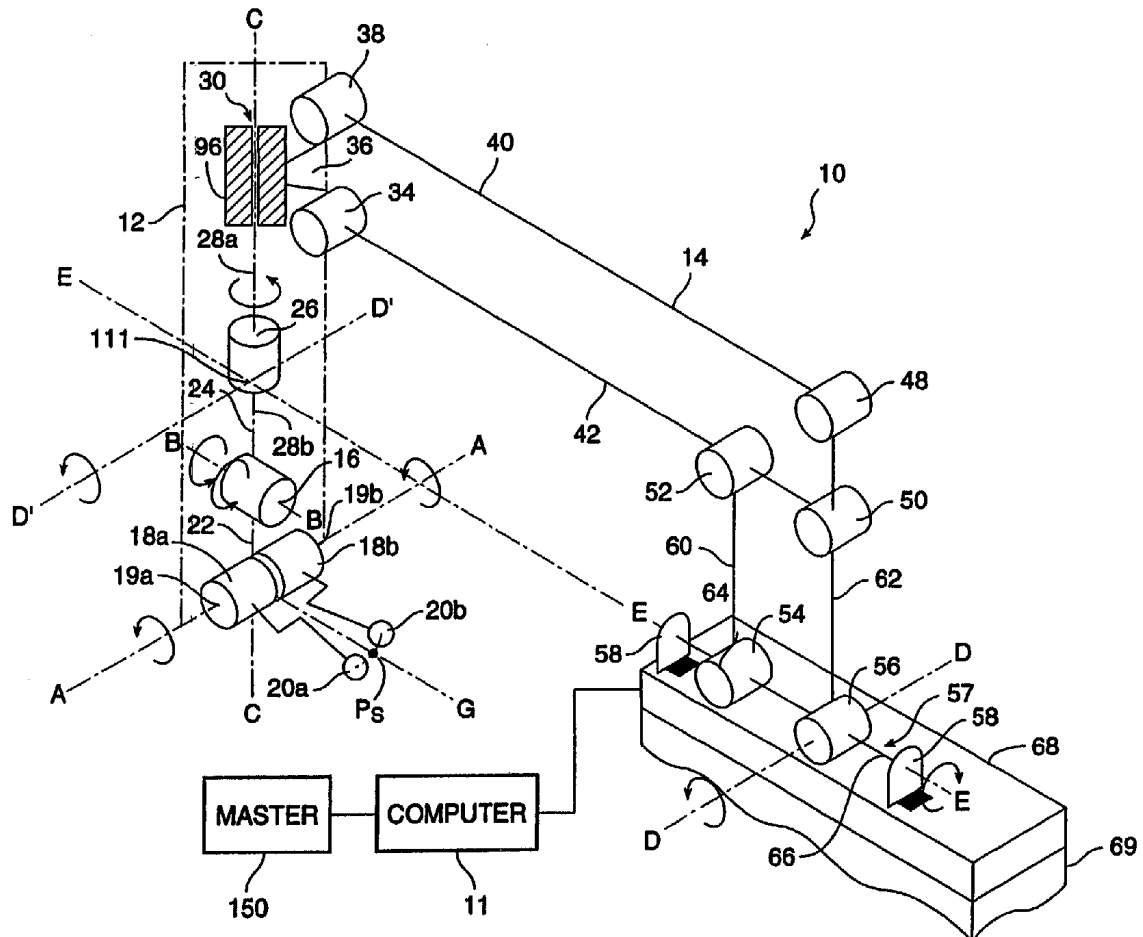


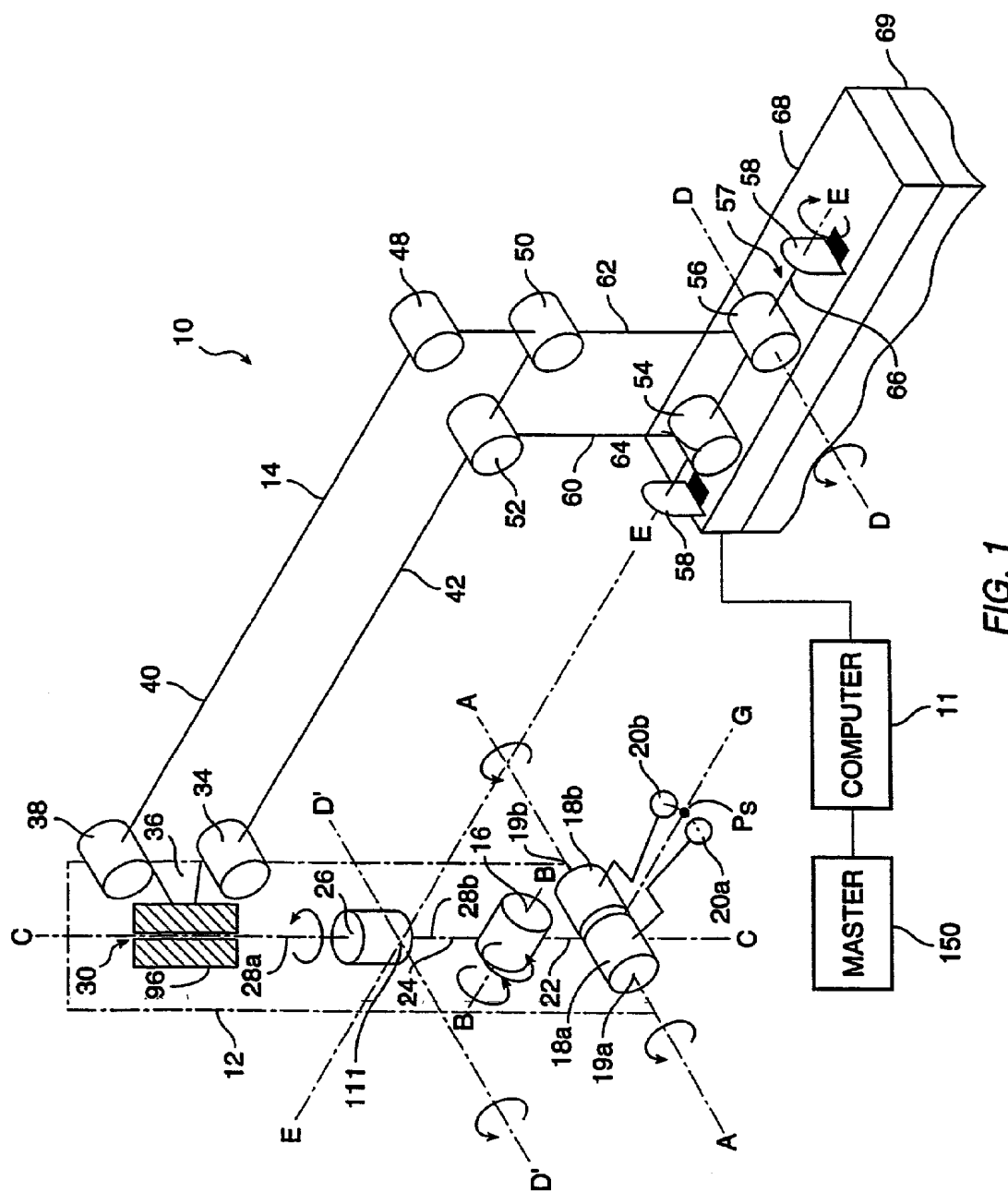


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(19) **United States**(12) **Patent Application Publication**
Madhani et al.(10) **Pub. No.: US 2002/0103476 A1**(43) **Pub. Date: Aug. 1, 2002**(54) **ARTICULATED SURGICAL INSTRUMENT
FOR PERFORMING MINIMALLY INVASIVE
SURGERY WITH ENHANCED DEXTERITY
AND SENSITIVITY**(75) Inventors: **Akhil J. Madhani**, Cambridge, MA
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Sunnyvale, CA 94086(21) Appl. No.: **10/076,812**(22) Filed: **Feb. 15, 2002****Related U.S. Application Data**(63) Continuation of application No. 09/340,946, filed on
Jun. 28, 1999, now patented, which is a continuationof application No. 09/030,661, filed on Feb. 25, 1998,
now patented, which is a continuation of application
No. 08/857,776, filed on May 16, 1997, now patented.(60) Provisional application No. 60/017,981, filed on May
20, 1996.**Publication Classification**(51) **Int. Cl.⁷** **A61B 17/00**(52) **U.S. Cl.** **606/1**(57) **ABSTRACT**

An articulated surgical instrument for enhancing the performance of minimally invasive surgical procedures. The instrument has a high degree of dexterity, low friction, low inertia and good force reflection. A unique cable and pulley drive system operates to reduce friction and enhance force reflection. A unique wrist mechanism operates to enhance surgical dexterity compared to standard laparoscopic instruments. The system is optimized to reduce the number of actuators required and thus produce a fully functional articulated surgical instrument of minimum size.





