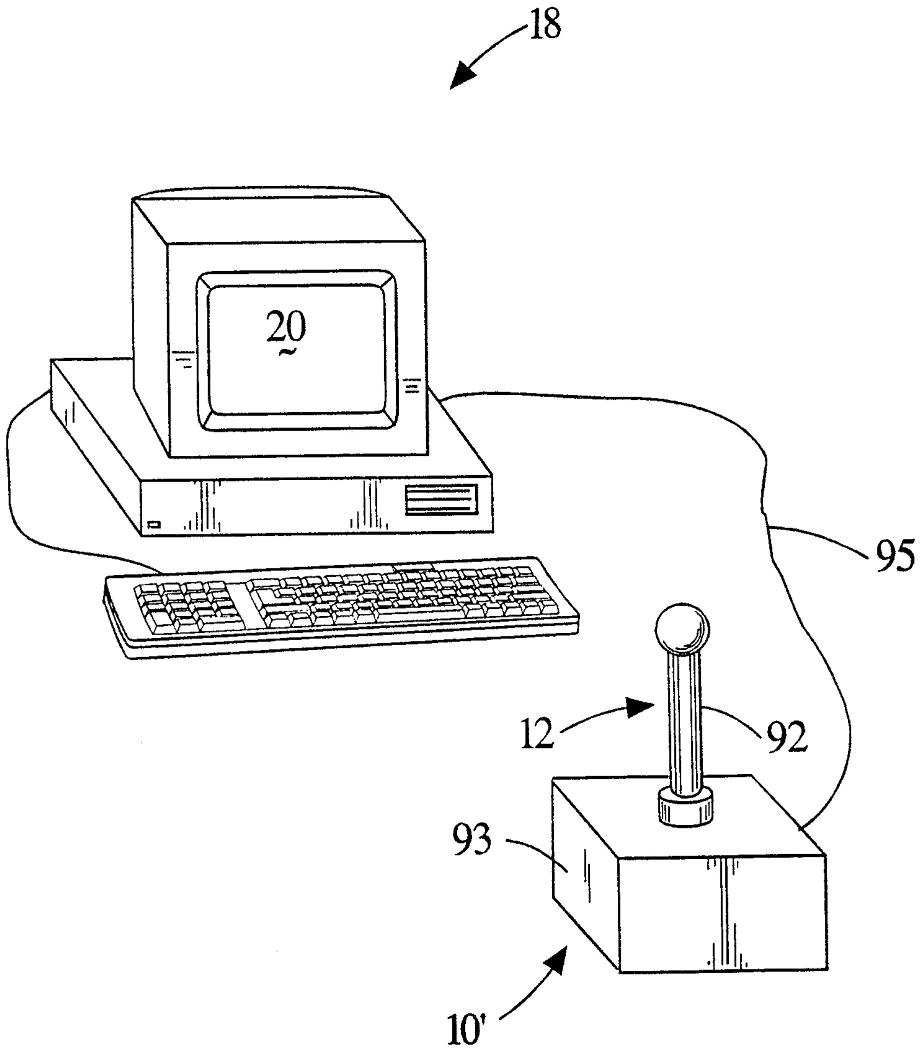

Fig. 6

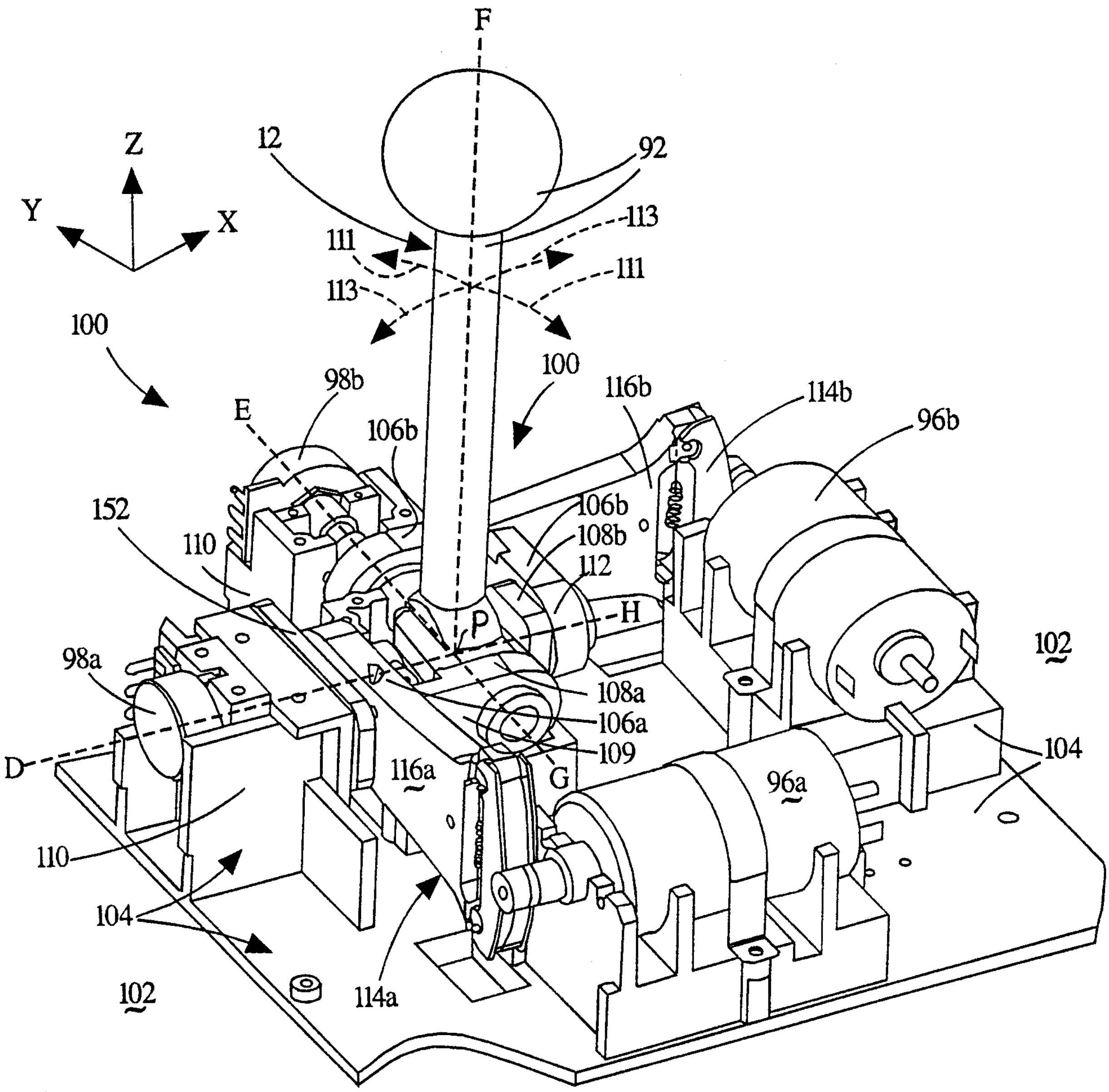
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FIG. 7

