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(54) **MECHANICAL MANIPULATOR FOR SURGICAL INSTRUMENTS**

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(Continued)

(56) **References Cited**

U.S. PATENT DOCUMENTS

2,764,301 A * 9/1956 Goertz B25J 3/00
414/7
2,771,199 A * 11/1956 Jelatis B25J 3/00
414/1
(Continued)

FOREIGN PATENT DOCUMENTS

CN 101584594 A 11/2009
CN 101637402 A 2/2010
(Continued)

OTHER PUBLICATIONS

International Search Report PCT/ISA/210 for International Application No. PCT/IB2011/054476 dated Mar. 19, 2012.
(Continued)

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(57) **ABSTRACT**

A novel mechanical system, based on a new cable driven mechanical transmission, able to provide sufficient dexterity, stiffness, speed, precision and payload capacity to actuate multi-DOF micro-manipulators. Besides the possibility of being used in several articulated surgical instruments and robotic systems for surgery or other applications involving remote manipulation, it enables the design of a novel fully mechanical surgical instrument, which offer the advantages of conventional laparoscopy (low cost, tactile feedback, high payload capacity) combined with the advantages of single port surgery (single incision, scarless surgery, navigation through several quadrants of the abdominal cavity) and
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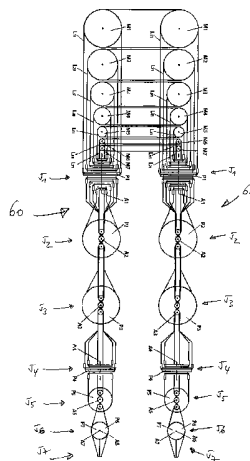
robotic surgery (greater degrees of freedom, short learning curve, high stiffness, high precision, increased intuition). The unique design of the proposed system provides an intuitive user interface to achieve such enhanced maneuverability, allowing each joint of a teleoperated slave system to be driven by controlling the position of a mechanically connected master unit.