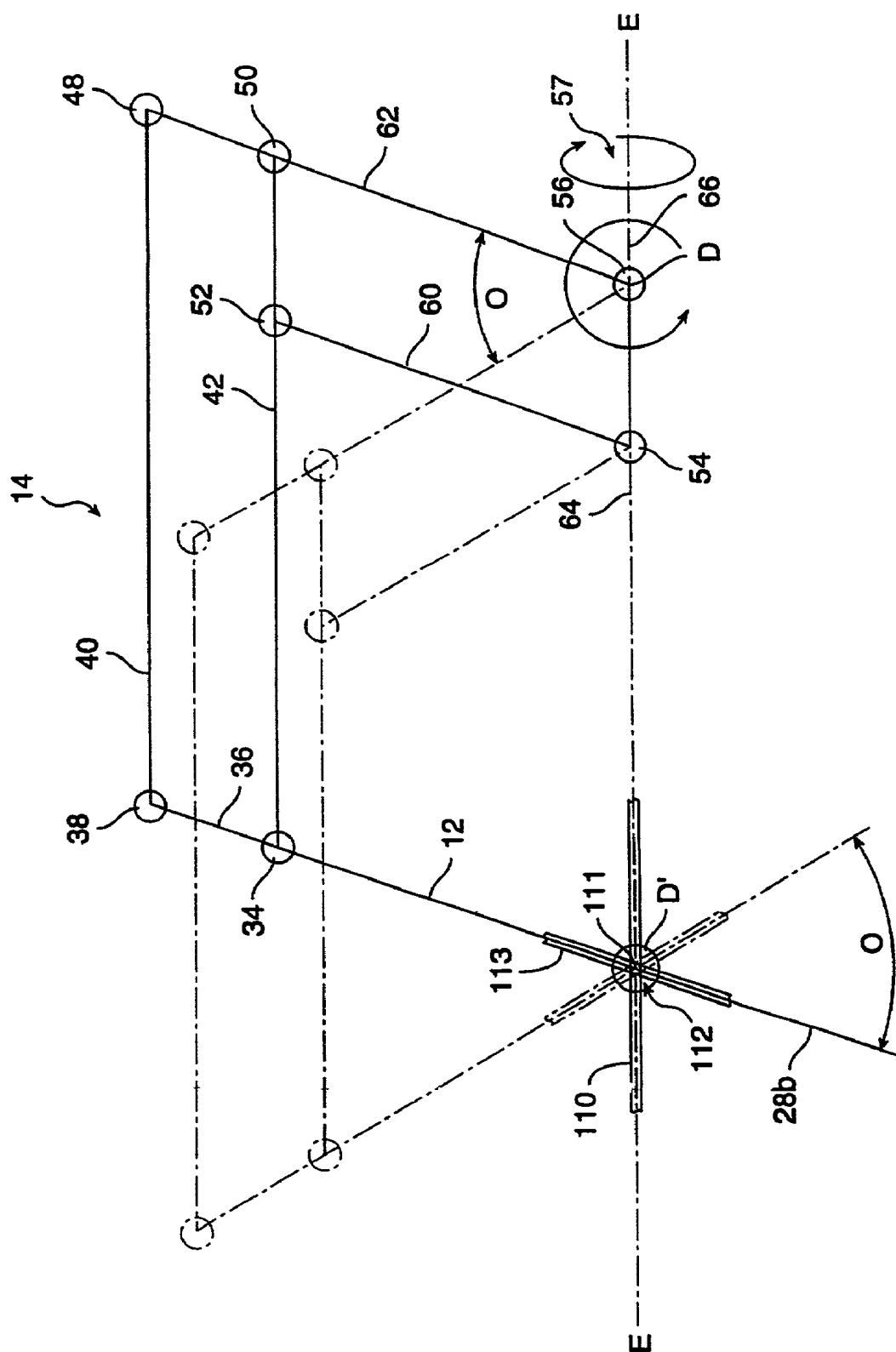


FIG. 2

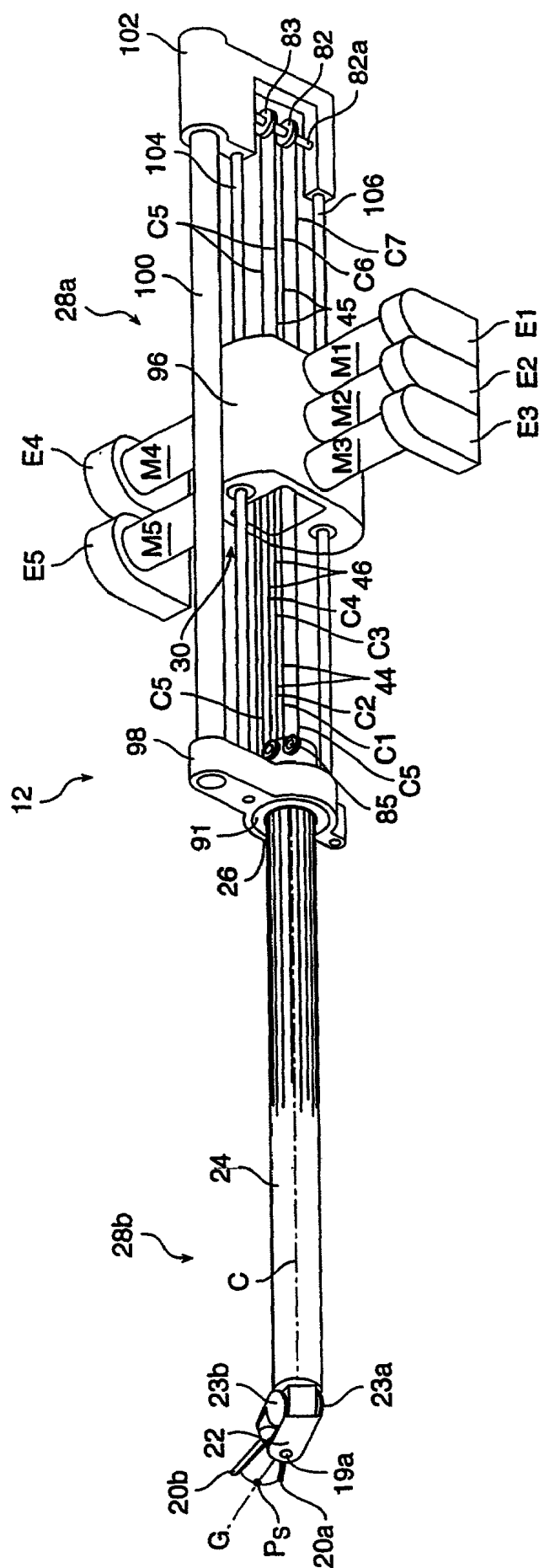


FIG. 3

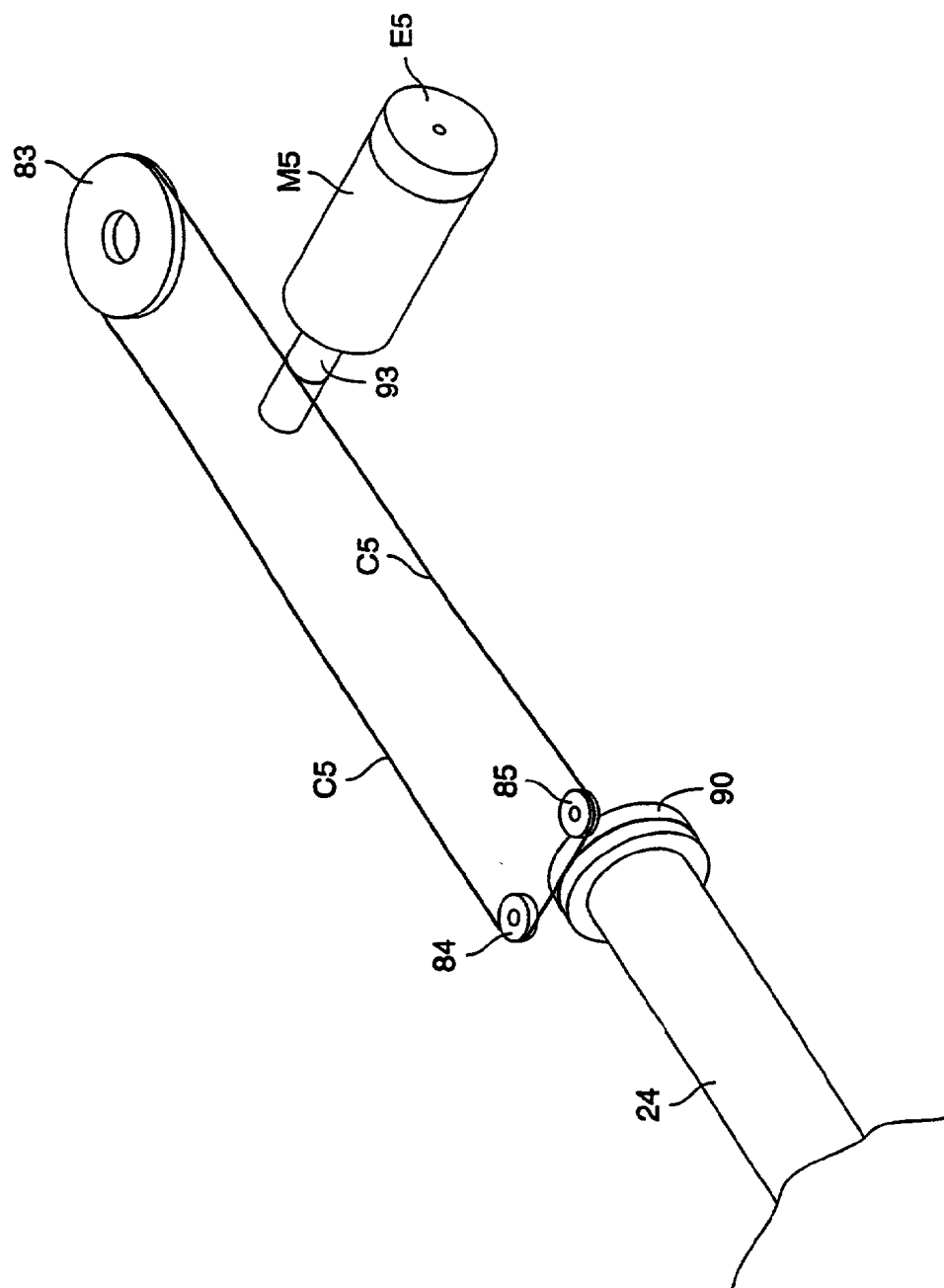


FIG. 4

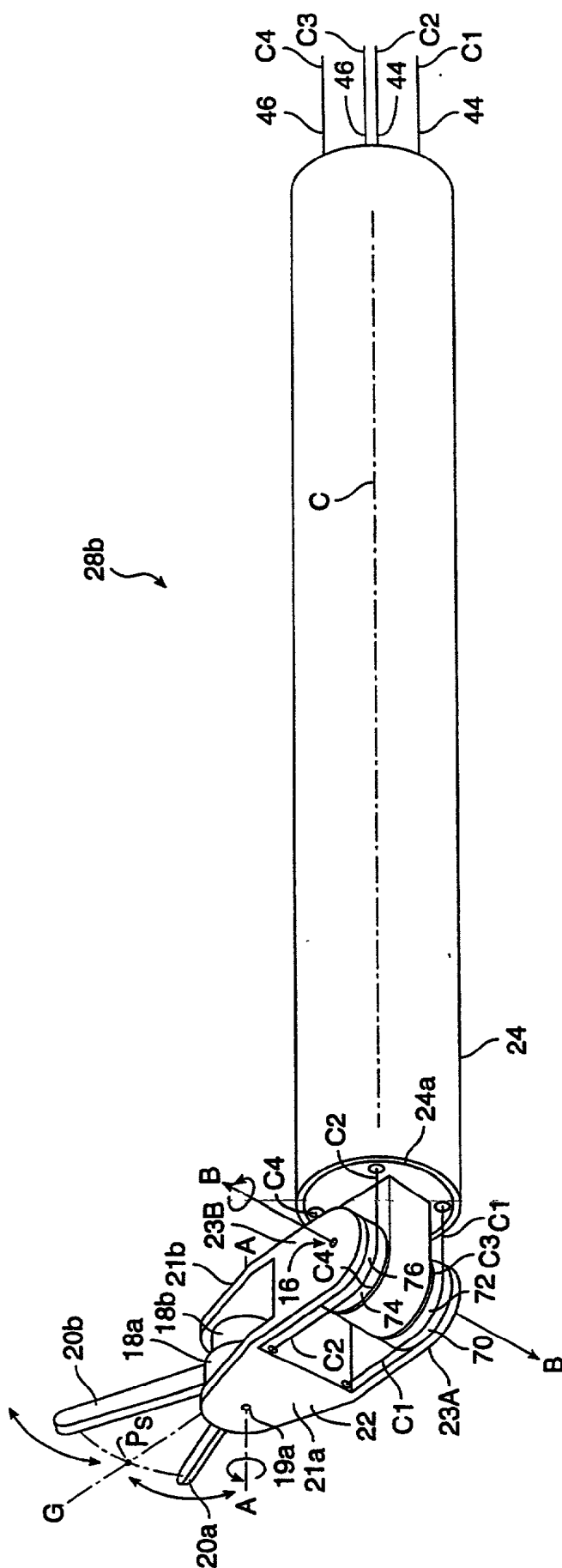


FIG. 5

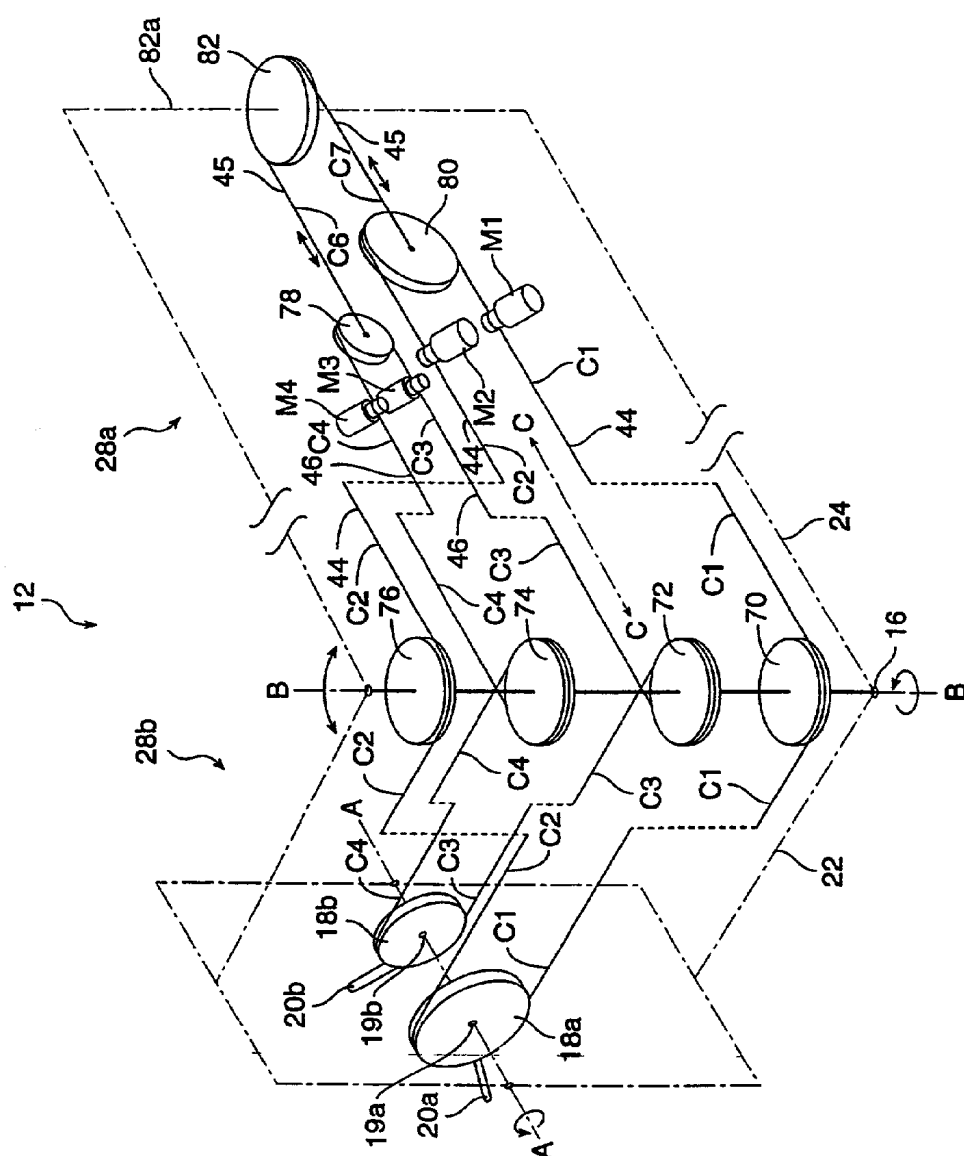


FIG. 6

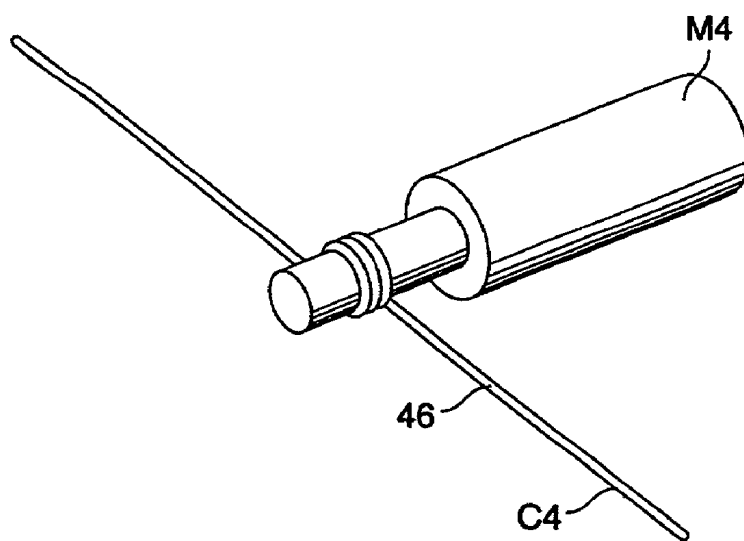


FIG. 7A

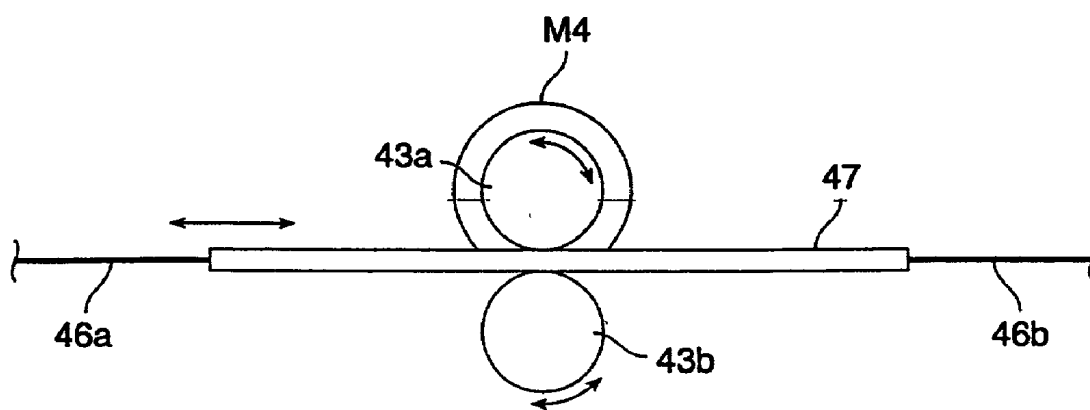


FIG. 7B

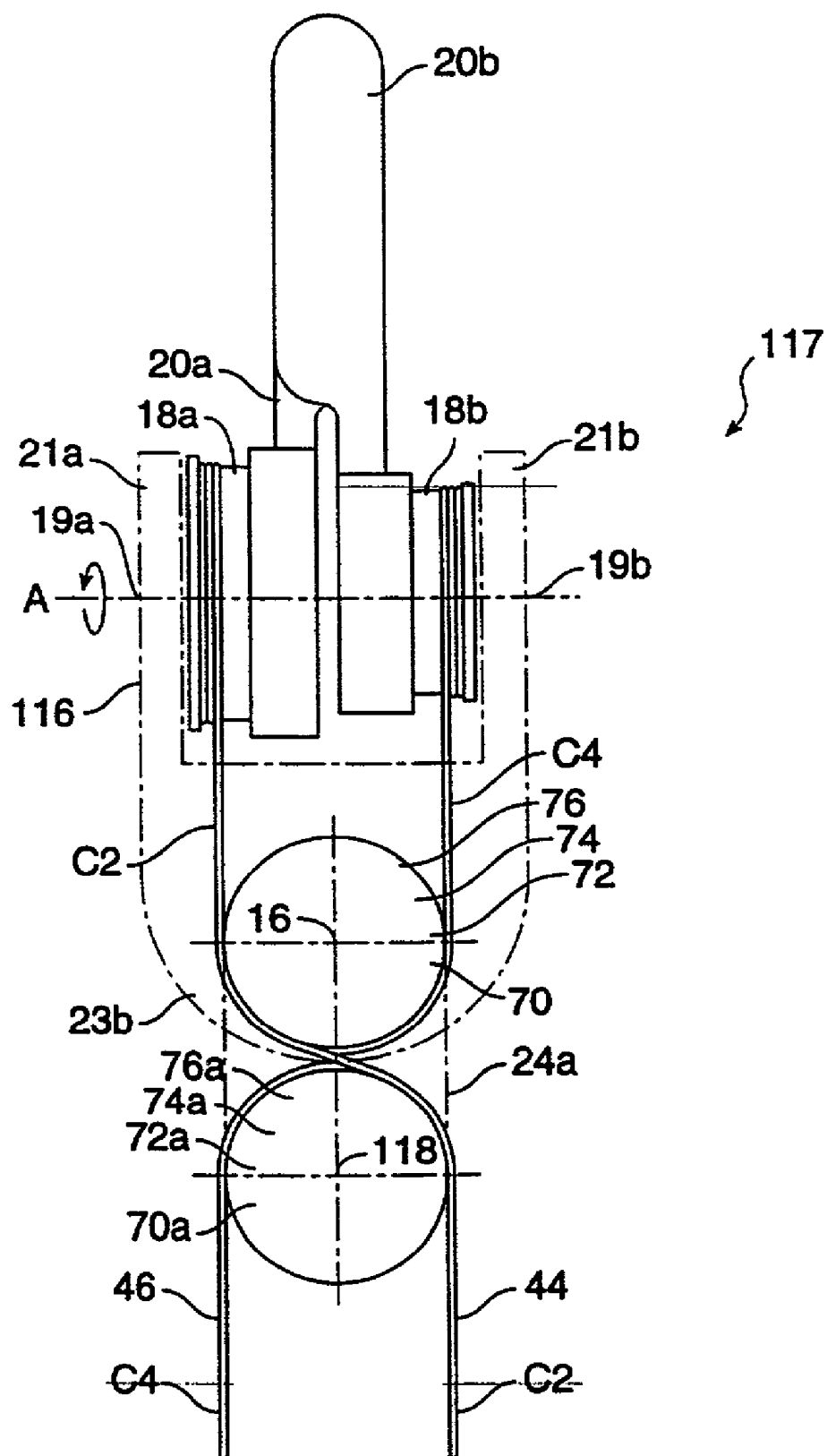


FIG. 8

**ARTICULATED SURGICAL INSTRUMENT FOR
PERFORMING MINIMALLY INVASIVE SURGERY
WITH ENHANCED DEXTERITY AND
SENSITIVITY**

**CROSS-REFERENCES TO RELATED
APPLICATIONS**

[0001] This application is a continuation of, and claims the benefit of priority from, co-pending U.S. patent application Ser. No. 09/340,946, filed Jun. 28, 1999, which is a continuation of U.S. patent application Ser. No. 09/030,661, filed Feb. 25, 1998 (now U.S. Pat. No. 5,976,122), which is a continuation of U.S. patent application Ser. No. 08/857,776, filed May 16, 1997 (now U.S. Pat. No. 5,792,135), which claims priority to U.S. Provisional Application No. 60/017,981, filed May 20, 1996, the full disclosures of which are incorporated herein by reference.

**STATEMENT AS TO RIGHTS TO INVENTIONS
MADE UNDER FEDERALLY SPONSORED
RESEARCH OR DEVELOPMENT NOT
APPLICABLE**

**REFERENCE TO A "SEQUENCE LISTING," A
TABLE, OR A COMPUTER PROGRAM LISTING
APPENDIX SUBMITTED ON A COMPACT
DISK. NOT APPLICABLE**

BACKGROUND OF THE INVENTION

[0002] 1. Field of the Invention

[0003] This invention relates generally to methods and apparatus for enhancing the performance of minimally invasive surgery. This invention relates particularly to surgical instruments that augment a surgeon's ability to perform minimally invasive surgical procedures. This invention relates more particularly to a novel articulated surgical instrument for minimally invasive surgery which provides a high degree of dexterity, low friction, low inertia and good force reflection.

[0004] 2. Background of the Invention

[0005] Minimally invasive medical techniques are aimed at reducing the amount of extraneous tissue which must be damaged during diagnostic or surgical procedures, thereby reducing patient recovery time, discomfort, and deleterious side effects. Approximately 21,000,000 surgeries are now performed each year in the United States. It is estimated that 8,000,000 of these surgeries can potentially be performed in a minimally invasive manner. However, only about 1,000,000 surgeries currently use these techniques due to limitations in minimally invasive surgical instruments and techniques and the additional surgical training required to master them.