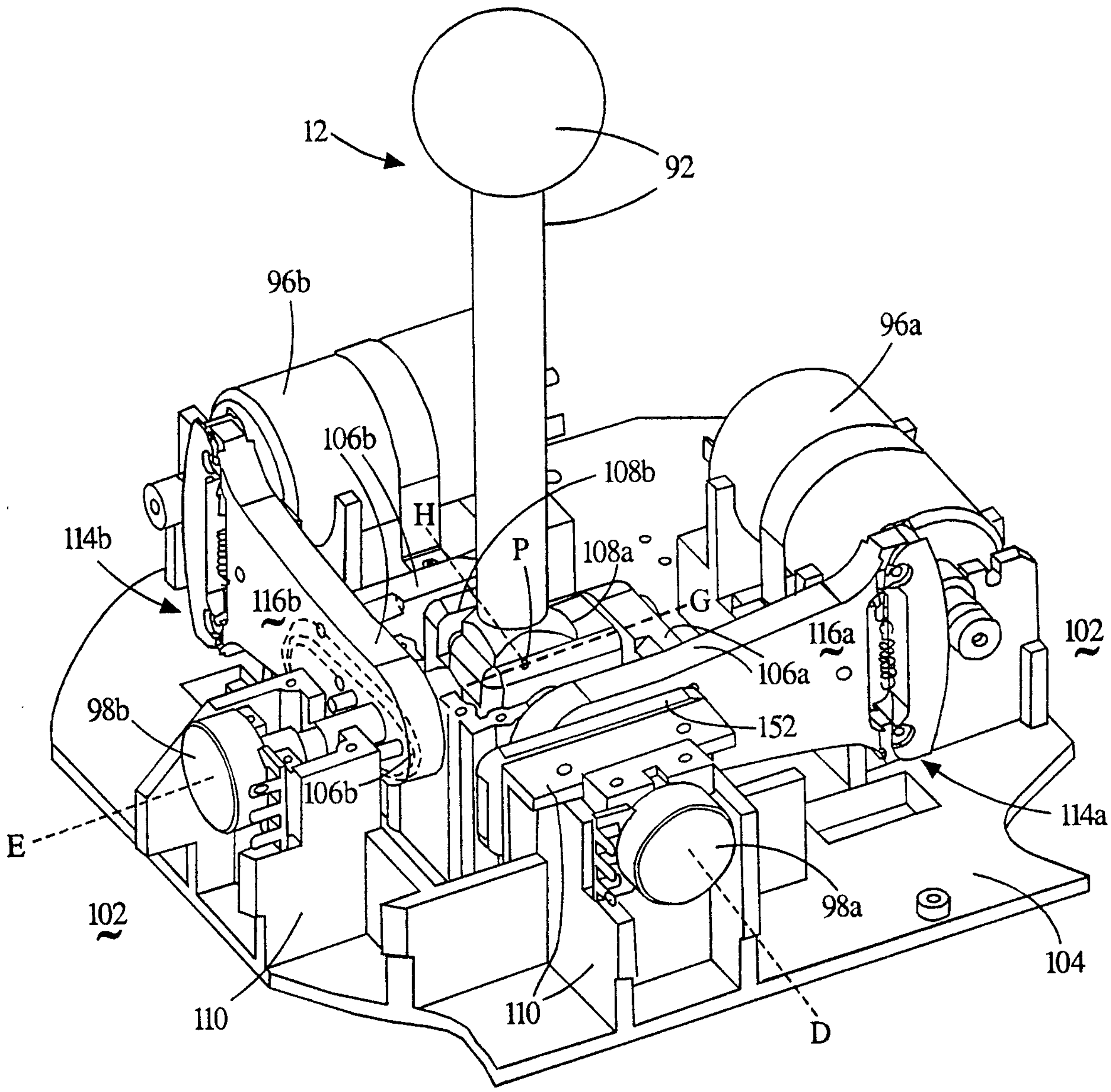
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