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(56) **References Cited**

U.S. PATENT DOCUMENTS

2,774,488	A	*	12/1956	Goertz B25J 3/00
				414/7
2,846,084	A		8/1958	Goertz et al.
3,065,863	A	*	11/1962	Saunders, Jr. B25J 3/00
				414/2
3,095,096	A	*	6/1963	Chesley B25J 3/00
				414/7
3,212,651	A	*	10/1965	Specht B25J 3/00
				414/7
3,261,480	A	*	7/1966	Haaker B25J 3/00
				414/7
3,297,172	A	*	1/1967	Haaker B25J 3/00
				414/2
3,391,801	A	*	7/1968	Haaker B25J 3/00
				414/1
3,425,569	A	*	2/1969	Haaker B25J 3/00
				414/7
4,221,516	A	*	9/1980	Haaker B25J 3/00
				414/5
4,756,655	A		7/1988	Jameson
5,147,357	A		9/1992	Rose et al.
5,207,114	A		5/1993	Salisbury et al.
5,209,747	A		5/1993	Knoepfler
5,304,203	A		4/1994	El-Mallawany et al.
5,308,358	A		5/1994	Bond et al.
5,330,502	A		7/1994	Hassler et al.
5,368,606	A		11/1994	Marlow et al.
5,383,888	A		1/1995	Zvenyatsky et al.
5,484,435	A		1/1996	Fleenor et al.
5,599,151	A		2/1997	Daum et al.
5,603,723	A		2/1997	Aranyi et al.
5,631,973	A	*	5/1997	Green H04N 13/0497
				382/128
5,649,956	A		7/1997	Jensen et al.
5,710,870	A		1/1998	Ohm et al.
5,716,352	A		2/1998	Viola et al.
5,735,874	A		4/1998	Measamer et al.
5,784,542	A	*	7/1998	Ohm B25J 3/04
				700/247
5,797,900	A		8/1998	Madhani et al.
5,810,716	A		9/1998	Mukherjee et al.
5,810,805	A		9/1998	Sutcu et al.
5,828,813	A	*	10/1998	Ohm B25J 3/04
				700/260
5,908,436	A		6/1999	Cuschieri et al.
5,951,587	A		9/1999	Qureshi et al.
6,026,701	A		2/2000	Reboulet
6,197,017	B1		3/2001	Brock et al.
6,206,903	B1		3/2001	Ramans
6,233,504	B1		5/2001	Das et al.
6,281,651	B1	*	8/2001	Haanpaa B25J 9/1689
				318/568.11
6,358,249	B1		3/2002	Chen et al.
6,361,534	B1		3/2002	Chen et al.
6,364,879	B1		4/2002	Chen et al.
6,371,952	B1		4/2002	Madhani et al.
6,394,998	B1		5/2002	Wallace et al.
6,435,794	B1	*	8/2002	Springer B25J 3/04
				340/407.1
6,554,844	B2		4/2003	Lee et al.
6,786,896	B1		9/2004	Madhani et al.
6,788,999	B2	*	9/2004	Green B25J 3/04
				348/E13.014
6,850,817	B1	*	2/2005	Green A61B 1/00193
				348/E13.014
6,852,107	B2	*	2/2005	Wang A61B 19/22
				600/102
6,902,560	B1		6/2005	Morley et al.
6,951,535	B2	*	10/2005	Ghodoussi A61B 34/75
				600/101
6,991,627	B2		1/2006	Madhani et al.
6,994,708	B2		2/2006	Manzo
7,090,637	B2		8/2006	Danitz et al.
7,101,363	B2		9/2006	Nishizawa et al.
7,204,836	B2		4/2007	Wagner et al.
7,232,440	B2		6/2007	Dumbauld et al.
7,306,597	B2		12/2007	Manzo
7,316,681	B2		1/2008	Madhani et al.
7,338,513	B2		3/2008	Lee et al.
7,364,582	B2		4/2008	Lee
7,398,707	B2		7/2008	Morley et al.
7,481,824	B2		1/2009	Boudreaux et al.
7,608,039	B1		10/2009	Todd
7,615,002	B2		11/2009	Rothweiler et al.
7,615,067	B2		11/2009	Lee et al.
7,674,255	B2		3/2010	Braun
7,699,855	B2		4/2010	Anderson et al.
7,819,894	B2		10/2010	Mitsuishi et al.
7,824,401	B2		11/2010	Manzo et al.
7,828,798	B2		11/2010	Buysse et al.
7,976,458	B2		7/2011	Stefanchik et al.
8,048,084	B2		11/2011	Schneid
8,105,320	B2		1/2012	Manzo
8,114,017	B2		2/2012	Bacher
8,137,263	B2		3/2012	Marescaux et al.
8,224,485	B2		7/2012	Unsworth
8,287,469	B2		10/2012	Stefanchik et al.
8,292,889	B2		10/2012	Cunningham et al.
8,306,656	B1		11/2012	Schaible et al.
8,308,738	B2		11/2012	Nobis et al.
8,332,072	B1		12/2012	Schaible et al.
8,336,751	B2		12/2012	Scirica
8,347,754	B1		1/2013	Veltri et al.
8,353,898	B2		1/2013	Lutze et al.
8,357,161	B2		1/2013	Mueller
8,382,742	B2		2/2013	Hermann et al.
8,403,832	B2		3/2013	Cunningham et al.
8,418,904	B2		4/2013	Wenchell et al.
8,496,152	B2		7/2013	Viola
8,523,900	B2		9/2013	Jinno et al.
8,540,748	B2		9/2013	Murphy et al.
8,562,592	B2		10/2013	Conlon et al.
8,568,444	B2		10/2013	Cunningham
8,579,176	B2		11/2013	Smith et al.
8,591,397	B2		11/2013	Berkelman et al.
8,603,077	B2		12/2013	Cooper et al.
8,617,203	B2		12/2013	Stefanchik et al.
8,663,270	B2		3/2014	Donnigan et al.
8,668,689	B2		3/2014	Dumbauld et al.
8,668,702	B2		3/2014	Awtar et al.
8,696,666	B2		4/2014	Sanai et al.
8,709,000	B2		4/2014	Madhani et al.
8,768,509	B2		7/2014	Unsworth