[0006] Advances in minimally invasive surgical technology could have a dramatic impact. The average length of a hospital stay for a standard surgery is 8 days, while the average length for the equivalent minimally invasive surgery is 4 days. Thus, the complete adoption of minimally invasive techniques could save 28,000,000 hospital days, and billions of dollars annually in hospital residency costs alone. Patient recovery times, patient discomfort, surgical side effects, and time away from work are also reduced with minimally invasive surgery.

[0007] The most common form of minimally invasive surgery is endoscopy. Probably the most common form of endoscopy is laparoscopy which is minimally-invasive inspection and surgery inside the abdominal cavity. In standard laparoscopic surgery, a patient's abdomen is insufflated with gas, and cannula sleeves are passed through small (approximately ½ inch) incisions to provide entry ports for laparoscopic surgical instruments.

[0008] The laparoscopic surgical instruments generally include a laparoscope for viewing the surgical field, and working tools such as clamps, graspers, scissors, staplers, and needle holders. The working tools are similar to those used in conventional (open) surgery, except that the working end of each tool is separated from its handle by an approximately 12-inch long extension tube.

[0009] To perform surgical procedures, the surgeon passes instruments through the cannula and manipulates them inside the abdomen by sliding them in and out through the cannula, rotating them in the cannula, levering (i.e., pivoting) the instruments in the abdominal wall and actuating end effectors on the distal end of the instruments. The instruments pivot around centers of rotation approximately defined by the incisions in the muscles of the abdominal wall. The surgeon monitors the procedure by means of a television monitor which displays the abdominal worksite image provided by the laparoscopic camera.