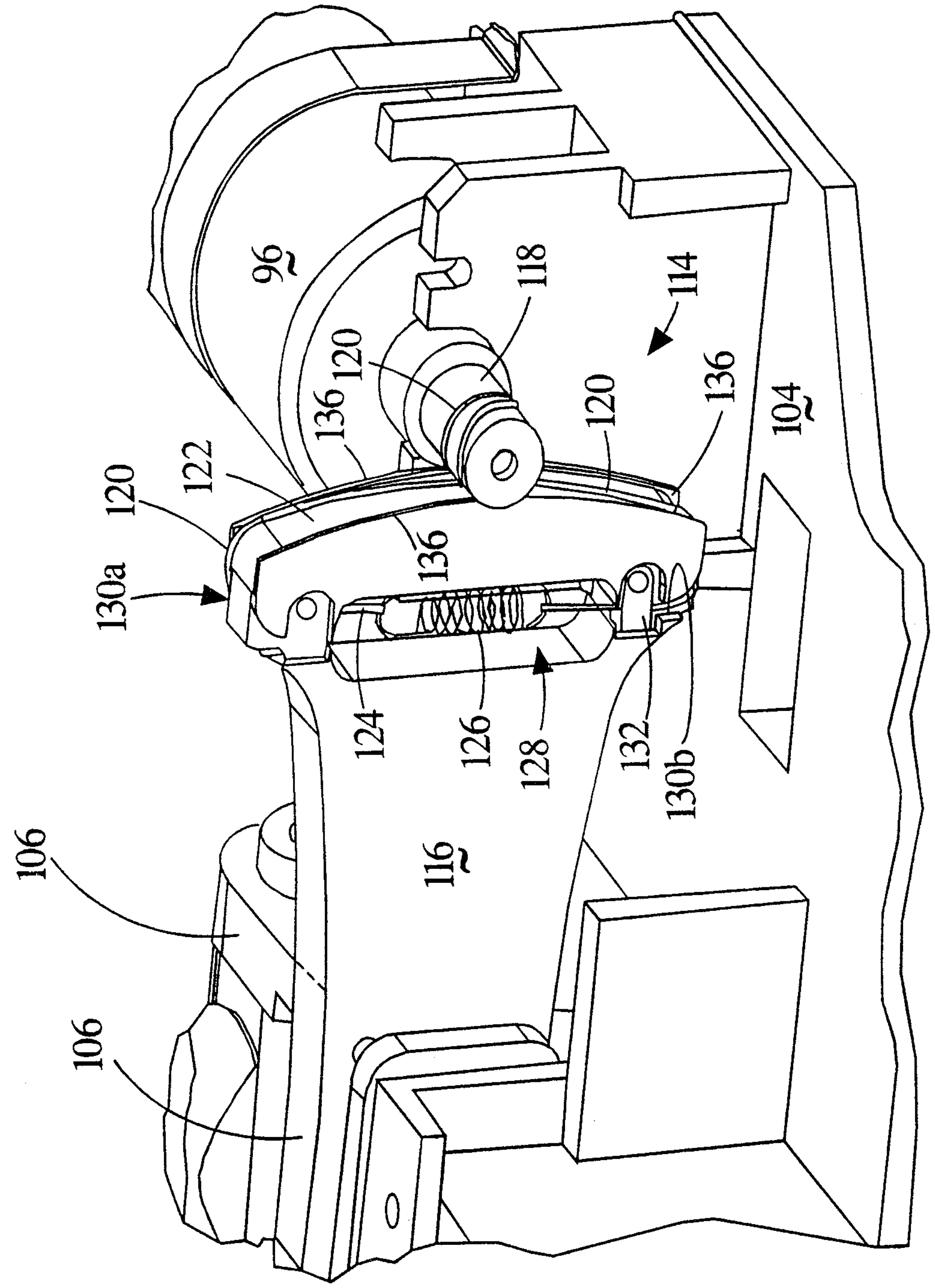
Fig. 8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106