(56)   **References Cited**

U.S. PATENT DOCUMENTS

8,792,688 B2	7/2014	Unsworth
8,801,752 B2	8/2014	Fortier et al.
8,818,560 B2	8/2014	Kishi
8,821,480 B2	9/2014	Burbank
8,828,046 B2	9/2014	Stefanchik et al.
8,845,517 B2	9/2014	Russo
8,845,622 B2	9/2014	Paik et al.
8,870,867 B2	10/2014	Walberg et al.
8,887,979 B2	11/2014	Mastri et al.
8,894,674 B2	11/2014	Balanev et al.
8,930,027 B2	1/2015	Schaible et al.
8,945,098 B2	2/2015	Seibold et al.
8,961,499 B2	2/2015	Paik et al.
8,961,514 B2	2/2015	Garrison
8,968,187 B2	3/2015	Kleyman et al.
8,989,844 B2	3/2015	Cinquin et al.
8,992,564 B2	3/2015	Jaspers
9,023,015 B2	5/2015	Penna
9,033,998 B1	5/2015	Schaible et al.
9,044,238 B2	6/2015	Orszulak
9,084,606 B2	7/2015	Greep
9,113,861 B2	8/2015	Martin et al.
9,149,339 B2	10/2015	Unsworth
9,307,894 B2	4/2016	Von Grunberg et al.
9,480,531 B2	11/2016	Von Grunberg
9,696,700 B2	7/2017	Beira et al.
2002/0040217 A1	4/2002	Jinno
2002/0049367 A1	4/2002	Irion et al.
2002/0072736 A1	6/2002	Tierney et al.
2003/0155747 A1	8/2003	Bridges
2003/0208186 A1	11/2003	Moreyra
2004/0049205 A1	3/2004	Lee et al.
2004/0116906 A1	6/2004	Lipow
2004/0236316 A1	11/2004	Danitz et al.
2004/0253079 A1	12/2004	Sanchez
2005/0096502 A1	5/2005	Khalili
2005/0204851 A1	9/2005	Morley et al.
2005/0240078 A1	10/2005	Kwon et al.
2006/0043698 A1	3/2006	Bridges
2006/0178559 A1	8/2006	Kumar et al.
2006/0183975 A1	8/2006	Saadat et al.
2006/0219065 A1	10/2006	Jinno et al.
2006/0235436 A1	10/2006	Anderson et al.
2006/0253109 A1	11/2006	Chu
2007/0088340 A1	4/2007	Brock et al.
2007/0137371 A1	6/2007	Devengenzo et al.
2007/0156123 A1	7/2007	Moll et al.
2007/0208375 A1	9/2007	Nishizawa et al.
2007/0299387 A1	12/2007	Williams et al.
2008/0046122 A1	2/2008	Manzo et al.
2008/0058776 A1	3/2008	Jo et al.
2008/0071208 A1	3/2008	Voegele et al.
2008/0103492 A1	5/2008	Morley et al.
2008/0177285 A1*	7/2008	Brock A61B 17/0483
		606/130
2008/0314181 A1	12/2008	Schena
2009/0036902 A1*	2/2009	DiMaio A61B 8/12
		606/130
2009/0198253 A1	8/2009	Omori
2009/0216249 A1	8/2009	Jinno et al.
2009/0247821 A1	10/2009	Rogers
2009/0248039 A1	10/2009	Cooper et al.
2009/0299141 A1	12/2009	Downey et al.
2010/0004508 A1	1/2010	Naito et al.
2010/0011900 A1	1/2010	Burbank
2010/0023025 A1	1/2010	Zeiner et al.
2010/0121347 A1	5/2010	Jaspers
2010/0160929 A1	6/2010	Rogers et al.
2010/0160940 A1	6/2010	Lutze et al.
2010/0170519 A1	7/2010	Romo et al.
2010/0305595 A1	12/2010	Hermann
2010/0318099 A1*	12/2010	Itkowitz A61B 19/2203
		606/130
2010/0318101 A1	12/2010	Choi
2011/0087236 A1	4/2011	Stokes et al.