[0010] Similar endoscopic techniques are employed in arthroscopy, retroperitoneoscopy, pelviscopy, nephroscopy, cystoscopy, cisternoscopia, sinoscopy, hysteroscopy and urethroscopy. The common feature of all of these minimally invasive surgical techniques is that they visualize a worksite within the human body and pass specially designed surgical instruments through natural orifices or small incisions to the worksite to manipulate human tissues and organs thus avoiding the collateral trauma caused to surrounding tissues which would result from creating open surgical access.

[0011] There are many disadvantages of current minimally invasive surgical technology. For example, existing MIS instruments deny the surgeon the flexibility of tool placement found in open surgery. Most laparoscopic tools have rigid shafts and are constrained to approach the worksite from the direction of the small incision. Additionally, the length and construction of many endoscopic instruments reduces the surgeon's ability to feel forces exerted by tissues and organs on the end effector of the tool. The lack of dexterity and sensitivity provided by endoscopic tools is a major impediment to the expansion of minimally invasive surgery.

[0012] Telesurgery systems for use in surgery are being developed to increase a surgeon's dexterity as well as to allow a surgeon to operate on a patient from a remote location. Telesurgery is a general term for surgical systems where the surgeon uses some form of servomechanism to manipulate the surgical instruments movements rather than directly holding and moving the tools. In a system for telesurgery, the surgeon is provided with an image of the patient's body at the remote location. While viewing the three-dimensional image, the surgeon performs the surgical procedures on the patient by manipulating a master device which controls the motion of a servomechanism-actuated instrument. The surgeon's hands and the master device are positioned relative to the image of the operation site in the

same orientation as the instrument is positioned relative to the act. During the operation, the instrument provides mechanical actuation and control of a variety of surgical instruments, such as tissue graspers, needle drivers, etc., that each perform various functions for the surgeon, i.e., holding or driving a needle, grasping a blood vessel or dissecting tissue.

