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METHODS, SYSTEMS, AND DEVICES RELATING TO FORCE CONTROL SURGICAL SYSTEMS

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(54) **METHODS, SYSTEMS, AND DEVICES RELATING TO FORCE CONTROL SURGICAL SYSTEMS**

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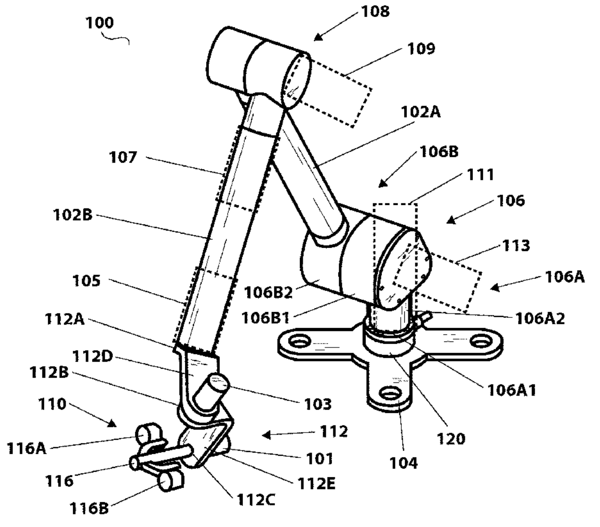
(57) **ABSTRACT**

The various embodiments herein relate to robotic surgical systems and devices that use force and/or torque sensors to measure forces applied at various components of the system or device. Certain implementations include robotic surgical devices having one or more force/torque sensors that detect or measure one or more forces applied at or on one or more arms. Other embodiments relate to systems having a robotic surgical device that has one or more sensors and an external controller that has one or more motors such that the sensors transmit information that is used at the controller to actuate the motors to provide haptic feedback to a user.

20 Claims, 10 Drawing Sheets



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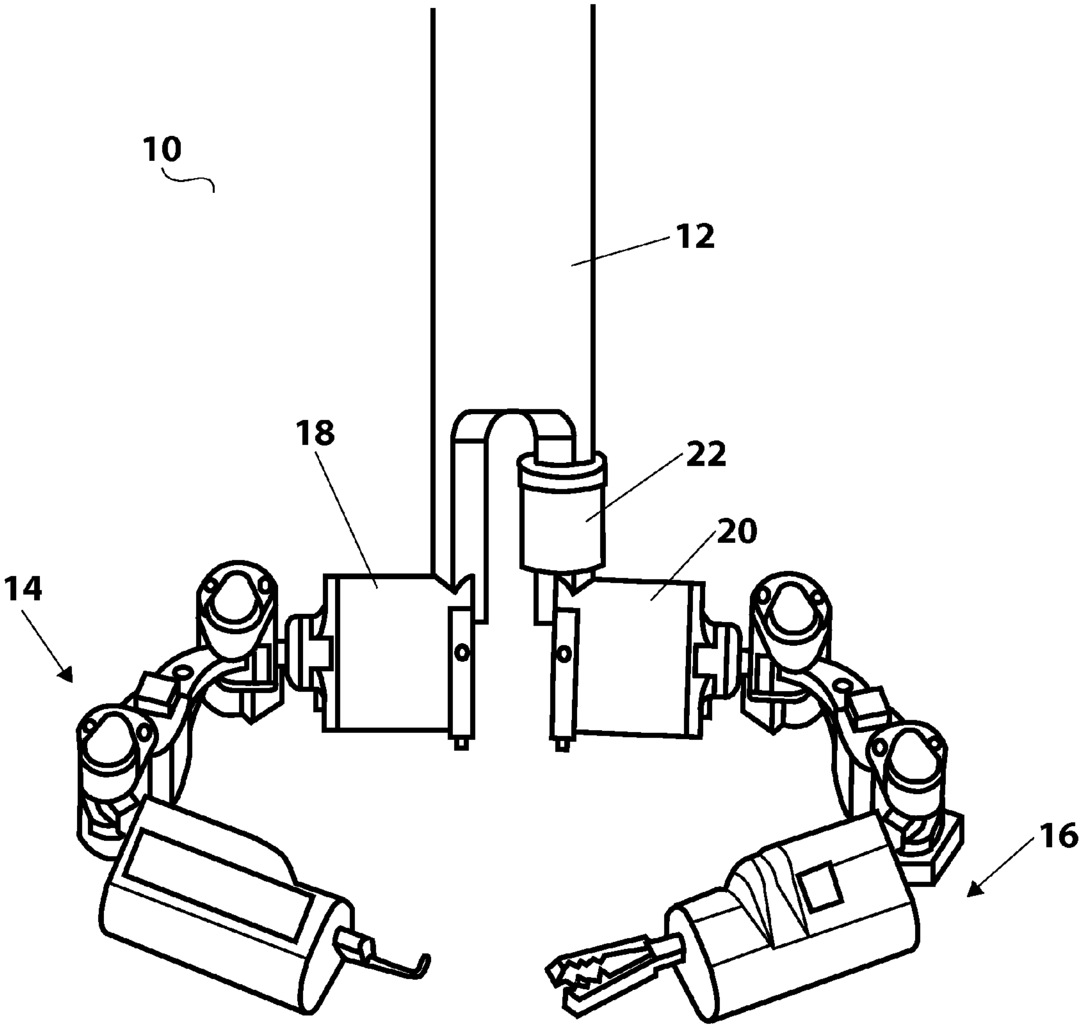

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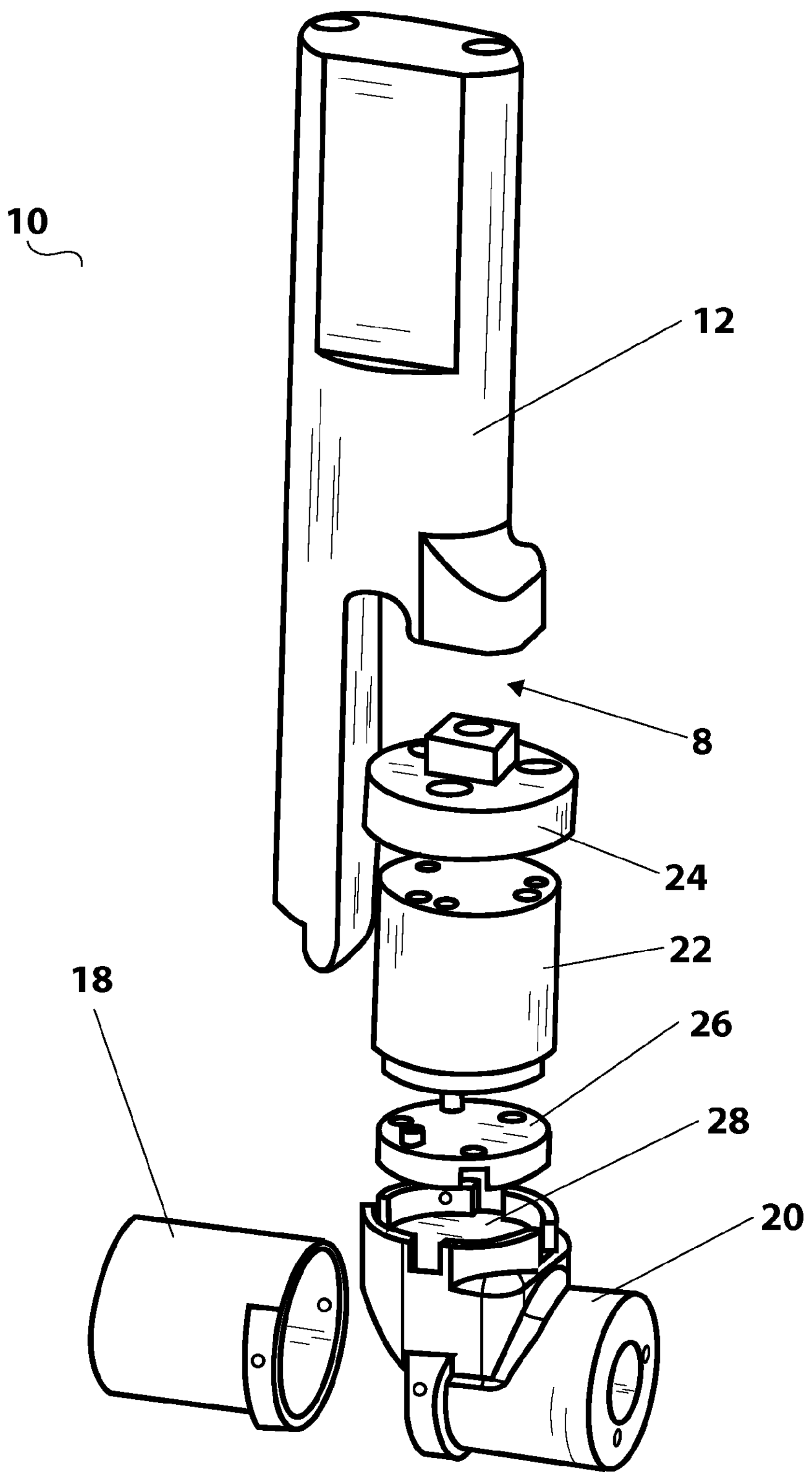

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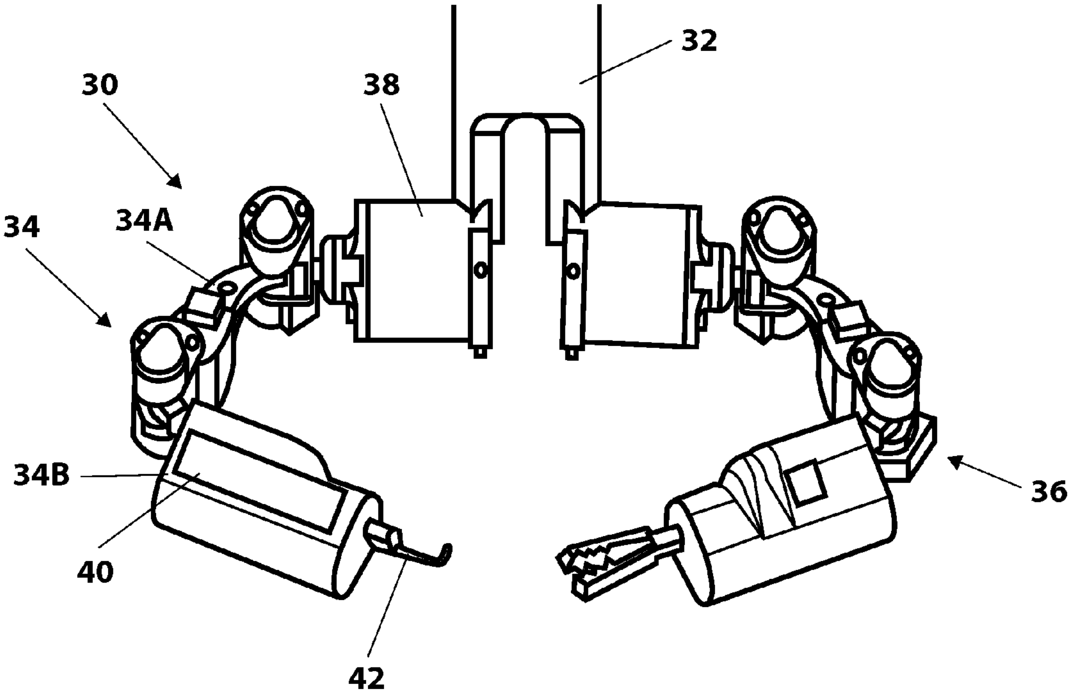