FIG. 9

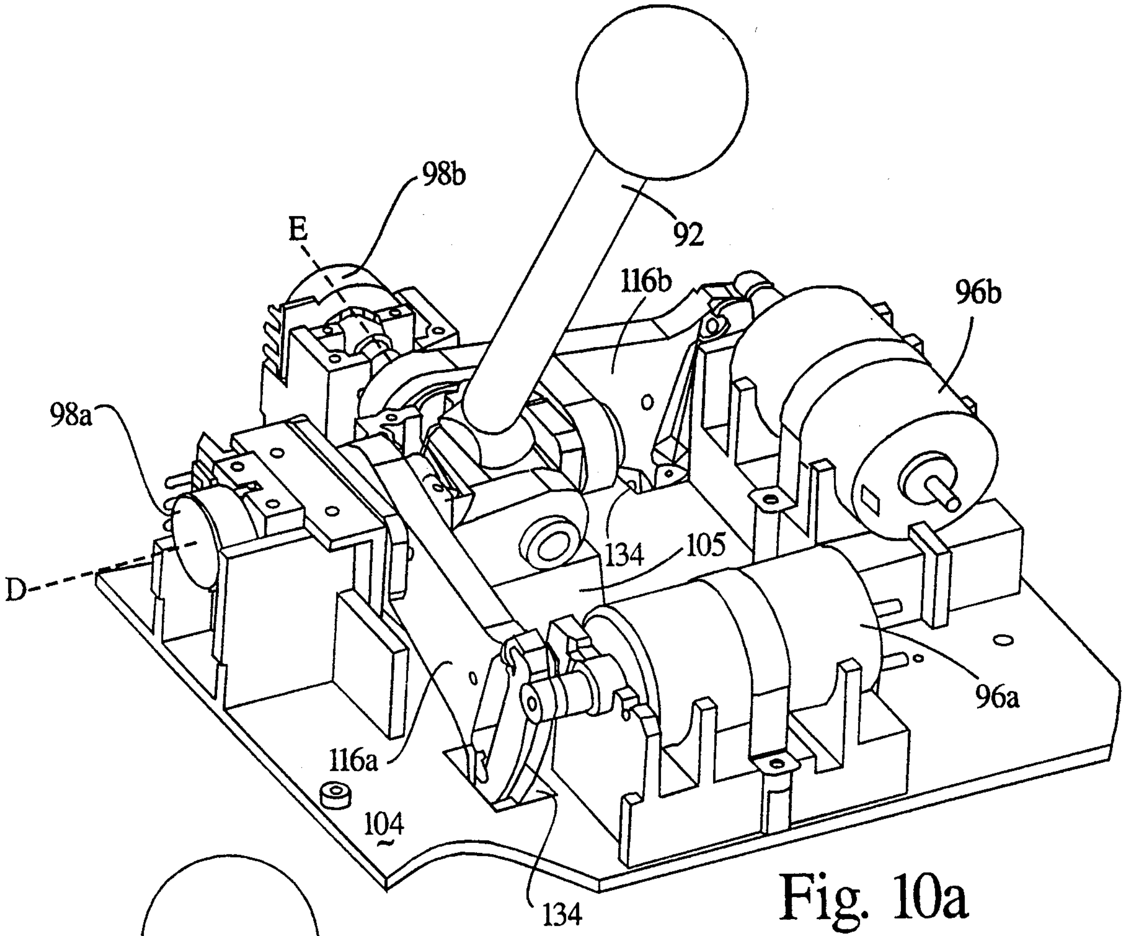


Fig. 10a