2011/0213346 A1	9/2011	Morley et al.
2011/0230867 A1	9/2011	Hirschfeld et al.
2011/0275901 A1	11/2011	Shelton, IV
2011/0276084 A1	11/2011	Shelton, IV
2011/0290854 A1	12/2011	Timm et al.
2011/0301419 A1	12/2011	Craft et al.
2012/0027762 A1	2/2012	Schofield
2012/0031114 A1	2/2012	Mueller et al.
2012/0095298 A1	4/2012	Stefanchik et al.
2012/0116163 A1	5/2012	Lutze et al.
2012/0132018 A1	5/2012	Tang et al.
2012/0143173 A1	6/2012	Steege et al.
2012/0158014 A1	6/2012	Stefanchik et al.
2012/0209292 A1	8/2012	Devengenzo et al.
2012/0253326 A1	10/2012	Kleyman
2012/0277762 A1	11/2012	Lathrop et al.
2012/0289973 A1	11/2012	Prisco et al.
2012/0289974 A1	11/2012	Rogers et al.
2012/0296341 A1	11/2012	Seibold et al.
2013/0123805 A1	5/2013	Park et al.
2013/0144274 A1	6/2013	Stefanchik et al.
2013/0245643 A1	9/2013	Woodard et al.
2013/0245647 A1	9/2013	Martin et al.
2013/0282027 A1	10/2013	Woodard et al.
2013/0304083 A1	11/2013	Kaercher et al.
2013/0304084 A1	11/2013	Beira et al.
2014/0005681 A1	1/2014	Gee et al.
2014/0018447 A1	1/2014	McGovern et al.
2014/0018780 A1	1/2014	Hirscheld
2014/0076088 A1	3/2014	Berkelman et al.
2014/0114481 A1	4/2014	Ogawa et al.
2014/0142595 A1	5/2014	Awtar et al.
2014/0166023 A1	6/2014	Kishi
2014/0180308 A1	6/2014	Von Grunberg
2014/0188091 A1	7/2014	Vidal et al.
2014/0188159 A1	7/2014	Steege
2014/0195010 A1*	7/2014	Beira A61B 17/00234
		700/3
2014/0200561 A1	7/2014	Ingmanson et al.
2014/0207150 A1	7/2014	Rosa et al.
2014/0230595 A1	8/2014	Butt et al.
2014/0249546 A1	9/2014	Shvartsberg et al.
2014/0263541 A1	9/2014	Leimbach et al.
2014/0263553 A1	9/2014	Leimbach et al.
2014/0276956 A1	9/2014	Crainich et al.
2014/0350570 A1	11/2014	Lee
2015/0057499 A1	2/2015	Erden et al.
2015/0057702 A1	2/2015	Edmondson et al.
2015/0060517 A1	3/2015	Williams
2015/0066018 A1	3/2015	Doll et al.
2015/0105821 A1	4/2015	Ward et al.
2015/0142018 A1	5/2015	Sniffin et al.
2015/0150575 A1	6/2015	Hartoumbekis et al.
2015/0250547 A1	9/2015	Fukushima et al.
2015/0265355 A1	9/2015	Prestel et al.
2016/0022365 A1	1/2016	Jensen et al.
2016/0051274 A1	2/2016	Howell et al.
2016/0151115 A1	6/2016	Karguth et al.
2016/0346053 A1	12/2016	Beira et al.
2016/0374766 A1	12/2016	Schuh