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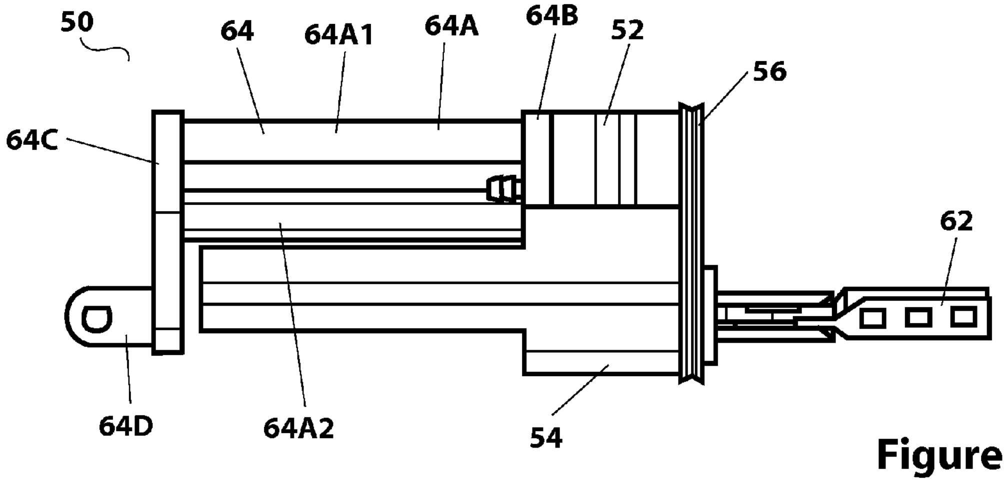

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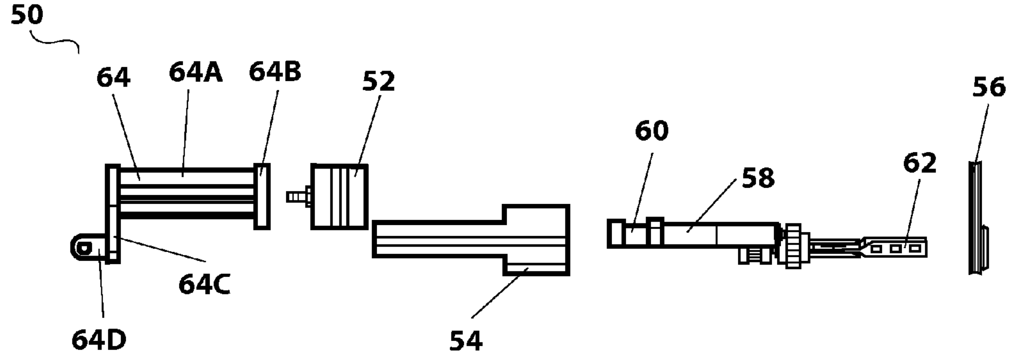

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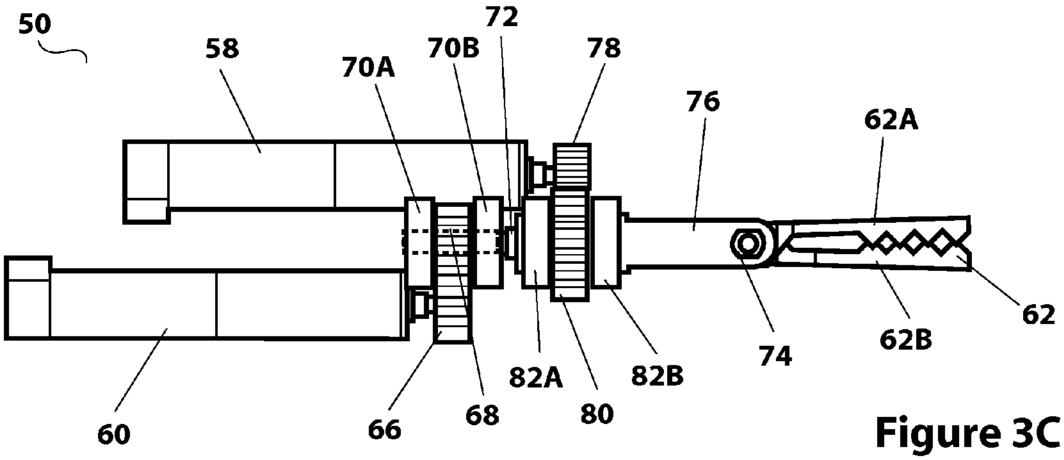

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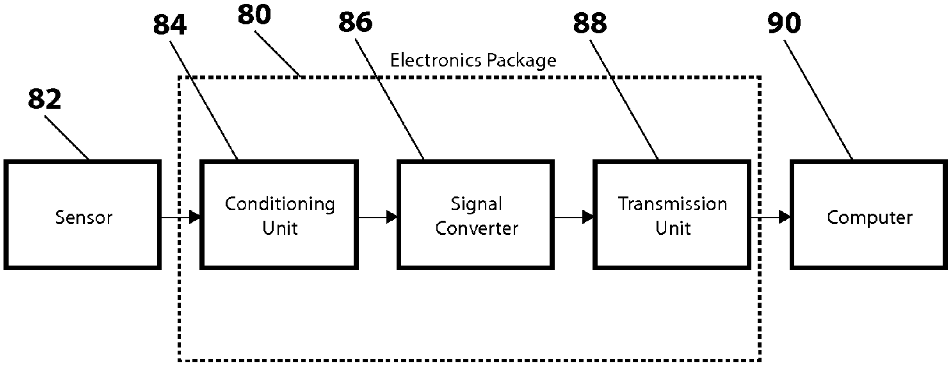

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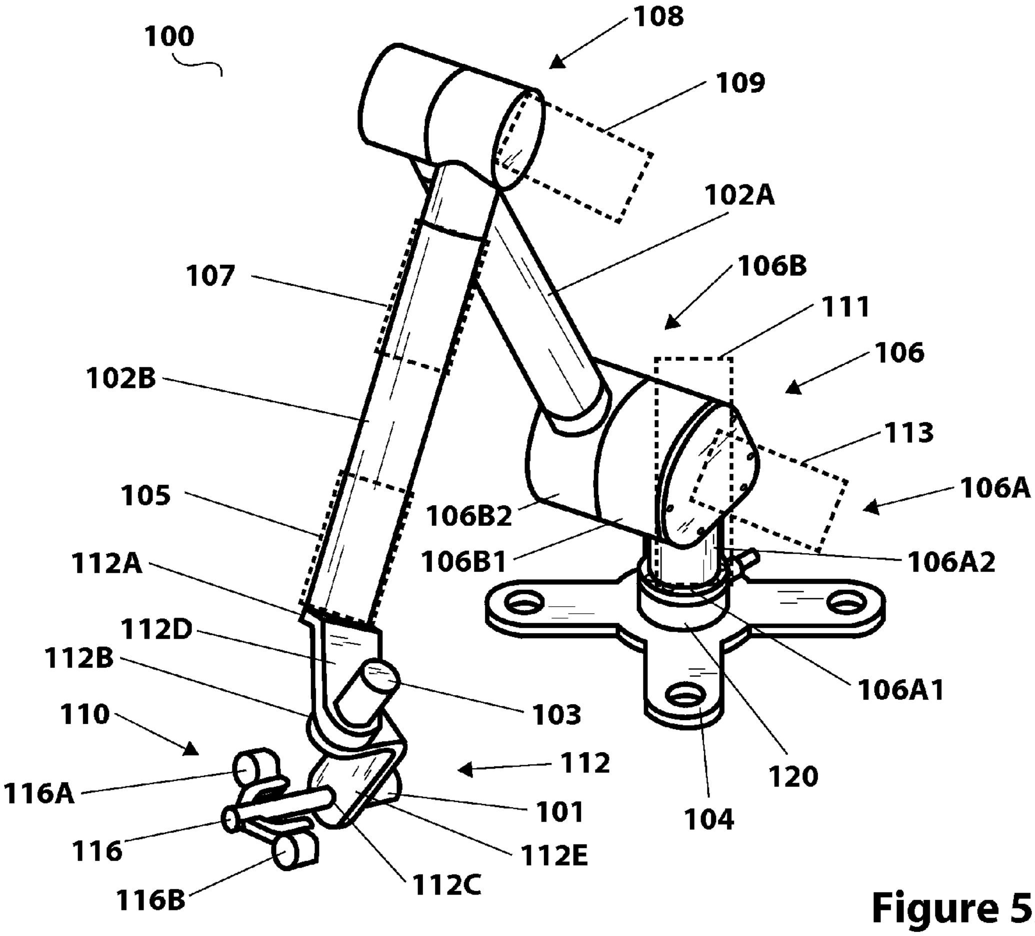