[0013] Such telesurgery systems have been proposed for both open and endoscopic procedures. An overview of the state of the art with respect to telesurgery technology can be found in "Computer Integrated Surgery: Technology And Clinical Applications" (MIT Press, 1996). Moreover, prior systems for telesurgery are described in U.S. Pat. Nos., 5,417,210, 5,402,801, 5,397,323, 5,445,166, 5,279,309, 5,299,288.

[0014] However methods of performing telesurgery using telemanipulators still require the development of dexterous surgical instruments capable of transmitting position, force, and tactile sensations from the surgical instrument back to the surgeon's hands as he/she operates the telesurgery system such that the system the surgeon has the same feeling as if manipulating the surgical instruments directly by hand. A system's ability to provide force reflection is limited by factors such as friction within the mechanisms, gravity, the inertia of the surgical instrument and forces exerted on the instrument at the surgical incision.

[0015] What is needed, therefore, is a surgical instrument that increases the dexterity with which a surgeon can perform minimally invasive surgical procedures.

[0016] It would also be desirable to provide a dexterous surgical apparatus having a wrist with two degrees-of-freedom.

[0017] It would further be desirable to provide a wrist mechanism that has low friction in order to provide the surgeon with sensitive feedback of forces exerted on the surgical instrument.

[0018] It would still further be desirable to provide a surgical instrument having a wrist mechanism for minimally invasive surgery which is suitable for operation in a telemanipulator mechanism.

BRIEF SUMMARY OF THE INVENTION

[0019] Accordingly, it is an object of this invention to provide a surgical instrument that increases the dexterity with which a surgeon can perform minimally invasive surgical procedures.

[0020] It is also an object of this invention to provide a dexterous surgical apparatus having a wrist with two degrees-of-freedom.

[0021] It is a further object of this invention to provide a wrist mechanism that has low friction in order to provide the surgeon with sensitive feedback of forces exerted on the surgical instrument.

[0022] It is a still further object of this invention to provide a surgical instrument having a wrist mechanism for minimally invasive surgery which is suitable for operation in a telemanipulator mechanism.

[0023] In accordance with the above objects of the invention applicants describe a compact articulated surgical

instrument suitable for endoscopic surgery. The instrument has two opposed pivoting jaws and a pivoting wrist member. The instrument is capable of providing force reflection with high sensitivity. The instrument is adapted to be coupled via a servomechanism to a master control operated by a surgeon.

BRIEF DESCRIPTION OF THE DRAWINGS

[0024] The foregoing and other objects, features and advantages of the invention will be apparent from the following more particular description of preferred embodiments of the drawings in which like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention.

[0025] FIG. 1 is a schematic drawing of a servomechanical surgery system including a force-reflecting surgical instrument mounted to a positioning mechanism.

[0026] FIG. 2 is a schematic drawing of a positioning mechanism in forward and rearward positions with the surgical instrument inserted into a patient.

[0027] FIG. 3 is a perspective view of a force-reflecting surgical instrument.

[0028] FIG. 4 is a schematic view of the cable drive actuation of the rotary motion of the force-reflecting surgical instrument.

[0029] FIG. 5 is a perspective view of the distal end of the force-reflecting surgical instrument.

[0030] FIG. 6 is a simplified schematic drawing of the force-reflecting surgical instrument showing the relationship of the cables and pulleys.

[0031] FIG. 7a is a perspective view of a cable wrapped around the drive shaft of a drive motor.

[0032] FIG. 7b is a schematic drawing showing another preferred method for driving the cables in the present invention.

[0033] FIG. 8 is a top view of the wrist member of another preferred force-reflecting surgical instrument.

DETAILED DESCRIPTION OF THE INVENTION

[0034] The surgical instrument in the first embodiment includes an elongate support member having a proximal portion and a distal portion lying along a longitudinal axis. A distal wrist member is rotatably coupled to the distal portion of the support member by a wrist joint. First and second opposed work members are mounted to respective first and second driven capstans. The first and second driven capstans are rotatably mounted to the wrist member by respective first and second capstan joints which preferably have a common axis. First, second, third and fourth intermediate idler pulleys are rotatably mounted to the wrist member about the wrist joint. A cable drive system including first, second, third and fourth cables is provided. Each intermediate idler pulley is engaged by one cable and each driven capstan is drivingly engaged by two cables. The cable drive system is capable of pivoting the wrist member about the wrist joint and pivoting the work members independently of each other about the capstan joints.

[0035] In preferred embodiments, a linear bearing is mounted in sliding engagement with the support member for allowing the distal portion of the support member to be reciprocated along the longitudinal axis relative to the proximal portion of the support member. In such embodiments the cable drive system is capable of translating the support member along the longitudinal axis. In preferred embodiments, the support member may also include a rotary joint separating the proximal and distal portions of the support member for allowing rotation of the distal portion relative to the proximal portion about the longitudinal axis. In such embodiments the first through fourth cables are capable of twisting about the longitudinal axis during rotation of the distal portion and the cable drive system comprises a fifth cable coupled to the rotary joint for rotating the distal portion about the longitudinal axis.

[0036] The present invention also provides a novel system for tensioning the first, second, third and fourth cables. A first proximal idler pulley rotatably engages and tensions the first and second cables. A second proximal idler pulley rotatably engages and tensions the third and fourth cables. Fifth and sixth cables are connected to the first and second proximal idler pulleys for tensioning the first and second proximal idler pulleys. A third more proximal idler pulley is rotatably mounted to a support member for rotatably engaging and tensioning the fifth and sixth cables.

[0037] The surgical instrument further includes a plurality of actuators, each for driving one of the cables of the cable drive system. The instrument preferably comprises one actuator for each degree-of-freedom of the instrument. The actuators are preferably servomotors which are positioned between the intermediate idler pulleys and the proximal idler pulleys. The servomotors are preferably directly coupled to the cables by means of a drive capstan mounted on the drive shaft of the servomotor.

[0038] The surgical instrument is adapted to be a slave device which is controlled by a master device and a controller. Movements of the instrument and the master device as well as forces exerted thereon may be scaled between the instrument and the master device. A positioning mechanism having two degrees-of-freedom may be mounted to the instrument for positioning the instrument over a work site. The positioning mechanism may provide the instrument with redundant degrees-of-freedom for positioning the endpoint. The combination of a positioning mechanism with the applicants articulated surgical instrument is adapted to enable a surgeon operating the master device to feel forces that are experienced by the instrument during positioning and use of the instrument with greater sensitivity than with prior systems.

[0039] Details about the preferred attributes of the surgical system are also described in applicants' copending applications titled "Force-Reflecting Surgical Instrument And Positioning Mechanism For Performing Minimally Invasive Surgery With Enhanced Dexterity And Sensitivity" and "Wrist Mechanism For Surgical Instrument For Performing Minimally Invasive Surgery With Enhanced Dexterity And Sensitivity" filed on even date herewith. The disclosures of these applications are incorporated herein by reference.

[0040] Referring to FIG. 1, telesurgery system 10 allows a surgeon at one location to perform surgery on a patient at another location. The surgeon may be in the same operating

room as the patient or many miles away. Telesurgery system 10 includes a force-reflecting surgical instrument 12 which is mounted by a bracket 36 to a positioning mechanism 14. Instrument 12 and positioning mechanism 14 are controlled by a computer 11 and a master device 150 which is manipulated by a surgeon at a remote location. Instrument 12 and positioning mechanism 14 are driven by drive motors M1, M2, M3, M4, M5, M6 and M7 (FIGS. 3, 4, 6 and 7a-b) in conjunction with a series of cables and pulleys.

[0041] Instrument 12 has low friction, low inertia and high bandwidth but a small range of motion. Positioning mechanism 14 has a large range of motion but typically has a higher inertia and a lower bandwidth than the instrument. The combination of instrument 12 and positioning mechanism 14 in a macro/micro actuation scheme results in a system with increased dynamic range compared to either of its individual components. Positioning mechanism 14 provides telesurgery system 10 with redundant degrees-of-freedom and helps position instrument 12 at a surgical worksite so that instrument 12 is generally in the proper location for performing the necessary surgery. Thus, by mounting instrument 12 on positioning mechanism 14, telesurgery system 10 is provided with high quality force control through the use of instrument 12 while at the same time having a large range of motion due to positioning mechanism 14. Instrument 12 is mounted on positioning mechanism by means of mounting bracket 36. Preferably, the Instrument 12 is releasably attached to positioning mechanism 14 using any suitable releasable attachment means such as screws, bolts, clamps.

[0042] Instrument 12 has a proximal portion 28a which is rotatably coupled to a distal portion 28b by a rotary joint 26. Proximal portion 28a is slidably coupled to a sliding bracket 96 which forms a sliding joint 30. Sliding bracket 96 is fixed to bracket 36. Bracket 36 is a mounting bracket which releasably connects instrument 12 to positioning mechanism 14. Distal portion 28b of instrument 12 includes a wrist member which is rotatably coupled to a tubular support member 24 by a wrist joint 16. Two opposed work members 20a and 20b are fixed to respective driven capstans 18a and 18b which are rotatably coupled to wrist member 22 about capstan joints 19a and 19b. The work members 20a and 20b can be the operative end of standard surgical instruments such as scissors, retractors, needle drivers and electrocautery instruments.

[0043] Instrument 12 has five degrees-of-freedom with sliding joint 30 providing linear motion along longitudinal axis C-C, rotary joint 26 providing rotational motion about axis C-C, wrist joint 16 providing rotational motion about axis B-B and capstan joints 19a and 19b providing rotational motion about axis A-A for work members 20a and 20b. Instrument 12 provides master device 150 with four degrees of force reflection so that the surgeon can have tactile feedback of surgical procedures. These degrees of force reflection include x, y and z forces exerted on the work members 20a and 20b, as well as the holding force between work members 20a and 20b. However, force reflection can be provided on more or fewer motion axes as required in any particular embodiment.