FOREIGN PATENT DOCUMENTS

CN	101732093 A	6/2010
CN	103717355 A	4/2014
DE	43 03 311 A1	8/1994
DE	19652792 C2	5/1999
DE	10314827 B3	4/2004
DE	10314828 B3	7/2004
DE	10 2012 222 755	6/2014
DE	10 2014 205 036 A1	9/2015
DE	10 2014 205 159 A1	9/2015
EP	0 595 291 A1	5/1994
EP	0 621 009 A1	10/1994
EP	0 677 275 A2	10/1995
EP	0677275 A2	10/1995
EP	0 776 739 A2	6/1997
EP	1 254 642 A1	11/2002
EP	1 279 371 B1	12/2004

(56) **References Cited**

FOREIGN PATENT DOCUMENTS

EP	1 886 630 A2	2/2008
EP	1 889 579 A2	2/2008
EP	2 058 090 A2	5/2009
EP	1 977 677	8/2009
EP	2 095 778 A1	9/2009
EP	1 889 583	4/2011
EP	2 377 477 B1	5/2012
EP	2 473 119 B1	7/2012
EP	2 044 893 B1	7/2013
EP	2 305 144 B1	10/2013
EP	2 653 110 A1	10/2013
EP	2 679 192 A2	1/2014
EP	2 736 680 B1	6/2014
EP	2 777 561 A1	9/2014
EP	2 837 340 A1	2/2015
EP	2 837 354 A1	2/2015
EP	2 554 131 B1	8/2015
GB	0 969 899 A	9/1964
JP	2004-041580 A	2/2004
JP	2007-290096 A	11/2007
JP	2008-104620 A	5/2008
JP	2009-018027 A	1/2009
KR	20110032444 A	3/2011
KR	20130031403 A	3/2013
SU	722754 A1	3/1980
WO	WO-82/00611 A1	3/1982
WO	WO-97/43942 A1	11/1997
WO	WO-98/25666 A1	6/1998
WO	WO-03/067341 A2	8/2003
WO	WO-03/086219 A2	10/2003
WO	WO-2004/052171 A2	6/2004
WO	WO-2005/009482 A2	2/2005
WO	WO-2005/046500 A1	5/2005
WO	WO-2006/086663 A2	4/2006
WO	WO-2007/133065 A1	11/2007
WO	WO-2008/130235 A2	10/2008
WO	WO-2009/091497 A2	7/2009
WO	WO-2009/095893 A2	8/2009
WO	WO-2009/145572 A2	12/2009
WO	WO-2009/157719 A2	12/2009
WO	WO-2010/019001 A2	2/2010
WO	WO-2010/030114 A2	3/2010
WO	WO-2010/050771 A2	5/2010
WO	WO-2010/083480 A2	7/2010
WO	WO-2010/096580 A1	8/2010
WO	WO-2010/130817 A1	11/2010
WO	WO-2012/020386 A1	2/2012
WO	WO-2012/049623 A1	4/2012
WO	WO-2013/007784 A1	1/2013
WO	WO-2013/014621 A2	1/2013
WO	WO-2014/012780 A1	1/2014
WO	WO-2014/018447 A1	1/2014
WO	WO-2014/067804 A1	5/2014
WO	WO-2014/094716 A1	6/2014
WO	WO-2014/094717 A1	6/2014
WO	WO-2014/094718 A1	6/2014
WO	WO-2014/094719 A1	6/2014
WO	WO-2014/145148 A1	9/2014
WO	WO-2014/156221 A1	10/2014
WO	WO-2014/201010 A1	12/2014
WO	WO-2014/201538 A1	12/2014
WO	WO-2015/081946 A1	6/2015
WO	WO-2015/081947 A1	6/2015
WO	WO-2015/088647 A1	6/2015
WO	WO-2015/088655 A1	6/2015
WO	WO-2015/111475 A1	7/2015
WO	WO-2015/113933 A1	8/2015
WO	WO-2015/129383 A1	9/2015
WO	WO-2015/139674 A1	9/2015
WO	WO-2016/030767 A9	3/2016
WO	WO-2016/083189 A1	6/2016
WO	WO-2016/097861 A1	6/2016
WO	WO-2016/097864 A2	6/2016
WO	WO-2016/097868 A1	6/2016
WO	WO-2016/097871 A1	6/2016
WO	WO-2016/097873 A2	6/2016
WO	WO-2016/162751 A1	10/2016
WO	WO-2016/162752 A1	10/2016
WO	WO-2016/189284 A1	12/2016
WO	WO-2017/037532 A1	3/2017
WO	WO-2017/064301 A1	4/2017
WO	WO-2017/064303 A1	4/2017
WO	WO-2017/064305 A1	4/2017
WO	WO-2017/064306 A1	4/2017