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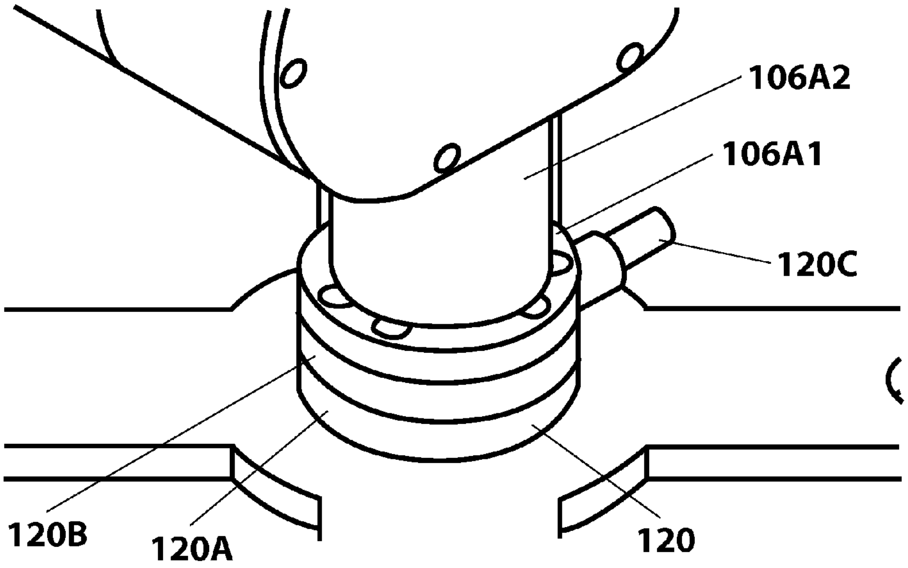

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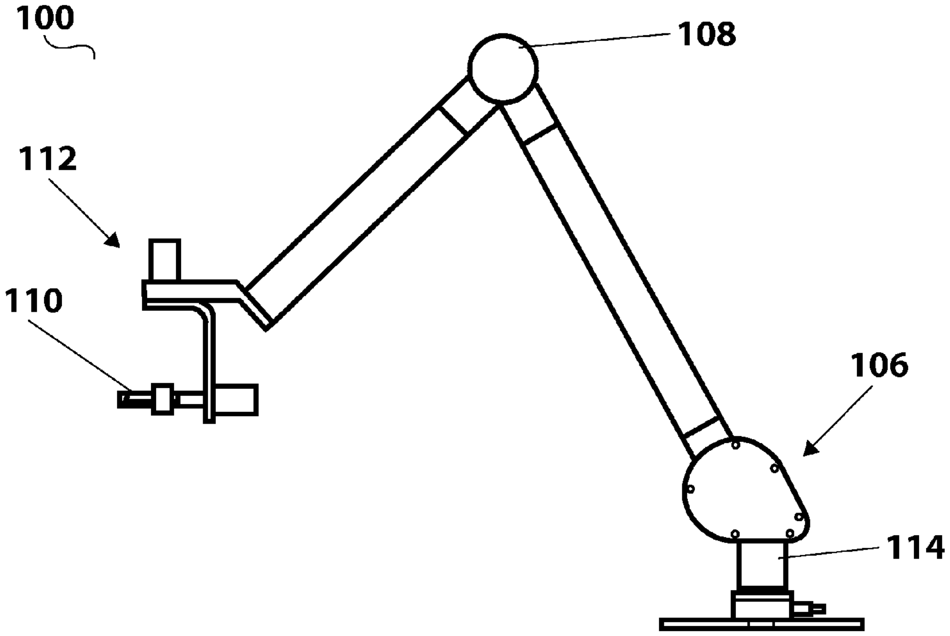

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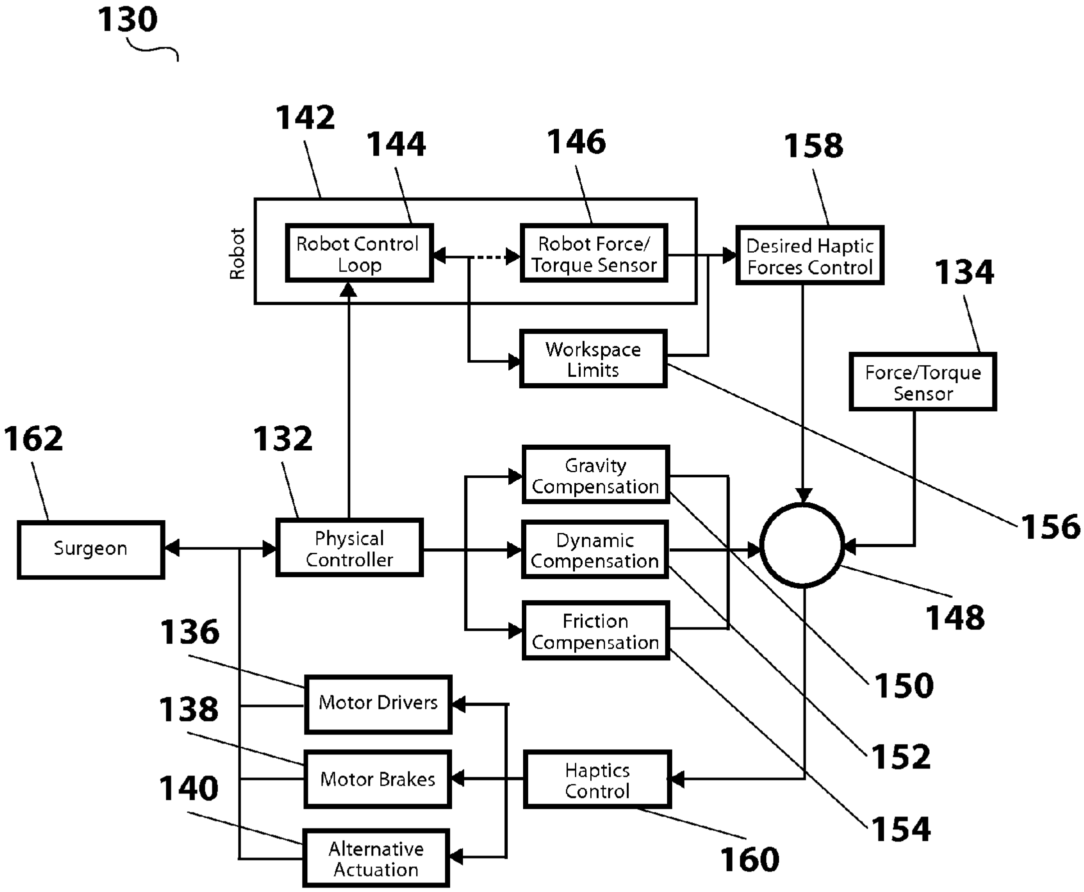
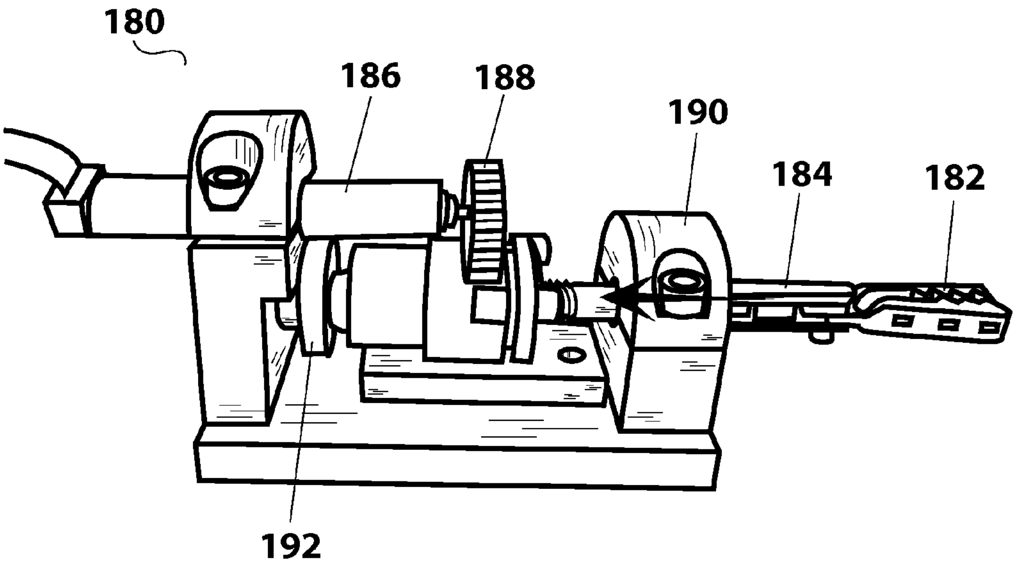

130
142
144
146
158
134
Robot
Robot Control Loop
Robot Force/ Torque Sensor
Desired Haptic Forces Control
Workspace Limits
Force/Torque Sensor
162
132
Surgeon
Physical Controller
Gravity Compensation
Dynamic Compensation
Friction Compensation
156
148
136
Motor Drivers
138
Motor Brakes
140
Alternative Actuation
Haptics Control
150
152
154
160

Figure 6



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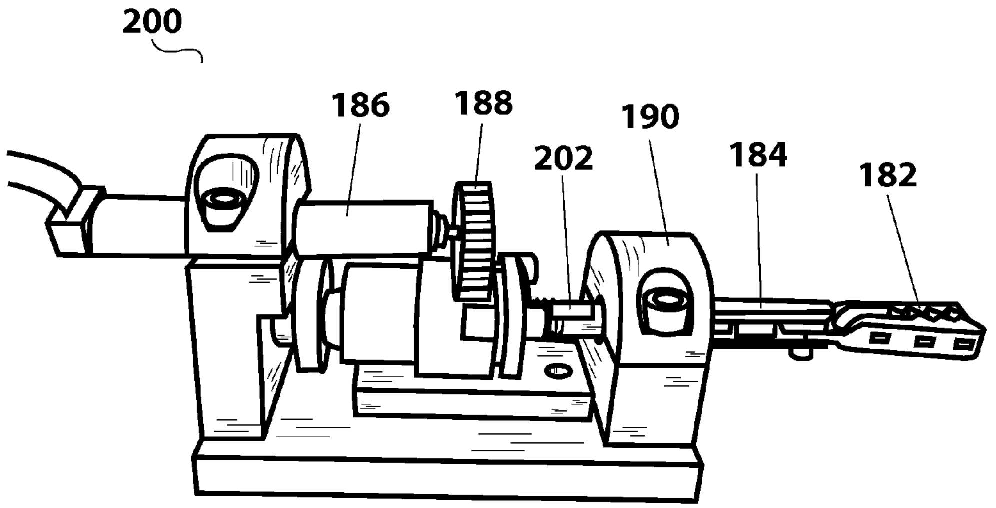