[0044] Positioning mechanism 14 is a two degree-of-freedom linkage which is preferably a four bar linkage which rotates about an axis E-E. Positioning mechanism 14

has a series of rigid members **36, 40, 42, 60** and **62** which are joined together by joints **34, 38, 48, 50, 52, 54, 56**. Positioning mechanism **14** also includes a base **68** having ears **58** which engage shafts **64** and **66** to form a joint **57** for pivoting about axis E-E. Joint **56** allows link **62** to rotate about axis D-D which is orthogonal to axis E-E. The four bar linkage of rigid members **36, 40, 42, 60** and **62** transmits this rotation to instrument **12** via bracket **36** causing instrument **12** to rotate about axis E-E and axis D'-D' (axis D'-D' is parallel to axis D-D and intersects axis E-E orthogonally). Thus the four bar linkage operates to move point P_s of instrument **12** about the surface of a sphere having its center at a remote center **111**. Although a four bar linkage has been shown, the articulated surgical instrument of the present invention can be supported by any suitable positioning mechanism. To be suitable for minimally invasive surgery the positioning mechanism must pivot the surgical instrument about axes that intersect at the orifice through which the instrument is inserted into the patient.

[0045] Haptic master device **150** suitable to control instrument **12** is a seven degree-of-freedom input device. During use the master **150** is fixed in place to a console or cart or similar stationary support such that the mount provides a fixed reference point. During use, the surgeon manipulates the position and orientation of the master mechanism relative to its stationary support. Linkages, motors and encoders of the master detect the surgeon's movements and transmit them to the computer. The motors of the master preferably also provide force feedback to the surgeon. This controls motions of instrument **12** and positioning mechanism **14** and thus controls the position of the distal end of instrument **12** relative to the surgical site.

[0046] One apparatus suitable for use as a master in the presently described system is described in U.S. Pat. No. 5,587,937, titled Force Reflecting Haptic Interface the contents of which are incorporated by reference herein. Another suitable master device is described in U.S. Pat. No. 5,576,727, titled Electromechanical Human-Computer Interface With Force-Feedback the contents of which are incorporated by reference herein. The haptic master apparatus disclosed in the above references would require the addition of a further powered degree-of-freedom to provide force reflection from gripping the work members. For example, finger grippers may be attached to a motor and encoder on a separate mechanism for operation by the other hand of the surgeon. Alternatively, finger grippers may be attached to a motor and encoder on the same device for operation by the surgeon.

[0047] When employing telesurgery system **10** for laparoscopic surgery, positioning mechanism **14** is mounted to a manually-operated setup joint (not shown). After the setup joint has been used to position the tool and lock the tool in place, the surgeon then manipulates master device **150** to move instrument **12** through a cannula **113** inserted through small incision **112** in the abdominal wall **110** of the patient. In response to manipulation of master device **150**, the distal portion **28b** of the instrument **12** is translated downwardly relative to positioning mechanism **14** along sliding joint **30** for insertion through cannula **113** and abdominal wall **110**.

[0048] Once within the abdomen, the distal portion **28b** of instrument **12** is further positioned over the desired surgical site. FIG. 2 depicts motion of mechanism **14** pivoted about

axis D-D in forward and rearward positions for making large position movements. Positioning mechanism **14** pivots about axes D-D and E-E to perform large movements of telesurgery system **10** while precise movements are made by the joints of instrument **12**. Point **111** on instrument **12** is a remote point of rotation from positioning mechanism **14** which coincides with entry wound **112**. When positioning mechanism **14** is pivoted about axes D and E, instrument **12** pivots about point **111**. Note that point **111** adjacent incision **112** remains stationary as the instrument **12** is pivoted within the patient. As a result, incision **112** only needs to be large enough to accept instrument **12**.

[0049] As positioning mechanism **14** pivots, if wrist member **22** or work members **20a/20b** engage tissue causing rotation about joints **16** or **19a/19b**, instrument **12** will reorient itself so that instrument **12** is maintained relative to positioning mechanism **14** in the middle of its workspace. If necessary, positioning mechanism **14** can slow down as instrument **12** is reorienting itself.

[0050] Once instrument **12** is in the proper position, by further manipulating master device **150**, the surgeon can perform the necessary surgical procedures on the patient with instrument **12**. Forces experienced by instrument **12** are reflected back to the surgeon by master device **150**. The reflected forces may be scaled up in order to allow the surgeon to better "feel" the surgical procedures. As a result, the surgeon can feel instrument **12** engaging types of tissue that do not provide much resistance. In addition, movements of master device **150** relative to instrument **12** may be scaled down so that the precision and dexterity of instrument **12** can be increased.

[0051] Positioning mechanism **14**, because it is optimized to have a large range of motion, is likely to have higher inertia, higher friction and lower resolution than instrument **12**. Moreover, friction forces in cannula **113** and disturbance forces at incision **112** may be applied to the positioning mechanism. However, in applicants' preferred embodiment, primarily the surgical instrument detects forces for force reflection. Therefore, the higher inertia and friction of the positioning mechanism and the extraneous forces acting on it are excluded from the force reflection system. Thus, the quality of the force reflection between the tip of the instrument **12** and the master device is greatly improved.

[0052] Referring to FIGS. 3, 4 and 5, instrument **12** is now described in greater detail. Tubular support member **24** of distal portion lies along axis C-C and houses a series of cables **C1, C2, C3** and **C4** which travel the length of tubular support member **24**. Cables **C1, C2, C3** and **C4** control the rotation of joints **19a, 19b** and **16** for controlling the operation of work members **20a** and **20b** and the orientation of wrist member **22**. Wrist member **22** includes two opposed distal ears **21a** and **21b** forming a clevis for supporting driven capstans **18a** and **18b** at respective capstan joints **19a** and **19b** which lie along axis A-A. Wrist member **22** also includes two opposed proximal ears **23a** and **23b** forming a clevis for supporting intermediate idler pulleys **70** and **72** which lie along axis B-B between ear **23a** and tongue **24a** at wrist joint **16**. Intermediate idler pulleys **74** and **76** are supported between ear **23b** and tongue **24a**. Cables **C1, C2, C3** and **C4** engage driven capstans **18a/18b** as well as intermediate idler pulleys **70, 72, 74** and **76** as described later in greater detail.

[0053] Work members **20a** and **20b** may be removably fixed to respective driven capstans **18a** and **18b**. Although work members **20a** and **20b** are depicted in the figures as being grippers, work members **20a** and **20b** can be replaced with other types of work members such as scissors, cutters, graspers, forceps or needle holders for stitching sutures. Typically, the work members are fixed to driven capstans **18a** and **18b** by a screw, clip or other suitable fastener. However, the work members may also be permanently affixed to the driven capstans by soldering or welding, or the like, or may be formed in one piece with the driven capstans.

[0054] Work members **20a** and **20b** together comprise one form of surgical end effector. Other surgical end effectors may be used in the surgical instrument of the present invention. End effectors simply may comprise standard surgical or endoscopic instruments with their handles removed including, for example, retractors, electrocautery instruments, microforceps, microneedle holders, dissecting scissors, blades, irrigators, and sutures. The end effectors will typically comprise one or two work members.

[0055] Proximal portion **28a** of instrument **12** includes support brackets **98** and **102** which are connected together by a support rod **100** as well as two guide rails **104** and **106**. A rotary bearing **91** forming rotary joint **26** is housed within support bracket **98** for supporting tubular support member **24**. Sliding bracket **96** is slidably mounted to guide rails **104** and **106** along linear bearings. As shown in FIG. 1, sliding bracket **96** is connected by bracket **36** to positioning mechanism **14**. Sliding bracket **96** preferably has about 8 inches of travel for surgical applications.

[0056] Drive motors **M1**, **M2**, **M3**, **M4** and **M5** are mounted to sliding bracket **96** and drive respective cables **C1**, **C2**, **C3** and **C4** and **C5**. Sliding bracket **96** supports each of the drive motors. During operation sliding bracket **96** is connected to positioning mechanism **14** by mounting bracket **36**. When instrument **12** is mounted on positioning mechanism **14**, the drive motors operate to move distal portion **28b** relative to sliding bracket **96**. Sliding bracket **96** thus forms the support bracket of the surgical instrument. Each drive motor **M1**, **M2**, **M3**, **M4** and **M5** includes a respective encoder **E1**, **E2**, **E3**, **E4** and **E5** for providing computer **11** with the rotational position of their respective drive shafts.

[0057] As shown in FIG. 4, drive motor **M5** has a drive shaft capstan **93** which engages a cable drive loop consisting of Cable **C5**. The cable passes around rear tensioning pulley **83**. The cable passes around idler pulleys **84** and **85** and around drive capstan **90** which forms the proximal end of tubular support member **24**. Thus rotation of actuation of motor **M5** can be used to rotate tubular support member **24** and the end effector it supports.

[0058] Referring to FIG. 6, the cable drive system of instrument **12** is now described in greater detail. Work members **20a** and **20b**, wrist member **22** and the translation of instrument **12** along longitudinal axis C-C are driven by cables **C1**, **C2**, **C3** and **C4** which are arranged in an N+1 actuation scheme. The N+1 actuation scheme allows the actuation of a three degree-of-freedom wrist using four cables. Four cables is the theoretical minimum possible number of tension elements required to drive three degrees-of-freedom and thus allows the instrument to be of minimum size and weight. Alternative actuation schemes using more

cables may be desirable in situations where the forces required for actuation of different motions differ greatly in magnitude. The disadvantage of using more cables is an increase in weight, complexity and minimum size.