OTHER PUBLICATIONS

Abbott, et al., "Design of an Endoluminal Notes Robotic System," IEEE/RSJ International Conference on Intelligent Robots and Systems, San Diego, CA, pp. 410-416 (2007).

Arata, et al., "Development of a dexterous minimally-invasive surgical system with augmented force feedback capability," IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 3207-3212 (2005).

Çavuşoğlu, et al., "Laparoscopic Telesurgical Workstation," IEEE Transactions on Robotics and Automation,(15)4:728-739 (1999).

Charles, et al., "Dexterity-enhanced Telerobotic Microsurgery," 8th International Conference Advanced Robotics, pp. 5-10 (1997).

Dachs, et al., "Novel Surgical Robot Field," 28th International Conference, Design: Minimizing the Operating Envelope Within the Sterile IEEE Engineering in Medicine Biology Society, New York, pp. 1505-1508 (2006).

Dario, et al., "Novel Mechatronic Tool for Computer-Assisted Arthroscopy," IEEE Transactions on Information Technology in Biomedicine, 4(1):15-29 (Mar. 2000).

Focacci, et al., "Lightweight Hand-held Robot for Laparoscopic Surgery," IEEE International Conference on Robotics & Automation, Rome, Italy, pp. 599-604 (2007).

Guthart, et al., "The Intuitive™ Telesurgery System: Overview and Application," IEEE International Conference on Robotics & Automation, San Francisco, CA, pp. 618-621 (2000).

Ikuta, et al., "Development of Remote Microsurgery Robot and New Surgical Procedure for Deep and Narrow Space," IEEE International Conference on Robotics & Automation, Taipei, Taiwan, pp. 1103-1108 (2003).

Ikuta, et al., "Hyper Redundant Miniature Manipulator 'Hyper Finger' for Remote Minimally Invasive Surgery in Deep Area," IEEE International Conference on Robotics & Automation, Taipei, Taiwan, pp. 1098-1102 (2003).

International Search Report & Written Opinion dated Jan. 18, 2013 in Int'l PCT Patent Appl Serial No. PCT/IB2012/053786.

International Search Report dated Mar. 23, 2012 in Int'l PCT Patent Appl Serial No. PCT/IB2011/054476.

Ishii, et al., "Development of a New Bending Mechanism and Its Application to Robotic Forceps Manipulator," IEEE International Conference on Robotics & Automation, Rome, Italy, pp. 238-243 (2007).

ISR & Written Opinion dated Feb. 17, 2016 in Int'l PCT Patent Appl Serial No. PCT/IB2015/002095.

ISR & Written Opinion dated May 23, 2016 in Int'l PCT Patent Appl Serial No. PCT/IB2015/002524.

ISR & Written Opinion dated Mar. 30, 2015 in Int'l PCT Patent Appl Serial No. PCT/EP2015/051473.

ISR & Written Opinion dated Apr. 26, 2016 in Int'l PCT Patent Appl Serial No. PCT/IB2015/002512.

ISR & Written Opinion dated May 24, 2016 in Int'l PCT Patent Appl Serial No. PCT/IB2015/002487.