Figure 8

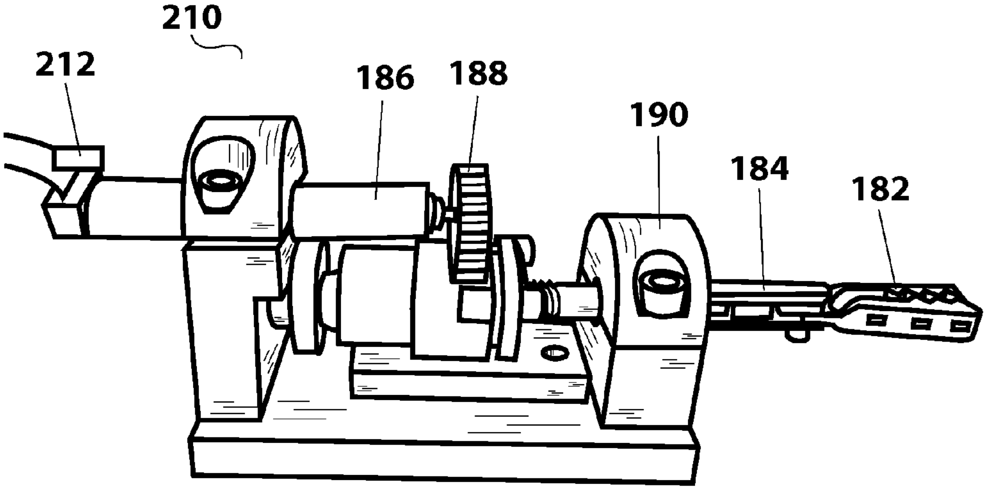

Figure 9

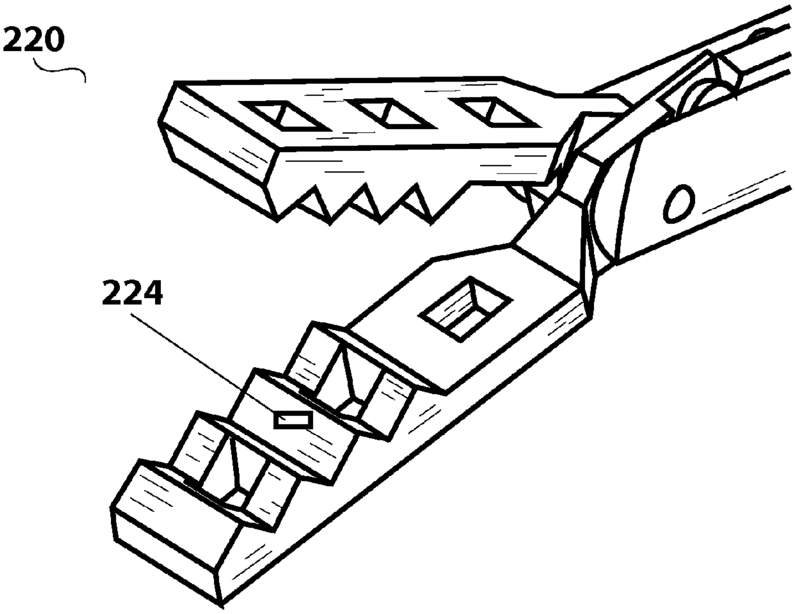

Figure 10A

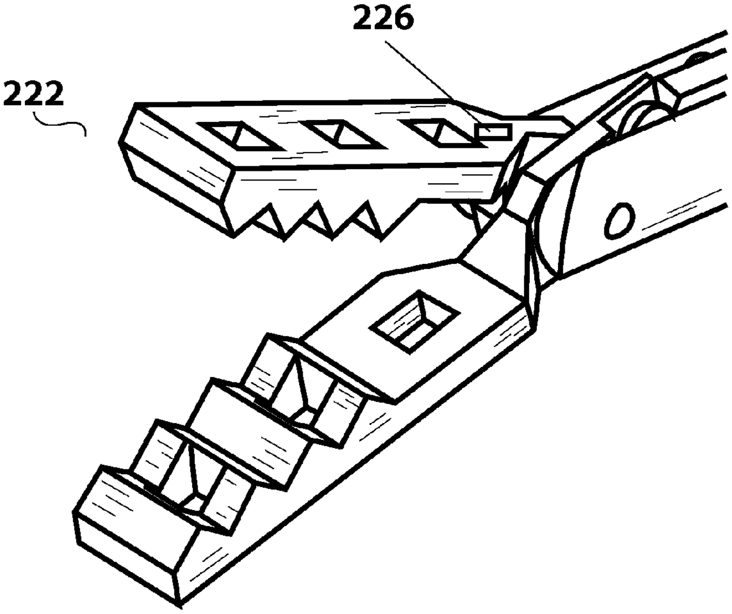

Figure 10B

METHODS, SYSTEMS, AND DEVICES RELATING TO FORCE CONTROL SURGICAL SYSTEMS

CROSS-REFERENCE TO RELATED APPLICATION(S)

This application claims priority to U.S. Provisional Application 61/781,594, filed on Mar. 14, 2013 and entitled "Methods, Systems, and Devices Relating to Force Control Surgical Systems," which is hereby incorporated herein by reference in its entirety.

GOVERNMENT SUPPORT

This invention was made with government support under Grant No. DGE-10410000 awarded by the National Science Foundation; Grant Nos. NNX09AO71A and NNX10AJ26G awarded by the National Aeronautics and Space Administration; and Grant No. W81XWF-09-2-0185 awarded by U.S. Army Medical Research and Materiel Command within the Department of Defense. Accordingly, the government has certain rights in this invention.

FIELD OF THE INVENTION

The various embodiments disclosed herein relate to robotic surgical systems and devices that use force and/or torque sensors to measure forces applied at various components of the system or device. Some exemplary implementations relate to various robotic surgical devices having one or more force/torque sensors that detect or measure one or more forces applied at or on one or more arms. Other embodiments relate to various systems that have a robotic surgical device and a controller, wherein the device has one or more sensors and the controller has one or more motors such that the sensors transmit information that is used at the controller to actuate the motors to provide haptic feedback to a user.

BACKGROUND OF THE INVENTION

Robotic surgical systems have surgical robotic devices or components positioned within a target cavity of a patient such that one or more arms or other components of such a device are configured to perform a procedure within the cavity. In these systems, an external controller is operably coupled to the surgical device such that a user can control or manipulate the device within the patient's cavity via the external controller. One disadvantage of such systems is the lack of tactile feedback for the user during the procedure. That is, the surgeon cannot "feel" the amount of force being applied by or on the arms or components of the surgical device within the patient's cavity in the same way that a surgeon would get some tactile feedback using standard laparoscopic tools (involving long tools inserted through trocars that are positioned into the cavity through incisions).

There is a need in the art for improved robotic surgical systems that can detect and/or measure forces applied at or on robotic surgical devices positioned within a patient and/or provide haptic feedback to the user at the external controller.

BRIEF SUMMARY OF THE INVENTION

Discussed herein are various robotic surgical devices, each having one or more force or torque sensors to measure force or torque applied to certain portions of the device. Additionally, surgical systems are also disclosed, each having an external controller that works in conjunction with sensors on a robotic surgical device to provide haptic feedback to a user.

In Example 1, a robotic surgical device comprises a device body configured to be positioned through an incision into a cavity of a patient, a first shoulder component operably coupled to the device body, a first arm operably coupled to the first shoulder component, and a force sensor operably coupled with the first arm. The first arm is configured to be positioned entirely within the cavity of the patient. The force sensor is positioned to measure an amount of force applied by the first arm.

Example 2 relates to the robotic surgical device according to Example 1, wherein the force sensor is disposed between the device body and the first shoulder component.

Example 3 relates to the robotic surgical device according to Example 1, wherein the force sensor is disposed on the first arm.

Example 4 relates to the robotic surgical device according to Example 3, wherein the first arm comprises an upper arm component and a forearm component, wherein the force sensor is disposed on the forearm component.

Example 5 relates to the robotic surgical device according to Example 1, wherein the first arm comprises an upper arm component and a forearm component, wherein the forearm component is operably coupled to the upper arm component at an elbow joint, wherein the forearm component comprises a link operably coupled at a distal end to the force sensor and operably coupled at a proximal end to an elbow joint.

Example 6 relates to the robotic surgical device according to Example 5, further comprising an interface plate disposed between the force sensor and the link.

Example 7 relates to the robotic surgical device according to Example 1, wherein the force sensor is positioned to measure the amount of force applied at a distal-most point on the first arm.

In Example 8, a robotic surgical system comprises a robotic surgical device configured to be positioned into a cavity of a patient through an incision, a processor, and a user controller operably coupled to the processor. The robotic surgical device comprises a device body, at least one arm operably coupled to the body, and at least one sensor operably coupled to the device. The processor is operably coupled to the at least one sensor. The user controller comprises a base, an upper arm component operably coupled to the base at a shoulder joint, a forearm component operably coupled to the upper arm component at an elbow joint, and a grasper operably coupled to the forearm component at a wrist joint. The shoulder joint comprises a first actuator operably coupled to the processor. The elbow joint comprises a second actuator operably coupled to the processor. The wrist joint comprises a third actuator operably coupled to the processor. The at least one sensor is configured to sense force or torque at the robotic surgical device and transmit force or torque information to the processor. The processor is configured to calculate the force or torque being applied at the robotic surgical device and transmit instructions to actuate at least one of the first, second, or third actuator based on the force or torque, thereby providing haptic feedback at the controller.

Example 9 relates to the robotic surgical system according to Example 8, wherein the at least one sensor is a force sensor operably coupled to the at least one arm.

Example 10 relates to the robotic surgical system according to Example 8, wherein the at least one sensor is a torque sensor operably coupled to a joint of the at least one arm.

Example 11 relates to the robotic surgical system according to Example 8, wherein the at least one sensor is a force sensor positioned between the device body and the at least one arm.

Example 12 relates to the robotic surgical system according to Example 8, wherein the at least one sensor is a force sensor disposed within the device body.

In Example 8, a robotic surgical device comprises a device body configured to be positioned through an incision into a cavity of a patient, a first arm operably coupled to the device body, a force sensor, and an end effector operably coupled to the actuator. The first arm comprises an actuator disposed within the first arm. Further, the first arm is configured to be positioned entirely within the cavity of the patient. The force sensor is operably coupled to the actuator. The end effector is positioned at a distal end of the first arm.

Example 14 relates to the robotic surgical device according to Example 13, further comprising a push/pull rod comprising a distal portion and a proximal portion, wherein the push/pull rod is operably coupled to the actuator at the proximal portion and further wherein the push/pull rod is operably coupled to the end effector at the distal portion.