[0059] In FIG. 6, the rotational motion of joint **26** about axis C-C is omitted in order to more easily show cables **C1-C4**. Such rotation results only in twisting of the cables **C1-C4** between motors **M1-M4** and pulleys **70**, **72**, **74** and **76**. The cables are however arranged in tubular support member **24** such that this twisting does not significantly change the length of the cable path. Care should however be taken to prevent over-rotation of the instrument which would cause the cables to twist into contact with each other and create friction between the cables.

[0060] As shown in FIG. 6, cables **C1** and **C2** form two sides of a continuous cable loop **44**. Cable **C1** of loop **44** engages a proximal idler pulley **80**, the drive shaft of motor **M1**, intermediate idler pulley **70** and driven capstan **18a**. Cable loop **44** returns from driven capstan **18a** as cable **C2** and engages intermediate idler pulley **76**, the S drive shaft of motor **M2** and proximal idler pulley **80**.

[0061] As shown in FIG. 6, cables **C3** and **C4** form two sides of a continuous loop of cable **46**. Cable **C3** of cable loop **46** engages proximal idler pulley **78**, the drive shaft of motor **M3**, intermediate idler pulley **72** and driven capstan **18b**. Cable loop **46** returns from driven capstan **18b** as cable **C4** and engages intermediate idler pulley **74**, the drive shaft of motor **M4** and proximal idler pulley **78**.

[0062] As shown in FIG. 6, proximal idler pulleys **78** and **80** are tensioned by cables **C7** and **C6** which are fixed to the center of proximal idler pulleys **78** and **80**. Cables **C7** and **C6** form two sides of a single cable **45** which engages proximal idler pulley **82** which is rotatably mounted to support bracket **102** by shaft **82a**. Shaft **82a** is preferably movably mounted to support bracket **102** by a mechanism such as a lead screw. The lead screw may then be adjusted to appropriately tension cables **C7** and **C6**. The tension is also applied via idler pulleys **78** and **80** to cables **C1**, **C2**, **C3** and **C4**. A similar lead screw tensioning scheme can be used to tension cable **C5** by longitudinal movement of idler pulley **83**. It may be required for idler pulleys **82** and **83** to be mounted on separately adjustable shafts for these purpose instead of single shaft **82a** illustrated in FIG. 3.

[0063] Driven capstans **18a** and **18b** may have different diameters in order to allow cables **C1** through **C4** to suitably engage their respective intermediate idler pulleys. Cables **C1** and **C2** engage the outer intermediate idler pulleys **70** and **76** while cables **C3** and **C4** engage the inner intermediate idler pulleys **72** and **74**. Proximal idler pulleys **78** and **80** are sized such that pulley **80** is larger than pulley **78** to keep the cables straight.

[0064] Drive motors **M1**, **M2**, **M3** and **M4** control rotation of wrist member **22** about axis B-B, translation of instrument **12** longitudinally along axis C-C and rotation of work members **22a** and **22b** independent of each other about axis A-A by driving cables **C1**, **C2**, **C3** **C3/C4** driven by drive motors **M3** and **M4** in order to rotate wrist member **22** about axis B-B. Drive motor **M1** drives cable **C1** in opposition to cable **C2** driven by drive motor **M2** to rotate capstan **18a** and attached work member **20a** about axis A-A. In addition, drive motor **M3** drives cable **C3** in opposition to cable **C4**

driven by drive motor M4 to rotate capstan 18b and attached work member 20b about axis A-A. All four drive motors M1, M2, M3 and M4 drive cables C1, C2, C3 and C4 simultaneously to translate instrument 12 along longitudinal axis C-C.

[0065] Locating drive motors M1, M2, M3, M4 and M5 on sliding bracket 96 makes the distal portion 28b of instrument 12 have a small moving mass since the motors themselves remain stationary during actuation of the instrument. Although the motors are moved by positioning mechanism 14, the weight and inertia of the motors do not affect force reflection. This is because, as stated above, in the preferred embodiment, only the instrument is used to reflect forces to the master. In addition, employing cables instead of gears to control instrument 12 minimizes the amount of friction and backlash within instrument 12. The combination of small moving masses and low friction enables instrument 12 to provide force reflection to master device 150 with high sensitivity.

[0066] Certain possible changes to the configuration of pulleys, cables and motors described above will be apparent to those of skill in the art. Although cables C1/C2, C3/C4, C5 and C7/C6 have been depicted to be sides of the same cables, cables C1-C7 alternatively can each be individual cables which are fixed to driven capstans 18a and 18b, and proximal idler pulleys 78, 80 and 82. Moreover, although drive motors M1, M2, M3 and M4 have been depicted to drive cables C1, C2, C3 and C4 respectively, alternatively, some drive motors can be relocated from cables C1-C4 onto cables C7 and C6 for driving cables C7 and C6. The choice of the particular drive scheme employed in a particular embodiment will depend on the constraints of the forces required to be exerted by the instrument and the need to reduce the inertia and friction of the parts of the instrument that move during its actuation.

[0067] The surgical instrument of the present invention has been illustrated as using drive motors M1, M2, M3, M4 and M5. This drive motors may be standard servo motors having position encoders as shown in FIG. 3. However, other actuators may be used, such as hydraulic actuators and piezoelectric motors. To be used as an actuator in the present surgical instrument a drive mechanism should be able to provide variable and controllable force and position control.

[0068] Cables C1, C2, C3, C4, C7, C8 and C9 are driven by being wrapped about the drive shaft of their respective drive motors M1, M2, M3, M4, M5, M6 and M7. This cable drive method and an alternative cable drive method are illustrated in more detail in FIGS. 7a and 7b. For example, in FIG. 7a, cable C4 of cable loop 46 is wrapped around the drive shaft of motor M4. Cable C4 is preferably wrapped two times around the drive shaft to provide enough friction between the cable C4 and the drive shaft to prevent slippage. In order to further prevent slippage the cable may be fixed to the drive shaft at one point by soldering, welding or mechanical fixing means. However, in such an embodiment the range of motion of the cable is limited by the length of cable wrapped around the drive shaft or capstan thus several turns of cable are usually required.

[0069] FIG. 7b depicts another preferred method for driving cables. For example, motor M4 includes a drive wheel 43a and an idler wheel 43b for frictionally driving an elongate member 47 therebetween. Cable C4 consists of two halves, 46a and 46b which are fixed to opposite ends of member 47.

[0070] FIG. 8 depicts the distal end and wrist member 116 of another preferred instrument 117. Instrument 117 differs from instrument 12 in that instrument 117 includes eight intermediate idler pulleys instead of four. Instrument 117 includes intermediate idler pulleys 76, 74, 72 and 70 at wrist joint 16 but also includes intermediate idler pulleys 76a, 74a, 72a and 70a which are positioned adjacent to idler pulleys 76, 74, 72 and 70 on tongue 24a along shaft 118. Cables C1, C2, C3 and C4 do not make a complete wrap around each intermediate idler pulley but instead contacts a variable amount of the surface of each pulley varying in a range between 0° and 180° over the range of motion of the wrist about axis 16. This prevents the cables from crossing each other and rubbing together which prevents friction and noise.

[0071] Although the present invention has been described for performing laparoscopic surgery, it may also be used for other forms of endoscopic surgery as well as open surgery. The present manipulator could also be employed for any suitable remote controlled application requiring a dexterous manipulator with high quality force feedback. Moreover, while this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the spirit and scope of the invention as defined by the appended claims.

What is claimed is:

1. An articulated instrument for minimally invasive surgery, comprising:

- an elongate support member having a proximal portion and a distal end with a longitudinal axis therebetween;
- a pivotal wrist member disposed at the distal end of the elongate support member; and
- a surgical end effector coupled to the wrist member, the end effector including at least one end effector work member, the work member being removably fixed to the wrist member;

said articulated instrument having a size and shape suitable for distal insertion into an internal surgical site through an aperture.

2. The articulated instrument of claim 1, further comprising at least one wrist drive element coupled to the wrist member and adapted for coupling to at least one actuator for pivoting the wrist member about a wrist joint.

3. The articulated instrument of claim 2, wherein the wrist drive element includes a cable.

4. The articulated instrument of claim 1, wherein the at least one end effector work member includes at least a pair of work members pivotally coupled to the wrist member, wherein at least one work member can pivot relative to the other work member of the pair.

5. The articulated instrument of claim 4, further comprising at least one end effector drive element coupled to at least one end effector work member and adapted for coupling to at least one actuator for pivoting the work member relative to the wrist member.

6. The articulated instrument of claim 5, wherein the end effector includes at least one pivotally-mounted capstan coupled to the end effector drive element, and the at least one end effector work member is removably fixed to the capstan.

7. The articulated instrument of claim 6, wherein the end effector drive element includes a cable.

8. The articulated instrument of claim 4, wherein one of said work members is pivotally connected to the other work member, and both work members are pivotally connected to the wrist member.

9. The articulated instrument of claim 1, wherein the at least one end effector work member is removably fixed to the wrist member by at least one of a screw and a clip.

10. The articulated instrument of claim 1, wherein the end effector comprises a gripper, a scissors, a cutter, a graspers, a forceps, a needle holder, a retractor, an electrocautery instrument, a microforceps, a microneedle holder, a dissecting tool, a blade, or an irrigator, or a combination of these.

11. The articulated instrument of claim 1, further comprising at least one substitute member adapted to be removably fixed to the wrist member to replace the at least one end effector work member.