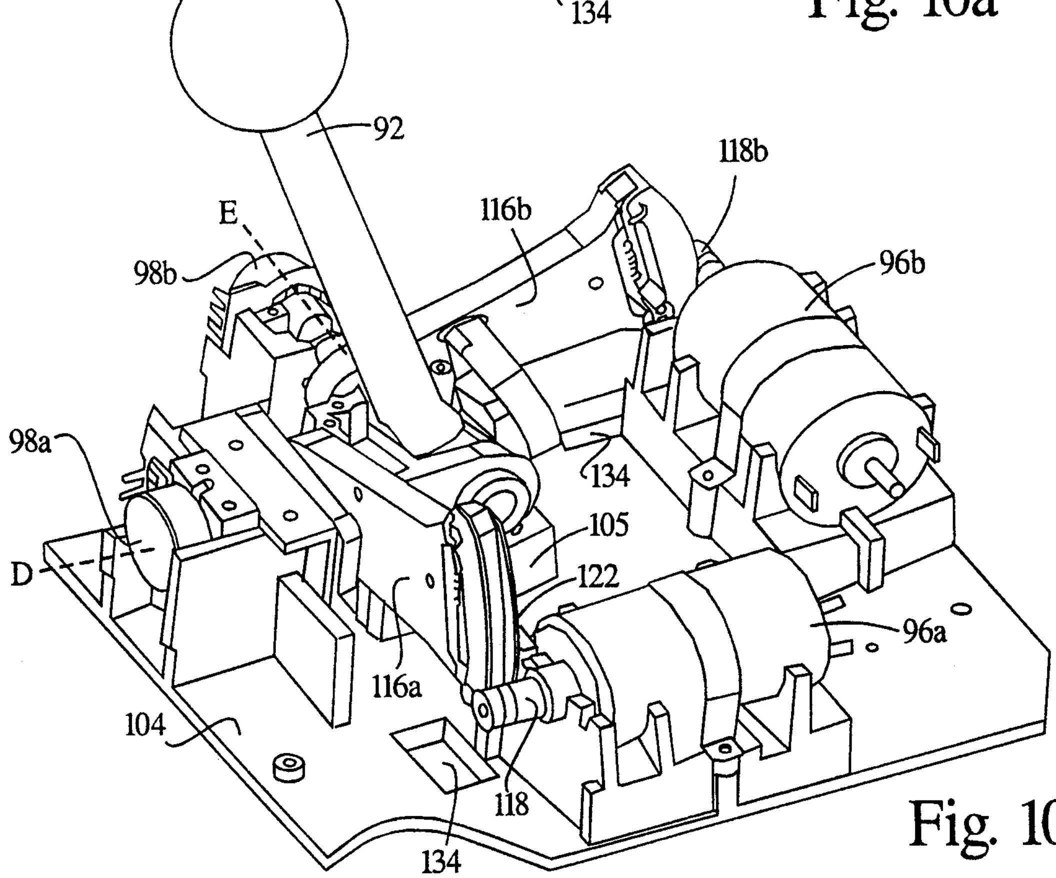


Fig. 10b