Example 15 relates to the robotic surgical device according to Example 14, wherein the force sensor is disposed proximal to the actuator and is operably coupled to the proximal portion of the push/pull rod.

Example 16 relates to the robotic surgical device according to Example 14, wherein the end effector is a grasper, wherein the grasper comprises an open configuration when the push/pull rod is urged to a distal position, and further wherein the grasper comprises a closed configuration when the push/pull rod is urged to a proximal position.

Example 17 relates to the robotic surgical device according to Example 14, wherein the force sensor is operably coupled to the push/pull rod such that the force sensor is positioned along the length of the push/pull rod.

Example 18 relates to the robotic surgical device according to Example 13, wherein the end effector is a grasper.

Example 19 relates to the robotic surgical device according to Example 13, further comprising a shaft operably coupled to the end effector and a first gear operably coupled to the shaft, wherein the actuator comprises a second gear operably coupled to the first gear.

Example 20 relates to the robotic surgical device according to Example 19, wherein actuation of the actuator causes the shaft to rotate, thereby causing the end effector to rotate.

While multiple embodiments are disclosed, still other embodiments of the present invention will become apparent to those skilled in the art from the following detailed description, which shows and describes illustrative embodiments of the invention. As will be realized, the invention is capable of modifications in various obvious aspects, all without departing from the spirit and scope of the present invention. Accordingly, the drawings and detailed description are to be regarded as illustrative in nature and not restrictive.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**A is a perspective view of a robotic surgical device with a force sensor, according to one embodiment.

FIG. **1**B is an exploded perspective view of a portion of the robotic surgical device of FIG. **1**A.

FIG. **2** is a perspective view of a robotic surgical device with a force sensor, according to another embodiment.

FIG. **3**A is a side view of certain components of an arm of a robotic surgical device with a force sensor, according to one embodiment.

FIG. **3**B is an exploded side view of certain components of the arm of FIG. **3**A.

FIG. **3**C is a side view of certain components of the arm of FIG. **3**A.

FIG. **4** is a schematic depiction of an electronics package relating to the output of data from a sensor, according to one embodiment.

FIG. **5**A is a perspective view of a controller, according to one embodiment.

FIG. **5**B is an exploded perspective view of a portion of the controller of FIG. **5**A.

FIG. **5**C is a side view of the controller of FIG. **5**A.

FIG. **6** is a schematic flow chart relating to a surgical system having an external controller and a robotic device, according to one embodiment.

FIG. **7** is a perspective view of an arm of a robotic surgical device with a force sensor, according to one embodiment.

FIG. **8** is a perspective view of an arm of a robotic surgical device with a force sensor, according to another embodiment.

FIG. **9** is a perspective view of an arm of a robotic surgical device with a force sensor, according to a further embodiment.

FIG. **10**A is a perspective view of an end effector of a robotic surgical device with a force sensor, according to one embodiment.

FIG. **10**B is a perspective view of an end effector of a robotic surgical device with a force sensor, according to another embodiment.

DETAILED DESCRIPTION

The various embodiments herein relate to a surgical device configured to detect and measure the amount of force applied by the arm of the device. In certain embodiments, the surgical device is a robotic device with a robotic arm and at least one force sensor configured to detect the amount of force. In one embodiment, the force that is measured is the amount of force applied to the distal end of the robotic arm (also referred to herein as the "endpoint"). The information relating to the amount of force is then transmitted from the sensor to an external controller.

FIGS. 1A and 1B depict one embodiment of a robotic surgical device **10** having a body **12** and two robotic arms **14**, **16**. The body **12** has two shoulders: a right shoulder **18** and a left shoulder **20**. The right arm **14** is coupled to the right shoulder, and the left arm **16** is coupled to the left shoulder **20**. In this implementation, the force sensor **22** is operably coupled to the body **12** between the body **12** and the left shoulder **20**. As best shown in FIG. 1B, the distal portion of the body **12** in one embodiment has a recessed portion **8** defined therein as shown, and sensor **22** is positioned in the recessed portion **8** and coupled to the body **12** in that recessed portion **8**.

Further, in certain implementations, the sensor **22** is coupled at its proximal end to a proximal connection component **24** and at its distal end to a distal connection component **26**. In the embodiment depicted in FIG. 1B, the proximal connection component **24** is a proximal recessed component or proximal female connection component (also referred to herein as a "cup") **24** that is configured to receive and couple to the proximal end of the sensor. Further, the distal connection component **26** is a distal plate **26** have at least one projection (or "pin") **26**A disposed on the proximal face of the plate **26** that is configured to mate with an appropriate opening (not shown) in the distal end of the sensor **22**. In addition, the proximal connection component **24** has a projection **24**A on its proximal face that is configured to mate with an appropriate opening (not shown) in the body **12**. Plus, the distal plate **26** is configured to be received in a recessed portion or female connection **28** in the shoulder **20**. In this embodiment, the proximal connection component **24** and distal connection component **26** can provide a substantially rigid coupling of the sensor **22** to the body **12** and shoulder **20**. In alternative embodiments, the device **10** can have no shoulder components and the force sensor **22** can be positioned instead between the body **12** and the left arm **16** (rather than between the body **12** and the shoulder **20**).

According to one implementation, this configuration results in the sensor **22** being positioned close to the incision in the patient when the device **10** is positioned correctly for purposes of a procedure. Given the position of the force sensor **22** proximal to the shoulder **20**, it is understood that the sensor **22** will be subject to greater forces (due to the weight and length of the left arm **16**) in comparison to a sensor positioned somewhere along or in a portion of the arm **16** itself. It is further understood that the position of the sensor **22** will also result in the sensor's **22** force detection being influenced by any forces applied anywhere along the length of the arm **16**. The force sensor **22** is configured to detect and collect data relating to the amount of force being applied by the arm **16** during a procedure. In certain embodiments, the data is used to calculate the amount of force being applied at the most distal point on the arm **36** (the endpoint).

In one specific implementation, the force sensor **22** is a force torque sensor **22**. Alternatively, the sensor **22** can be any known force or torque sensor as described in further detail elsewhere herein.

An alternative embodiment of a robotic device **30** with a force sensor **40** is depicted in FIG. **2**. This device **30** also has a body **32** and right **34** and left **36** arms. This specific example is focused on the right arm **34**, but it is understood that the description applies equally to the left arm **36** as well. In this particular implementation as shown, the sensor **40** is positioned near the distal end of the forearm **34**B of the right arm **34**. The proximity of the sensor **40** to the endpoint **42** (where the force is being measured) allows for the use of a smaller sensor **40** (due to the lesser forces being applied to the sensor **40** due to its position), thereby requiring less space in the forearm **34**B and allowing for the possibility of a smaller forearm **34**B. Further, according to one embodiment, the positioning of the force sensor **40** so close to the endpoint **42** eliminates the influence of any forces applied to the arm proximal to the sensor **40**, thereby eliminating any irrelevant data created by such forces.

Alternatively, it is understood that the sensor **40** could be positioned anywhere on or within any of the components of either arm **34**, **36** of this device **30** or any other device described or contemplated herein. For example, with respect to the right arm **34**, a force sensor could be positioned within or on the right shoulder **38**, the right upper arm **34**A, or the right forearm **34**B. Alternatively, the sensor could be positioned on or within any part of the left arm **36**. Alternatively, the device **30** can have at least one sensor in each arm **34**, **36**. That is, in addition to the sensor **40** in the forearm **34**B of the right arm **34**, the device **30** can also have at least one sensor (not shown) on or in any component of the left arm **36**. In a further alternative, each arm **34**, **36** can have two or more sensors. In yet another implementation, the arms **34**, **36** can each have multiple sensors such that the sensors detect and collect redundant data. The redundant data can then be filtered using known methods such as, but not limited to, Kalman filtering, to provide a more robust calculation of the forces being applied by the surgical device **30** to the tissue of the patient.

In one embodiment, the force sensor (such as force sensors **22** or **40**) are force/torque sensors. According to another implementation, the force sensor is any sensor that can directly or indirectly measure the force at any point on the surgical device. Alternatively, any force sensor disclosed or contemplated herein can be any known sensor that can provide six degrees of force measurement. In another embodiment, the force sensor can be any known sensor that provides at least one dimension of force sensing. In a further alternative, the force sensor (including either of force sensors **22** or **40**) can be a collection, group, arrangement, or set of two or more sensors that can provide six degrees of force measurement. In yet another alternative, the force information can be gathered by measuring the amount of torque at one or more of the joints of the arm of the device. For example, in one embodiment, the amount of torque can be measured at both the shoulder joint (between the shoulder **38** and the upper arm **34**A) and the elbow joint (between the upper arm **34**A and the forearm **34**B) and that information can be used to calculate the amount of force being applied by the arm **34**. In one implementation, the amount of torque is measured using any known torque sensor. Alternatively, the torque can be measured by measuring the motor current or be measuring the windup in the joint (or joints) by comparing absolute position sensor data to incremental position data. In a further alternative, the amount of joint torque can be measured using any other known method for measuring torque.

It is understood that any of the sensors disclosed or contemplated herein can be commercially available sensors or custom sensors. In accordance with one implementation, the force sensor is a known force/torque sensor called Nano17™, which is commercially available from ATI Industrial Automation, located in Apex, N.C. Alternatively, the sensor is a known reaction torque sensor called TFF400™, which is commercially available from Futek Advanced Sensor Technology, Inc., located in Irvine, Calif.

The force data collected by the force sensor(s) (or torque data collected by the torque sensor(s)) can be transmitted to a processor present in the robotic device (such as device **10** or **30**) or in the external controller (not shown) and used to calculate the force being applied at the endpoint of the arm (or torque at the joint(s)). This will be described in further detail below. Known information relating to the dimensions of the robotic components and the kinematic arrangement of those components (such as the arm components) is incorporated into the calculation to determine the force at the endpoint (or torque at the joint(s)). Given that the calculation utilizes the dimensions of the components, the sensor(s) can be positioned anywhere along the robotic arm or even in the device body (as in FIG. **1**) so long as the position is taken into account in the calculation.