12. The articulated instrument of claim 11, wherein the substitute member is of a different surgical type than the at least one end effector work member.

13. A minimally invasive surgical system including:

an arm having a proximal end portion adapted to be attached to a base so as to permit a distal end portion of the arm to move relative to the base; and

an articulated surgical instrument mounted on the distal end of the arm, the instrument comprising:

an elongate support member having a proximal portion and a distal end with a longitudinal axis therebetween;

a pivotal wrist member disposed at the distal end of the elongate support member; and

at least one surgical end effector work member coupled to the wrist member, the work member being removably fixed to the wrist member;

said instrument having a size and shape suitable for distal insertion into an internal surgical site through an aperture; and

14. The surgical system of claim 13, further comprising a drive system including at least one wrist drive element coupled to the wrist member and adapted for coupling to at least one actuator for pivoting the wrist member about a wrist joint.

15. The surgical system of claim 14, wherein the wrist drive element includes a cable.

16. The surgical system of claim 13, wherein the at least one end effector work member includes at least a pair of work members pivotally coupled to the wrist member, wherein at least one work member can pivot relative to the other work member of the pair.

17. The surgical system of claim 16, further comprising at least one end effector drive element coupled to at least one end effector work member and adapted for coupling to at least one actuator for pivoting the work member relative to the wrist member.

18. The surgical system of claim 17, wherein the end effector includes at least one pivotally-mounted capstan coupled to the end effector drive element, and the at least one end effector work member is removably fixed to the capstan.

19. The surgical system of claim 18, wherein the end effector drive element includes a cable.

20. The surgical system of claim 16, wherein one of said work members is pivotally connected to the other work member, and both work members are pivotally connected to the wrist member.

21. The surgical system of claim 13, wherein the at least one end effector work member is removably fixed to the wrist member by at least one of a screw and a clip.

22. The surgical system of claim 13, wherein the end effector comprises a gripper, a scissors, a cutter, a graspers, a forceps, a needle holder, a retractor, an electrocautery instrument, a microforceps, a microneedle holder, a dissecting tool, a blade or an irrigator, or a combination of these.

23. The surgical system of claim 13, further comprising at least one substitute member adapted to be removably fixed to the wrist member to replace the at least one end effector work member.

24. The articulated instrument of claim 13, wherein the substitute member is of a different surgical type than the at least one end effector work member.

25. A method for minimally invasive surgery in a patient, comprising:

(a) providing an articulated surgical instrument including:

an elongate support member having a proximal portion and a distal end with a longitudinal axis therebetween;

a pivotal wrist member disposed at the distal end of the elongate support member; and

a surgical end effector coupled to the wrist member, the end effector including at least one end effector work member, the work member being removably fixed to the wrist member;

said articulated instrument having a size and shape suitable for distal insertion into an internal surgical site through an aperture.

(b) inserting a distal portion of the surgical instrument through an aperture in a patient's body to a location adjacent a surgical worksite, the distal portion including at least the wrist member and the end effector;

(c) performing a surgical treatment using the at least one end effector work member;

(d) removing the at least one end effector work member from the wrist member;

(e) providing a substitute member;

(f) replacing the at least one end effector work member by removably fixing the substitute member to the wrist member; and

(g) performing a surgical treatment using the substitute member.

26. The method of claim 25, further comprising the steps of:

(h) prior to the removing step (d), retracting the distal portion from the aperture in the patient's body; and

(i) following the replacing step (f), inserting the distal portion of the surgical instrument through an aperture in a patient's body to a location adjacent a surgical worksite.

27. The method of claim 25, further comprising the step of:

(j) moving the wrist member to position the end effector for surgical treatment.

28. The method of claim 27, wherein:

the articulated instrument provided in step (a) further includes at least one wrist drive element coupled to the wrist member and adapted for coupling to at least one actuator for pivoting the wrist member about a wrist joint; and

the moving step (j) includes actuating the wrist drive element to move the wrist member.

29. The method of claim 28, wherein the wrist drive element includes a cable.

30. The method of claim 25, wherein:

the articulated instrument provided in step (a) further includes at least one end effector drive element coupled to at least one end effector work member and adapted for coupling to at least one actuator for pivoting the work member relative to the wrist member; and

at least one of the treatment performing steps (c) and (g) includes actuating the end effector drive element to pivot the at least one end effector work member.

31. The method of claim 30, wherein the end effector includes at least one pivotally-mounted capstan coupled to the end effector drive element, and the at least one end effector work member is removably fixed to the capstan.

32. The method of claim 31, wherein the end effector drive element includes a cable.

33. The method of claim 25, wherein the at least one end effector work member of the articulated instrument provided in step (a) is removably fixed to the wrist member by at least one of a screw and a clip.

34. The method of claim 25, wherein the end effector of the articulated instrument provided in step (a) comprises a gripper, a scissors, a cutter, a graspers, a forceps, a needle holder, a retractor, an electrocautery instrument, a microforceps, a microneedle holder, a dissecting tool, a blade or an irrigator, or a combination of these.

35. The method of claim 25, wherein the substitute member provided in step (e) is a different surgical instrument type than the at least one end effector work member provided in step (a).

36. A minimally invasive surgical system comprising:

a base adapted to be fixed relative to a patient's body;

an instrument positioning mechanism;

an articulated surgical instrument assembly; and

an instrument drive system;

the instrument positioning mechanism including:

a support linkage having a proximal end and a distal end, the proximal end being coupled the base and the distal end being coupled to the articulated surgical instrument assembly;

a positioning drive system configured to move the distal end of the support linkage so as to move the articulated surgical instrument assembly in a plurality of degrees of freedom relative to the base;

the articulated surgical instrument assembly including:

a proximal portion and a distal portion, and an elongate support assembly having a proximal end and a distal end with a longitudinal axis therebetween;

a pivotal wrist joint disposed adjacent the distal end of the elongate support assembly, and

a surgical end effector including a first end effector element coupled to the wrist joint by a first pivotal end effector joint;

the proximal portion of the articulated surgical instrument assembly being adapted to releasably couple to the distal end of the instrument positioning mechanism;

the distal portion of the articulated surgical instrument assembly having a size and shape suitable for insertion through an aperture in the patient's body to extent to an internal surgical site; and

the instrument drive system including:

a plurality of actuators disposed adjacent the distal end of the positioning mechanism;

a plurality of elongate drive elements extending longitudinally from the plurality of actuators to operatively couple to a corresponding plurality of pivotal joints adjacent the distal portion of the articulated surgical instrument assembly;

the plurality of pivotal joints including at least the pivotal wrist joint and the first pivotal end effector joint;

the instrument drive system being configured to move the first end effector element in a plurality of degrees of freedom relative to the distal end of the positioning mechanism.

37. The surgical system of claim 36, wherein the positioning mechanism further comprises a linear bearing coupling the articulated surgical instrument assembly to the distal end of the support linkage, to permit axial translation of the articulated surgical instrument assembly relative to the base.

38. The surgical system of claim 36, wherein the cable elements are configured to hold the plurality of pivotal joints at fixed angles when the actuators do not move the cable elements and the articulated surgical instrument assembly is translated axially.

39. The surgical system of claim 36, wherein the elongate elements comprise cable elements including at least one portion of cable.

40. The surgical system of claim 39, wherein the cable elements are configured to twist within the elongate support assembly so that the distal portion of the articulated surgical instrument assembly can rotate about the axis relative to the positioning mechanism and the actuators.

41. The surgical system of claim 39, wherein at least one of the plurality of cable element comprises a continuous loop.

42. The surgical system of claim 39, wherein the positioning mechanism is configured to cause the articulated surgical instrument assembly to pivot about at least a first axis relative to the base.

43. The surgical system of claim 36, wherein the instrument drive system includes a rotational connection arranged to permit the elongate support assembly to rotate about the longitudinally axis.

44. The surgical system of claim 36, wherein the articulated surgical instrument assembly further includes a second end effector element coupled to the wrist joint by a second pivotal end effector joint so that the first and second end effector elements can manipulate tissues at the worksite therebetween.

45. The surgical system of claim 36, wherein the end effector joints pivot about a common end effector axis, and wherein the instrument drive system can move the first and second end effector elements independently.

46. The surgical system of claim 36, wherein at least one actuator of the instrument drive system includes a rounded drive capstan engaging at least one of the plurality of elongate drive elements, so as to cause the elongate drive element to move when the capstan is rotated so as to cause

the rotation of at least one of the plurality of rotary joints of the articulated surgical instrument assembly.

47. The surgical system of claim 46, wherein the elongate drive element comprises a cable element including at least one portion of cable.

48. The surgical system of claim 47, wherein the cable element comprises a continuous loop.

49. The surgical system of claim 36, wherein at least one of the plurality of elongate drive elements engages an idler pulley, so as to guide the elongate element intermediate the corresponding actuator and corresponding rotary joint.

50. The surgical system of claim 36, wherein at least one of the pivotal wrist joint and the first pivotal end effector joint includes a driven capstan portion, the driven capstan portion engaging at least one of the plurality of elongate drive elements, so as to cause the pivotal joint to rotate in response to movement of the elongate drive element.

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专利名称(译)	用于执行微创手术的铰接式手术器械，具有增强的灵活性和灵敏度		
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摘要(译)

一种用于增强微创外科手术的性能的铰接式外科手术器械。该仪器具有高灵活性，低摩擦，低惯性和良好的力反射。独特的电缆和滑轮驱动系统可以减少摩擦并增强力反射。与标准腹腔镜器械相比，独特的腕部机构可提高手术灵活性。该系统经过优化，可减少所需的执行器数量，从而生产出最小尺寸的全功能铰接式手术器械。