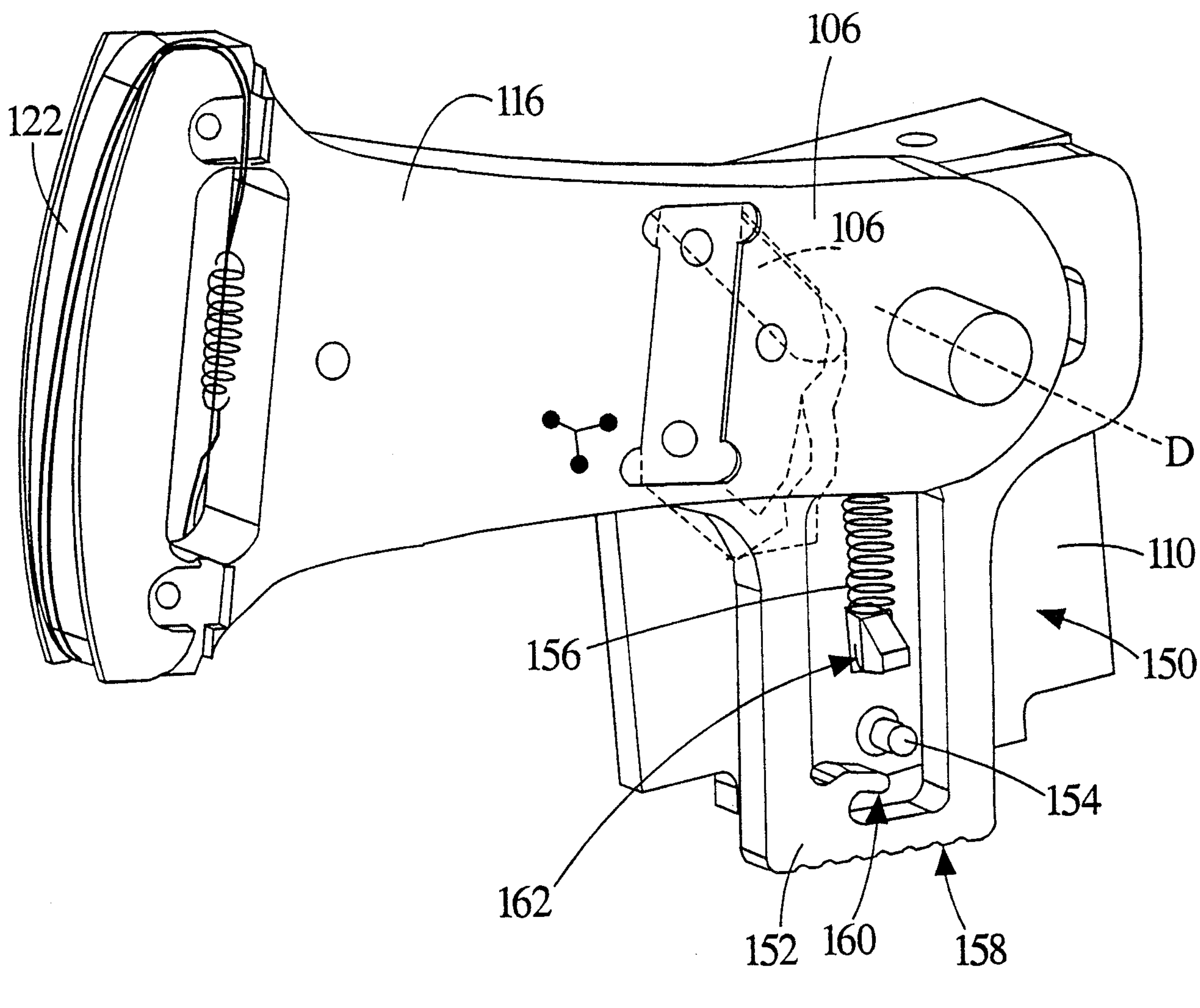
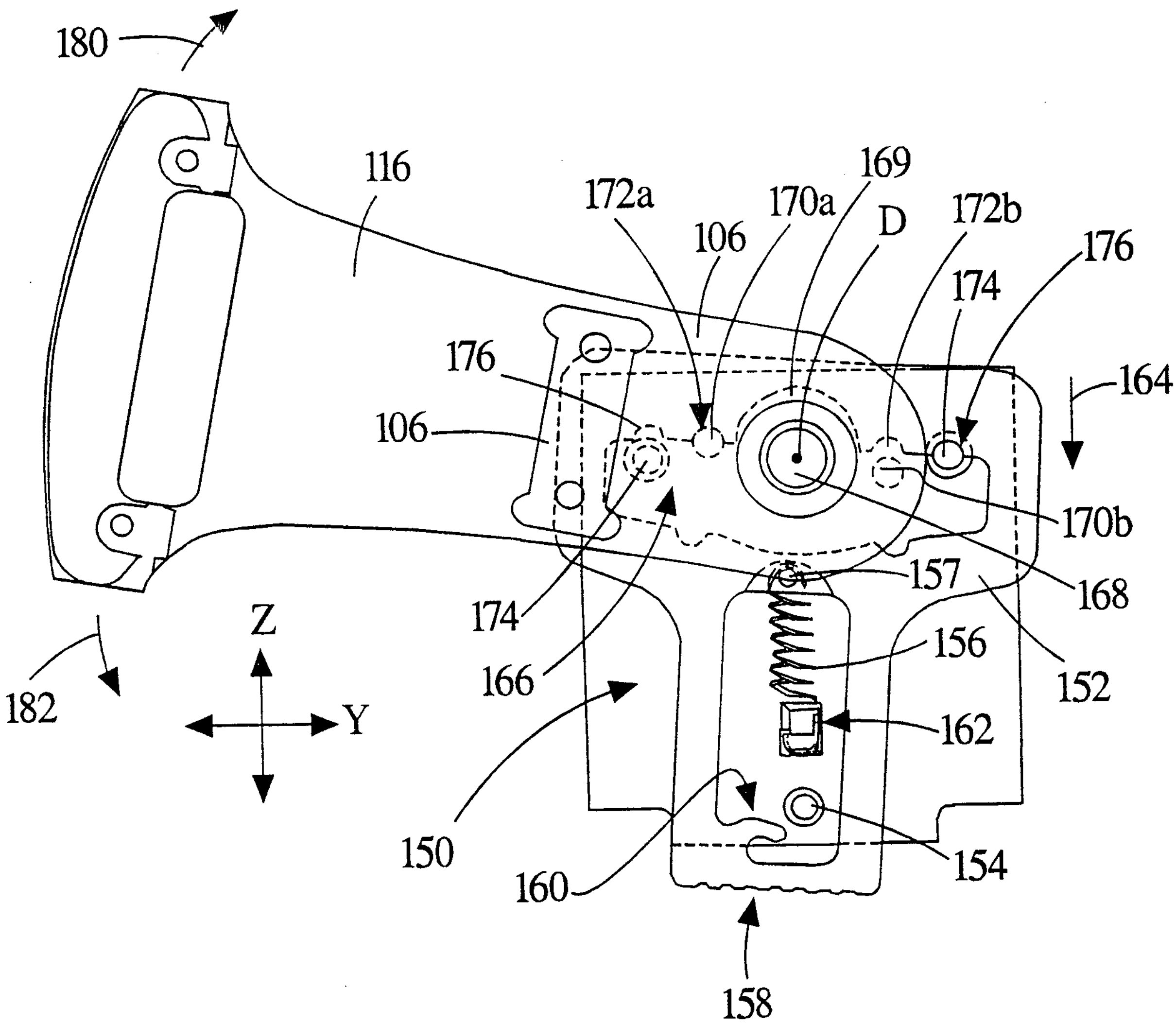