FIGS. **3**A, **3**B, and **3**C depict various aspects of a forearm **50** having a force sensor **52**, according to another implementation. The forearm **50** has a motor housing **54**, a front plate (also referred to herein as a "faceplate") **56**, two motors **58**, **60**, and an end effector **62** which is a grasper tool **62**. The motor housing **54** has the two motors **58**, **60** at least partially disposed therein and is coupled at its distal end to the front plate **56**. The forearm **50** also has a base link **64** that is configured to operably couple the sensor **52** to the elbow of the arm (not shown) as will be described in further detail below. The sensor **52** is positioned in the distal-most position in the forearm **50**.

As best shown in FIGS. **3**A and **3**B, the base link **64** has a body **64**A made up of two rod-like pieces **64**A**1**, **64**A**2** (as best shown in FIG. **3**A), an interface plate **64**B at the distal end of the link **64**, and an end plate **64**C at the proximal end having a coupling component **64**D. The interface plate **64**B is configured to couple to the sensor **52**. In one implementation, the plate **64**B is rigidly coupled to the sensor **52**. The body **64**A has space between and adjacent to the rod-like pieces **64**A**1**, **64**A**2** that can be configured to receive or provide space for on-board electronic components and wiring (not shown). The electronic components can include, but are not limited to, local motor driving boards, absolute positioning sensor boards, biometric sensor boards, and measurement boards to access the sensor data collected by the sensor **52**. The coupling component **64**D is configured to couple to the elbow joint (not shown) and/or the upper arm (not shown) of the device. In one embodiment, the coupling component **64**D as shown is a projection **64**D that defines a circular hole configured to receive and couple to an articulate shaft (not shown) of the upper arm (not shown). Alternatively, the coupling component **64**D can be any known mechanism, component, or apparatus for coupling a forearm to an upper arm or elbow of a medical device.

In one implementation, the base link **64** is physically separate from and not rigidly coupled to the motor housing **54**. This separation of the two components allows forces applied to the grasper **62** to be transferred through the front plate **56** and into the sensor **52** and reduces the diffusion of such forces. According to certain embodiments, the base link **64** is a cantilevered link **64** that allows the sensor **52** to measure the force applied on the arm **50**, and in some cases, the distal endpoint of the end effector **62**. Alternatively, the link **64** need not be a cantilevered link **64**, but instead can have one or more components that apply a known amount of force thereon. Regardless, the base link **64** allows the sensor **52** to accurately measure the force of interest.

As best shown in FIG. **3**C, the motor configuration made up of the two motors **58**, **60** is similar to a grasper end effector motor configuration as disclosed in U.S. Provisional Application 61/663,194, filed on Jun. 22, 2012, which is hereby incorporated herein by reference in its entirety. In this particular embodiment, the motor **60** is an open/close motor **60** that is rotationally fixed to motor gear **66**, which is threadably coupled to driven gear **68**, which is supported by two bearings **70**A, **70**B. In one embodiment, the bearings **70**A, **70**B are constrained by the motor housing **54**. The driven gear **68** defines a lumen (not shown) having internal threads (not shown). An externally-threaded drive rod **72** is positioned in the lumen of the driven gear **68** such that the driven gear **68** is operably coupled to the rod **72**. Due to the coupling of the internal threads of the driven gear **68** with the external threads of the rod **72**, rotation of the driven gear **68** causes the drive rod **72** to move laterally back and forth along the longitudinal axis of the drive rod **72**. The drive rod **72** is operably coupled to the grasper arms **62**A, **62**B at the pivot point **74** on the grasper yoke **76** such that the lateral movement of the drive rod **72** causes the grasper arms **62**A, **62**B to open and close.

The motor **58** is a rotational motor **58** that is rotationally fixed to motor gear **78**, which is threadably coupled to driven gear **80**, which is supported by two bearings **82**A, **82**B. In one embodiment, the bearings **82**A, **82**B are constrained by the motor housing **54**. The driven gear **80** is rotationally fixed to the grasper yoke **76**, which is rotationally fixed to the grasper arms **62**A, **62**B such that rotation of the rotational motor **58** causes rotation of the grasper tool **62**.

In one embodiment, the motors **58**, **60** are both 6 mm motors. Alternatively, the motors **58**, **60** are known brushed or brushless motors. The motors **58**, **60** can be any motors ranging in size from about 2 mm to about 15 mm in diameter, so long as the motors **58**, **60** provide sufficient force and speed profiles to achieve desired results. In accordance with one implementation, the motors **58**, **60** are coreless brushed motors called 0615 (6 mm) or 0816 (8 mm), which are commercially available from Micromo, located in Clearwater, Fla. Alternatively, the motors **58**, **60** are brushless motors called EC 6 mm and EC 10 mm, which are commercially available from Maxon Motor, located in Fall River, Mass. In a further alternative, the motors **58**, **60** can be any known motors used in medical devices.

As mentioned above, in use, any force sensor disclosed or contemplated herein (including, for example, any one or more of the force sensors **22**, **40**, **52** discussed and depicted above, or one or more torque sensors as also discussed above) is configured to detect and collect the amount of force (or torque) applied by the arm or arms of a surgical device.

As mentioned above, the information collected by the one or more sensors can then be outputted to a processor of some kind, such as a microprocessor in an external controller in communication with the surgical device. In one implementation, the data output occurs via an electronics package **80** as shown schematically in FIG. **4**. In this embodiment, the representative single sensor **82** outputs (or transmits) analog or digital signals that are proportional to the amount of force detected by the sensor **82**. The electronics package **80** can interpret and/or transmit these signals. The electronics package **80**, according to one implementation, has a conditioning unit **84**, a signal converting unit **86**, and a transmission unit **88**. It is understood that the sensor **82**, the conditioning unit **84**, the signal converting unit **86**, the transmission unit **88**, and computer **90** are all coupled to each other via at least one communication line. The communication line can be any line that can be used to carry signals from one component to another.

The conditioning unit **84** is configured to provide more robust or easier-to-detect signals. According to one embodiment, the conditioning unit **84** can be figured to filter, shift, amplify, or provide any other conditioning procedure to signals. The signal converting unit **86** is configured to convert analog signals to digital signals so that they can be used in a digital processor or computer. According to one embodiment, the signal converting unit **86** is an analog-to-digital converter ("ADC"). The transmission unit **88** is configured to transmit the signals from the electronics package **80** to the computer **90**.

In one implementation, if the output signals from the sensor **82** are digital signals, they can be transmitted or outputted to the conditioning unit **84** (where they are amplified or otherwise conditioned) and then transmitted directly to the transmission unit **88**, which transmits the signals to the computer **90**. Alternatively, in those embodiments in which the output signals are analog, the signals can be conditioned via the conditioning unit **84** and also converted into digital signals via the signal converting unit **86** before being transmitted by the transmission unit **88** to the computer **90**.

For purposes of this application, it is understood that the term "computer" is intended to mean any device that can be programmed to carry out arithmetic or logical operations. As such, "computer" encompasses any microprocessor, digital signal processor, or any other computer platform. This obviously would include any microprocessor, processor, or other type of computer incorporated into any external controller or user interface that is operably coupled to the surgical device.

According to one embodiment, the electronics package **80** is positioned on or in the surgical device (such as either of devices **10** or **30** as discussed above) and the computer **90** is positioned at a location that is external to the surgical device and the patient. Alternatively, both the electronics package **80** and the computer **90** are positioned on or in the robot. In yet another alternative, both the electronics package **80** and the computer **90** are positioned at some location external to the surgical device.

The computer **90** is configured to utilize the data for many end-user applications, including, for example, haptics, data collection for surgeon performance analytics, or for training purposes where the data is recorded and played back to trainees. In certain embodiments, the computer **90** uses the data to calculate the amount of force applied at the endpoint of one of the arms on the surgical device. Alternatively, the computer **90** can calculate the amount of force at any point on either of the arms.

In a further embodiment, the data can also be used for implementing methods of controlling the surgical device. That is, the information relating to the amount of force being applied by an arm of a device can be used to control that arm. In one example, if the arm contacts a cavity wall or an organ in the cavity, the force sensor **82** will sense the force applied to the arm as a result of this contact and the computer **90** can utilize that information to actuate the arm to perform some action to remedy the problem. For example, the computer **90** can actuate the arm to stop moving, shut down, reposition itself away from the point of contract, or take any other action to correct the problem. Various control methods that can be used by the computer **90** include force control, hybrid (force and position) control, admittance control, impedance control, or any combination of these or other known methods. In some embodiments, these methods can be used in conjunction with any combination of the existing position, velocity, acceleration, or current (torque control) control methods.

According to another implementation, the computer **90** can be configured to transmit the data to one or more other computers that can utilize the data for any of the applications described above or other applications.

Other embodiments of a surgical system relate to external controller embodiments having one or more force sensors (or other related types of sensors, such as torque sensors) that can be used to control a surgical device. FIGS. **5**A, **5**B, and **5**C depict an external controller **100** having a known configuration similar to various commercial embodiments. This particular controller **100** has a controller arm **102** made up of an upper arm (also referred to as a first or upper link, rod, or tube) **102**A and a forearm (also referred to as a second or lower link, rod, or tube) **102**B. The upper arm **102**A is rotatably coupled to a base **104** at a shoulder joint (also referred to as a first joint) **106** and the lower arm **102**B is rotatably coupled to the upper arm **102**A at an elbow joint (also referred to as a second joint) **108**. A grasper **110** is rotatably coupled to the lower arm **102**B at a wrist joint **112** and is configured to be grasped by a user (such as a surgeon).

As best shown in FIG. **5**A, according to one implementation, the shoulder joint **106** is actually made up of two different joints: a rotating yaw joint **106**A and a rotating pitch joint **106**B. The rotating yaw joint **106**A has a fixed joint component **106A1** coupled to the base **104** and a rotatable joint component **106A2** that is rotatably coupled to the fixed joint component **106A1** and rotates around an axis parallel to the longitudinal axis of the rotatable joint component **106A2** (and perpendicular to the plane of the base **104**). The rotating pitch joint **106**B has a fixed joint component **106**B**1** coupled to the rotatable joint component **106A2** and a rotatable joint component **10682** that is rotatably coupled to the fixed joint component **106**B**1** and rotates around an axis parallel to the plane of the base **104**.

Continuing with FIG. **5**A, the wrist joint **112** is actually made up of three joints **112**A, **112**B, **112**C. The first wrist joint **112**A is a rotatable coupling at the lower arm **102**B such that the wrist link **112**D rotates around an axis parallel to the longitudinal axis of the lower arm **102**B. The second wrist joint **1128** is a rotatable coupling of the wrist link **112**E to the wrist link **112**D such that the wrist link **112**E rotates around an axis that is perpendicular to the plane of the wrist link **112**D. The third wrist joint **112**C is a rotatable coupling of the grasper **110** to the wrist link **112**E such that the grasper **110** rotates around an axis perpendicular to the plane of the wrist link **112**E. These three joints **112**A, **112**B, **112**C provide three axes of rotation. According to one implementation, the three axes of rotation of the three joints **112**A, **112**B, **112**C all pass through a specific point.