ISR & Written Opinion dated Jun. 10, 2016 in Int'l PCT Patent Appl Serial No. PCT/IB2015/002533.

ISR & Written Opinion dated Jun. 13, 2016 in Int'l PCT Patent Appl Serial No. PCT/IB2015/002493.

ISR & Written Opinion dated Aug. 25, 2016 in Int'l PCT Patent Appl Serial No. PCT/IB2016/000542.

ISR & Written Opinion dated Sep. 2, 2016 in Int'l PCT Patent Appl Serial No. PCT/IB2016/000543.

ISR & Written Opinion dated Feb. 2, 2017 in Int'l PCT Patent Appl Serial No. PCT/IB2016/001286.

(56)   **References Cited**

OTHER PUBLICATIONS

Kobayashi, et al., "Small Occupancy Robotic Mechanisms for Endoscopic Surgery," International Conference on Medical Image Computing and Computer assisted Interventions, pp. 75-82 (2002).
Lang, et al., Intra-operative robotics: NeuroArm., Acta Neurochir Suppl, 109:231-236 (2011).
Mayer, et al., "The Endo[PA]R System for Minimally Invasive Robotic Surgery," IEEE/RSJ International Conference on Intelligent Robots and Systems, Sendai, Japan, pp. 3637-3642 (2004).
Mitsuishi, et al., "Development of a Remote Minimally Invasive Surgical System with Operational Environment Transmission Capability," IEEE International Conference on Robotics & Automation, Taipei, Taiwan, pp. 2663-2670 (2003).
Mitsuishi, et al., Master-slave robotic platform and its feasibility study for micro-neurosurgery, Int. J. Med. Robot., 9(2):180-9 (2013).
Morita, et al., Microsurgical robotic system for the deep surgical field: development of a prototype and feasibility studies in animal and cadaveric models, J. Neurosurg., 103(2):320-7 (2005).
Nakamura, et al., "Multi-DOF Forceps Manipulator System for Laparoscopic Surgery-Mechanism miniaturized & Evaluation of New Interface," 4th International Conference on Medical Image Computing and Computer assisted Interventions (MICCAI2001), pp. 606-613 (2001).
Peirs, et al., "Design of an advanced tool guiding system for robotic surgery," IEEE International Conference on Robotics & Automation, Taipei, Taiwan, pp. 2651-2656 (2003).