FIG. 11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Z
Y
182
162
150
160
154
158

FIG. 12

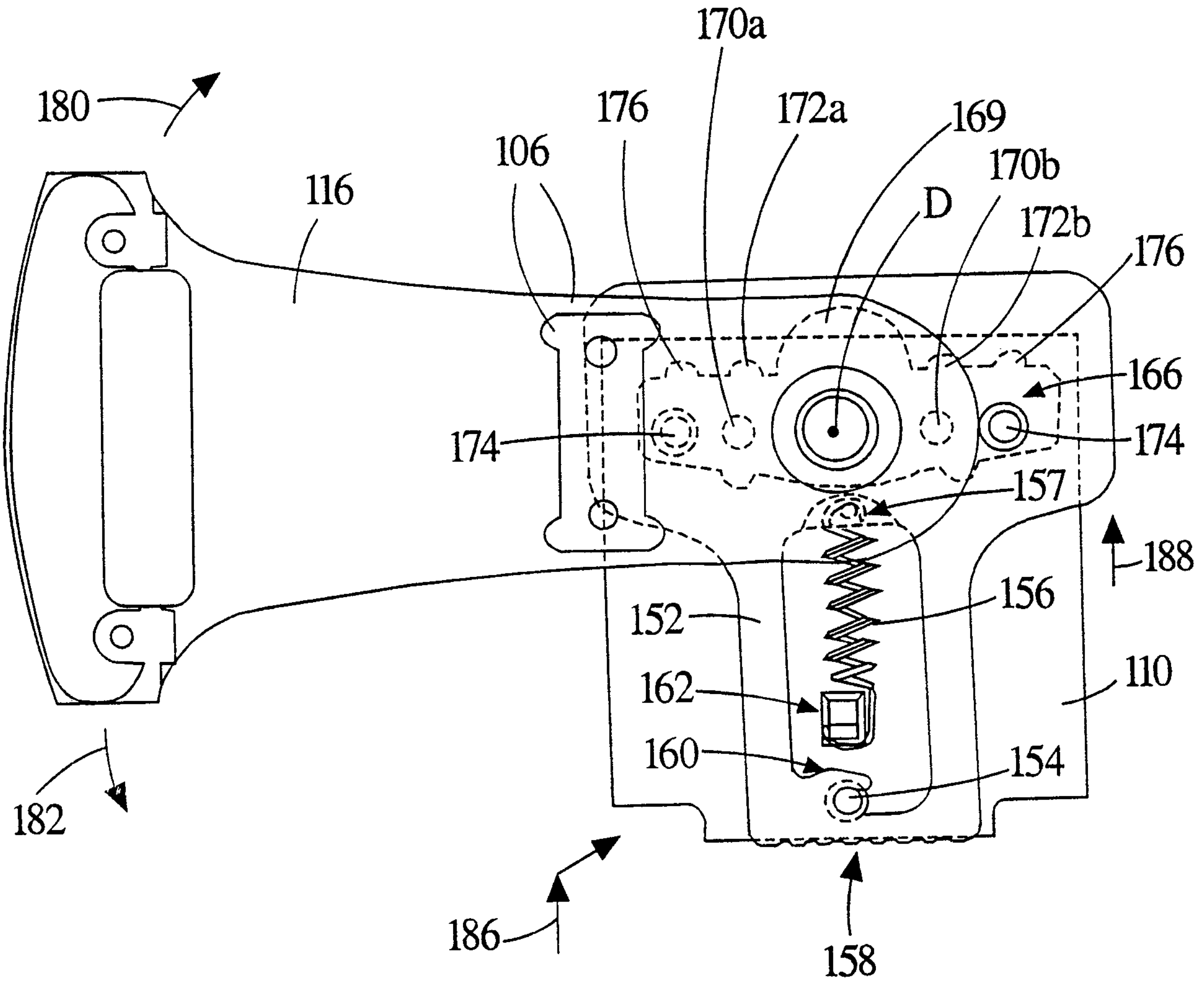
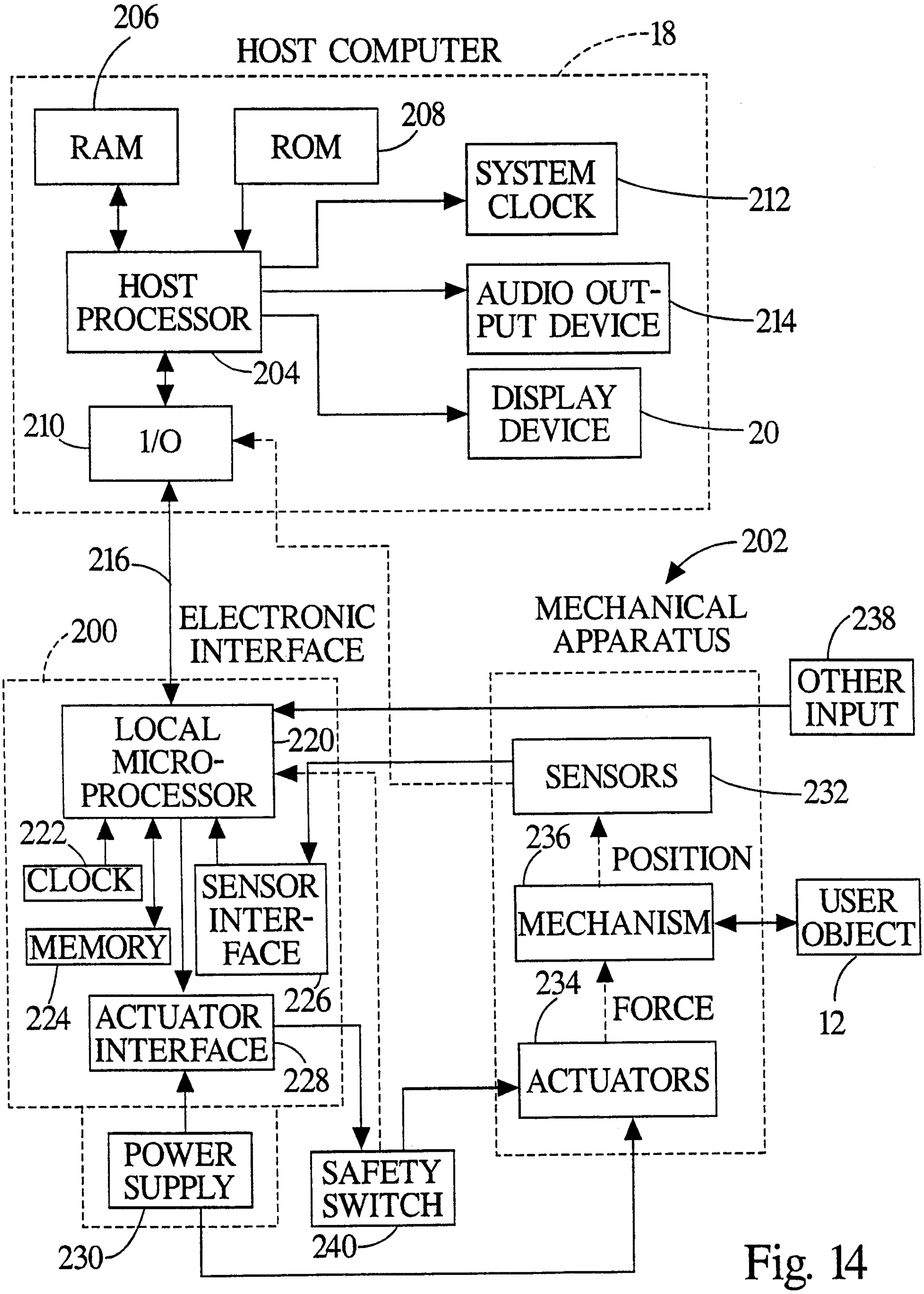

170a
180
176
172a
169
106
170b
116
D
172b
176
166
174
174
157
188
156
152
110
162
160
154
182
186
158

FIG. 13


206
HOST COMPUTER
18
RAM
ROM
208
SYSTEM CLOCK
212
HOST PROCESSOR
AUDIO OUTPUT DEVICE
214
204
DISPLAY DEVICE
210
I/O
20
216
202
ELECTRONIC INTERFACE
MECHANICAL APPARATUS
200
238
OTHER INPUT
LOCAL MICRO-PROCESSOR
220
SENSORS
232
222
236
POSITION
CLOCK
SENSOR INTER-FACE
MEMORY
MECHANISM
USER OBJECT
224
226
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FORCE
12
ACTUATOR INTERFACE
228
ACTUATORS
POWER SUPPLY
SAFETY SWITCH
230
240

Fig. 14