In this embodiment, the grasper **110** has a pinch mechanism **116** made up of two finger loops **116**A, **116**B. In one implementation, the grasper **110** has a configuration that is substantially similar to the grasper used in the Da Vinci® system.

The controller **100** in this implementation also has motors that operate to provide haptic feedback. More specifically, the shoulder joint **106** has at least one motor positioned within the joint **106** (or otherwise operably coupled thereto). In one example, the motor **111** is coupled to or positioned within the joint **106** and operably coupled to the joint **106** such that the motor **111** can actuate the movement of the rotating yaw joint **106**A. In another example, the motor **113** is coupled to the joint **106** and operably coupled thereto such that the motor **113** can actuate the movement of the rotating pitch joint **106**B. Similarly, the elbow joint **108** also has at least one motor positioned within the joint **108** (or otherwise operably coupled thereto). In one example, the motor **109** is coupled to the joint **108** as shown. Alternatively, the motor **107** is disposed within the forearm **102**B and operably coupled to the joint **108**. Further, the wrist joint **112** can also have one or more motors operably coupled to one or more of the wrist joints **112**A, **112**B, **112**C. For example, a motor **105** can be disposed within the forearm **102**B that is operably coupled to the wrist link **112**D such that the motor **105** can actuate the movement of the wrist link **112**D. Alternatively, a motor **103** can be operably coupled to the wrist joint **1128** to actuate the movement of the wrist link **112**E. In a further alternative, a motor **101** can be operably coupled to the wrist joint **112**C to actuate the movement of the grasper **110**. In operation, it is understood that the motors are used to provide haptic feedback to the user or surgeon during a procedure. That is, the one or more force sensors (or torque sensors), such as any of the sensors discussed above, operably coupled to the surgical device sense force applied to at least one arm of the device (or torque at one or more joints) and that information is transmitted back to a processor as discussed above. The processor can use that information to calculate the force or torque being applied and transmit instructions based on that information to the motors in the controller **100** to actuate those motors to generate similar force or torque in the controller **100** that can be felt by the user or surgeon at the grasper **110**, thereby giving the user or surgeon feedback in the form of force (resistance) similar to the feedback the surgeon or user would receive if she or he was holding the actual surgical device component experiencing the force.

In one embodiment, the motors in the controller **100** are known brushed or brushless motors. The motors can be any motors ranging in size from about 4 mm to about 30 mm in diameter, so long as the motors provide sufficient force and speed profiles to achieve desired results. In accordance with one implementation, the motors are any motors within that size range that are commercially available from Micromo, located in Clearwater, Fla. or from Maxon Motor, located in Fall River, Mass. In a further alternative, the motors can be any known motors of appropriate size used in medical devices or related controller components.

According to one implementation as best shown in FIG. **5**B, the controller **100** has a force sensor **120** associated with the shoulder joint **106**. More specifically, in one embodiment, the sensor **120** has a first component **120**A coupled to the base **104** and a second component **120**B coupled to the fixed joint component **106A1**. In use, the sensor **120** detects any force applied to either the fixed joint component **106A1** or the base **104**. The sensor **120** also has a connection component **120**C that extends from the sensor **120** to a computer or other type of processor. Alternatively, one or more sensors can be positioned anywhere on or within the controller **100** at any location between the base **104** and the finger loops **116**A, **116**B. In accordance with another aspect, a single six-axis force sensor is positioned within or coupled to the yaw joint **106**A (like sensor **120**) and a separate sensor (not shown) is positioned on the grasper **110**. Using analytical or iterative methods, force data from the sensor **120** at the yaw joint **106**A and known information about the structural parameters of the controller **100** can be used by a processor to determine internal and external forces while the separate sensor on the grasper **110** can be used to determine grasping pressures or other relevant information. In a further implementation, separate sensors can be positioned at every joint **106**, **108**, **112** and provide feedback. In yet another embodiment, a single sensor is positioned somewhere on or operably coupled to the grasper **110**.

In operation, it is understood that the one or more force sensors on the controller **100** are configured to sense force applied to the controller **100** by the user or surgeon, and that information is transmitted back to a processor as discussed above. The processor can use that information to calculate the force or torque being applied at the controller **100** and take that information into account for purposes of creating appropriate haptic feedback to the user at the controller **100** using the one or more motors described above that are operably coupled to the controller **100**, thereby helping to ensure that the appropriate amount of force is being applied to the user's hand during use of the controller **100**.

It is understood that the one or more sensors used with a controller (such as the controller **10**) can be any of the force or torque sensors discussed above in relation to the surgical device embodiments. It is further understood that one or more sensors can be operably coupled in a similar fashion in similar configurations with any known controller having any known configuration that is capable of at least one directional force.

FIG. **6** depicts a schematic representation of a surgical system **130** having an external controller **132** that is operably coupled to a surgical device **142**. The external controller **132** can be any known controller (including, for example, the controller **100** discussed above) having at least one force sensor **134**, along with at least one set of actuators or motors chosen from at least one of the following: motor drivers **136**, motor brakes **138**, and/or some other known type of actuators **140**. The surgical device **142** can be any known surgical device (including, for example, either of the devices **10**, **30** discussed above) having a control system **144** (typically in the form of a microprocessor or other type of computer) and at least one force sensor **146**. As a result, this system **130** allows a surgeon **162** (or other user) to use the controller **132** to operate the surgical device **142** while the force sensors **134**, **148** provide the system with force information that allows the system to provide haptic feedback to the surgeon **162** through the controller **132**.

In use, the surgeon manipulates the controller **132** to control the surgical device **142**. As a result of that manipulation, the controller **132** transmit information to the control system **144** in the surgical device **142**. In one embodiment, the information transmitted by the controller **132** constitutes measurements relating to the physical position of the arm (or arms) of the controller **132**. The information is used by the control system **144** to actuate the arm (or arms) of the surgical device **142** to move as desired by the surgeon **162**. The force sensor **146** operates as discussed above with respect to sensors **22**, **40**, **52** by sensing the force applied to the device **142**. In this implementation, the sensor **146** outputs that information to a haptic control process or application **158** running on a processor or computer **148** (which can be the same as the computer **90** discussed above or a similar processor, microprocessor, or computer) to determine the desired haptic forces (the amount of feedback force desired to be provided to the surgeon **162**) via known methods such as, for example, proportional or exponential force feedback, impedance control, admittance control, or hybrid control.

According to one embodiment, the workspace limitations of the surgical device **142** can also be taken into account in this system **130**. That is, the workspace limitation information can be saved in the device control system **144** (and provided to the haptic control algorithms **158**) or it can be stored in the processor **148**. In one embodiment, the information is modeled as an inward force that simulates a wall. Regardless, the information is used to transmit information to the controller that actuates one or more of the actuators **136**, **138**, **140** to generate forces at the controller **132** that help to prevent the surgeon **162** from exceeding the workspace of the surgical device **142**. In one embodiment, the information actuates the actuator(s) **136**, **138**, **140** to provide direct force or vibration at the controller **132**. Alternatively, the system can provide visual cues to the surgeon **162**.

In one implementation, the computer **148** can also be configured to compensate for the outside forces in the system caused by gravity, friction, and inertia. That is, the force sensor **134** associated with the controller **132** detects and collects information about all forces being applied to the controller **132**, not just the forces applied by the surgeon **162**. This force information is provided to the computer **148** in one lump sum that includes all such forces. In this embodiment, the system **130** can take one or more of the outside forces into account and compensate for or "cancel out" those outside forces.

For example, one implementation of the system **130** allows for compensation for gravity. That is, the processor **148** can use structural and positional information about the controller **132** to calculate the effect of gravity on the controller **132** and effectively "subtract" that amount of force or otherwise "cancel out" that amount of force from the force detected by the sensor **134**. As a result, in an ideal embodiment of the system **130**, when the surgeon removes her hands from the controller **132**, the controller **132** should not fall but instead should appear weightless as a result of the compensation for gravity.

Another implementation allows for dynamic compensation. That is, the processor **148** can use structural and positional information about the controller **132** to calculate the effect of inertia and other dynamic forces on the controller **132** during use and effectively "subtract" or otherwise "cancel out" that amount of force from the force detected by the sensor **134**. As a result, rapid movements by the surgeon **162** would not create reaction forces provided as haptic feedback to the surgeon **162** and the effect would be that the mass of the controller **132** would not impose any forces on the system **130**.

In a further embodiment, the system **130** can allow for friction compensation. That is, the processor **148** can use one or more force sensors in the controller **132** to detect any unexpected forces experienced by the controller **132** when force is applied to the handles of the controller **132** by the surgeon **162**. Those unexpected forces can then be effectively "subtracted" from the force detected by the sensor **134**. The result is a frictionless system that exhibits little resistance to movement.

In one embodiment, the system **130** can have only one form of compensation, such as, for example, gravity compensation. Alternatively, the system **130** can have two forms of compensation. In a further alternative, the system **130** can compensate for all three types of external forces: gravity, dynamic forces, and friction.

Once the computer has added up the total amount of the outside/unwanted forces to be compensated for, that amount is subtracted from the total amount of force information provided by the force sensor **134**. The result of the calculation is the "error" between the amount of force actually applied to the controller **132** by the surgeon **162** and the amount of force that was desired. Information about this "error" amount is provided to a haptic control system or application **160** that actuates one or more of the actuators (the motor drivers **136**, the motor brakes **138**, and/or the other actuators) in the controller **132** to add or subtract that amount of force needed based on the error, thereby providing the haptic feedback to the surgeon **162**. Hence, the haptic control system **160** determines the appropriate amount of haptic forces to generate in the controller **132**.

Another force-sensing grasper **180** embodiment is depicted in FIG. **7**. In this implementation, the force being measured is the force applied along the drivetrain of the end effector. That is, the force sensor is integrated into the actuation component(s) or motor(s) of the end effector to measure directly the force applied by that component/motor (those components/motors) to the end effector. The end effector **180** is configured to transmit force feedback information to the surgical system, wherein the force feedback information is any information relating to the force which the end effector **180** is applying during use of the end effector **180**. In certain implementations, this information can be used to adjust the amount of force being applied when it is determined that the force is too great or insufficient for the action being performed.

In this specific embodiment as shown, as mentioned above, the end effector **180** is a grasper end effector **180** having a grasper tool **182**. The actuation system provided for this grasper end effector **180** in the embodiment as shown is merely an exemplary, known system and constitutes only one of many types and configurations of actuation systems that can be used for actuating a grasper tool **182**, including the various systems discussed in the embodiments above. As shown, the grasper end effector **180** is configured to have two degrees of freedom. That is, the grasper tool **182** rotates about its long axis and moves between an open configuration and a closed configuration. To achieve movement of the grasper tool **182** between the open and closed configurations, the grasper end effector **180** has a shaft **184** that contains a threaded inner push/pull rod (not shown) that is coupled to the actuator or motor **186** (shown in FIG. **7** as a motor and gearhead) via the gears **188**. The shaft **184** has an internal lumen (not shown) defined within the shaft **184**, and the lumen has internal threads that match up with the external threads on the push/pull rod (not shown). In use, the motor **186** actuates the rotation of the gears **188**, which causes the inner push/pull rod (not shown) to rotate. In contrast, the shaft **184** is restrained such that it cannot rotate. In one embodiment, the shaft **184** is fixed rotationally via a clamp **190**. Thus, the meshing of the threads of the rod with the internal threads of the shaft **184** means that the rotation of the rod within the restrained shaft **184** causes the rod to translate laterally, thereby causing the grasper tool **182** to move between its open and closed positions.

In one embodiment, the force-sensing grasper **180** operates to sense the amount of force being applied by the grasper tool **182** by measuring the amount of axial force being transmitted through the push/pull rod (not shown) in the shaft **184**. More specifically, the device has a sensor **192** that is positioned such that it can measure the force generated through the coupling of the gears **188** and the push/pull rod (not shown) coupled to the shaft **184**. That is, the sensor **192** is positioned in FIG. **7** such that it is operably coupled to a proximal portion of the push/pull rod. In one embodiment, the sensor **192** measures tension and compression. According to one exemplary implementation, the sensor **192** is a force sensor **192** that measures axial loading. For example, the sensor **192** can be one of the ELFS Series of load cells available from Entran Sensors & Electronics in Fairfield, N.J. Alternatively, the sensor **192** can be any known type of force sensor.

FIG. **8** depicts another embodiment of a force-sensing end effector **200**. In this embodiment, the sensor **202** is positioned on the push/pull rod (not shown) proximal to the clamp **190**. In one embodiment, the sensor **202** is positioned on or in operable coupling with the push/pull rod (not shown) within the shaft **184**. Alternatively, the sensor **202** is positioned on or externally to the shaft **184**, but still operably coupled to the push/pull rod. The sensor **202** is configured to measure the force applied to the push/pull rod (not shown).

FIG. **9** depicts yet another implementation of a force-sensing end effector **210**. In this embodiment, the sensor **212** is operably coupled to the motor **186** such that the sensor **212** measures the current consumed by the motor **186**. The information relating to the current can be used to determine the amount of force being applied by the grasper tool **182**.

FIGS. **10**A and **10**B depict two additional embodiments of force-sensing end effectors **220**, **222** that measure contact force at the graspers (rather than measuring directly the force applied by the actuator(s)/motor(s)). In the embodiment shown in FIG. **10**A, a sensor **224** is positioned on the grasper tool **182** itself. More specifically, the sensor **224** is positioned on the internal face of one of the two jaws of the tool **182** such that the sensor **224** measures the contact force on the internal face of the jaw. Alternatively, as shown in FIG. **10**B, a sensor **226** can be positioned on an external face of a jaw of the grasper tool **182** near the pivot axis of the tool **182** such that the sensor **226** measures the deflection of the grasper. Using the deflection information, the force applied to the tool **182** can be determined.

Although the present invention has been described with reference to preferred embodiments, persons skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the invention.

What is claimed is:

1. A robotic surgical system comprising:

(a) a robotic surgical device configured to be positioned into a cavity of a patient through an incision, the device comprising:
  (i) a device body;
  (ii) at least one arm operably coupled to the body, wherein the at least one arm is configured to be positioned entirely within the cavity of the patient; and
  (iii) at least one sensor operably coupled to the device;
(b) a processor operably coupled to the at least one sensor; and
(c) a user controller operably coupled to the processor, the user controller comprising:
  (i) a base;
  (ii) an upper arm component operably coupled to the base at a shoulder joint, wherein the shoulder joint comprises a first actuator operably coupled to the processor;
  (iii) a forearm component operably coupled to the upper arm component at an elbow joint, wherein the elbow joint comprises a second actuator operably coupled to the processor; and
  (iv) a grasper operably coupled to the forearm component at a wrist joint, wherein the wrist joint comprises a third actuator operably coupled to the processor,
wherein the at least one sensor is configured to sense force or torque at the robotic surgical device and transmit force or torque information to the processor,
wherein the processor is configured to calculate the force or torque being applied at the robotic surgical device and transmit instructions to actuate at least one of the first, second, or third actuator based on the force or torque, thereby providing haptic feedback at the controller.

2. The robotic surgical system of claim **1**, wherein the at least one sensor is a force sensor operably coupled to the at least one arm.

3. The robotic surgical system of claim **1**, wherein the at least one sensor is a torque sensor operably coupled to a joint of the at least one arm.

4. The robotic surgical system of claim **1**, wherein the at least one sensor is a force sensor positioned between the device body and the at least one arm.

5. The robotic surgical system of claim **1**, wherein the at least one sensor is a force sensor disposed within the device body.

6. A robotic surgical system comprising:

(a) a robotic surgical device comprising:
  (i) a device body configured to be positioned through an incision into a cavity of a patient;
  (ii) a first shoulder component operably coupled to the device body;
  (iii) a first arm operably coupled to the first shoulder component, wherein the first arm is configured to be positioned entirely within the cavity of the patient; and
  (iv) a sensor operably coupled to the device,
wherein the device body is configured to be disposed in the incision when the first arm is positioned within the cavity;
(b) a processor operably coupled to the sensor; and
(c) a user controller operably coupled to the processor, the user controller comprising:
  (i) a base;
  (ii) a controller upper arm component operably coupled to the base at a shoulder joint, wherein the shoulder joint comprises a first actuator operably coupled to the processor;
  (iii) a controller forearm component operably coupled to the controller upper arm component at an elbow joint, wherein the elbow joint comprises a second actuator operably coupled to the processor; and
  (iv) a grasper operably coupled to the controller forearm component at a wrist joint, wherein the wrist joint comprises a third actuator operably coupled to the processor,
wherein the sensor is configured to sense force or torque at the robotic surgical device and transmit force or torque information to the processor, and
wherein the processor is configured to calculate the force or torque being applied at the robotic surgical device and transmit instructions to actuate at least one of the first, second, or third actuator based on the force or torque, thereby providing haptic feedback at the controller.

7. The robotic surgical system of claim **6**, wherein the sensor is disposed between the device body and the first shoulder component.

8. The robotic surgical system of claim **6**, wherein the sensor is disposed on the first arm.

9. The robotic surgical system of claim **8**, wherein the first arm comprises a first arm upper arm component and a first arm forearm component, wherein the sensor is disposed on the first arm forearm component.

10. The robotic surgical system of claim **6**, wherein the first arm comprises a first arm upper arm component and a first arm forearm component, wherein the first arm forearm component is operably coupled to the first arm upper arm component at an elbow joint, wherein the first arm forearm component comprises a link operably coupled at a distal end to the force sensor and operably coupled at a proximal end to the elbow joint.

11. The robotic surgical system of claim **10**, further comprising an interface plate disposed between the force sensor and the link.

12. The robotic surgical system of claim **6**, wherein the sensor is positioned to measure the amount of force applied at a distal-most point on the first arm.

13. A robotic surgical system comprising:

(a) a robotic surgical device comprising:
  (i) a device body configured to be positioned through an incision into a cavity of a patient;
  (ii) a first arm operably coupled to the device body, the first arm comprising an arm actuator disposed within the first arm, wherein the first arm is configured to be positioned entirely within the cavity of the patient;
  (iii) a sensor operably coupled to the arm actuator; and
  (iv) an end effector operably coupled to the arm actuator, the end effector positioned at a distal end of the first arm;
(b) a processor operably coupled to the sensor; and
(c) a user controller operably coupled to the processor, the user controller comprising:
  (i) a base;

(ii) a controller upper arm component operably coupled to the base at a shoulder joint, wherein the shoulder joint comprises a first actuator operably coupled to the processor;

(iii) a controller forearm component operably coupled to the forearm upper arm component at an elbow joint, wherein the elbow joint comprises a second actuator operably coupled to the processor; and

(iv) a controller grasper operably coupled to the controller forearm component at a wrist joint, wherein the wrist joint comprises a third actuator operably coupled to the processor,

wherein the sensor is configured to sense force or torque at the robotic surgical device and transmit force or torque information to the processor,

wherein the processor is configured to calculate the force or torque being applied at the robotic surgical device and transmit instructions to actuate at least one of the first, second, or third actuator based on the force or torque, thereby providing haptic feedback at the controller.

14. The robotic surgical system of claim **13**, further comprising a push/pull rod comprising a distal portion and a proximal portion, wherein the push/pull rod is operably coupled to the arm actuator at the proximal portion and further wherein the push/pull rod is operably coupled to the end effector at the distal portion.

15. The robotic surgical system of claim **14**, wherein the sensor is disposed proximal to the arm actuator and is operably coupled to the proximal portion of the push/pull rod.

16. The robotic surgical system of claim **14**, wherein the end effector is a device grasper, wherein the device grasper comprises an open configuration when the push/pull rod is urged to a distal position, and further wherein the device grasper comprises a closed configuration when the push/pull rod is urged to a proximal position.

17. The robotic surgical system of claim **14**, wherein the sensor is operably coupled to the push/pull rod such that the sensor is positioned along the length of the push/pull rod.

18. The robotic surgical system of claim **13**, wherein the end effector is a device grasper.

19. The robotic surgical system of claim **13**, further comprising a shaft operably coupled to the end effector and a first gear operably coupled to the shaft, wherein the arm actuator comprises a second gear operably coupled to the first gear.

20. The robotic surgical system of claim **19**, wherein actuation of the arm actuator causes the shaft to rotate, thereby causing the end effector to rotate.

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