Sallé, et al., "Optimal Design of High Dexterity Modular MIS Instrument for Coronary Artery Bypass Grafting," IEEE International Conference on Robotics & Automation, New Orleans, LA, pp. 1276-1281 (2004).
Seibold, et al., "Prototype of Instrument for Minimally Invasive Surgery with 6-Axis Force Sensing Capability," IEEE International Conference on Robotics & Automation, Barcelona, Spain, pp. 496-501 (2005).
Simaan et al., "Dexterous System for Laryngeal Surgery: Multi-Backbone Bending Snake-like Slaves for Teleoperated Dexterous Surgical Tool Manipulation," IEEE International Conference on Robotics & Automation, New Orleans, LA, pp. 351-357 (2004).
Swiss Search Report dated Jun. 4, 2012 in Swiss Patent Application No. CH 00702/12.
Tavakoli, et al., "Force Reflective Master-Slave System for Minimally Invasive Surgery," IEEE/RSJ International Conference on Intelligent Robots and Systems, Las Vegas, NV, pp. 3077-3082 (2003).
Taylor, et al., "Steady-Hand Robotic System for Microsurgical Augmentation," The International Journal of Robotics Research, 18(12):1201-1210 (1999).
Yamashita, et al., "Development of Endoscopic Forceps Manipulator Using Multi-Slider Linkage Mechanisms," The 1st Asian Symposium on Computer Aided Surgery—Robotic and Image-Guided Surgery, Ibaraki, Japan, 4 pages (2005).
Zeus, "Robotic Surgical System" available at http://allaboutroboticsurgery.com/zeusrobot.html.
Aesculap Surgical Technologies, Aesculap® Caiman®, Advanced Bipolar Seal and Cut Technology Brochure, 6 pages (retrieved Aug. 31, 2015).
International Search Report & Written Opinion dated Feb. 2, 2017 in Int'l PCT Patent Appl. Serial No. PCT/IB2016/001286.
Stryker®, Endoscopy, Take a Look Around, Ideal Eyes™ HD, Articulating Laparoscope Brochure, 2 pages (2009).
www.cttc.co/technologies/maestro-non-robotic-dexterous-laproscopic-instrument-writs-providing-seven-degrees, "Maestro: Non-Robotic Dexterous Laproscopic Instrument With a Wrist Providing Seven Degrees of Freedom", accessed Nov. 12, 2015, 4 pages.
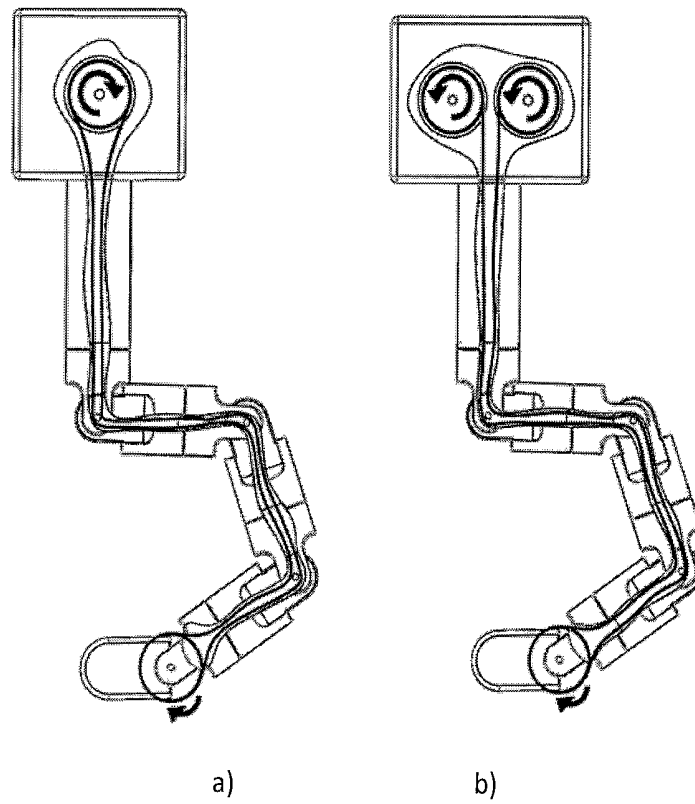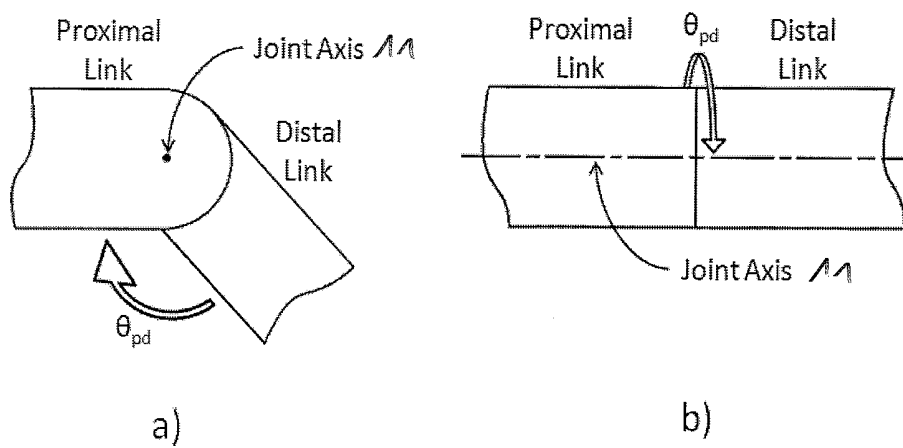
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a)   b)
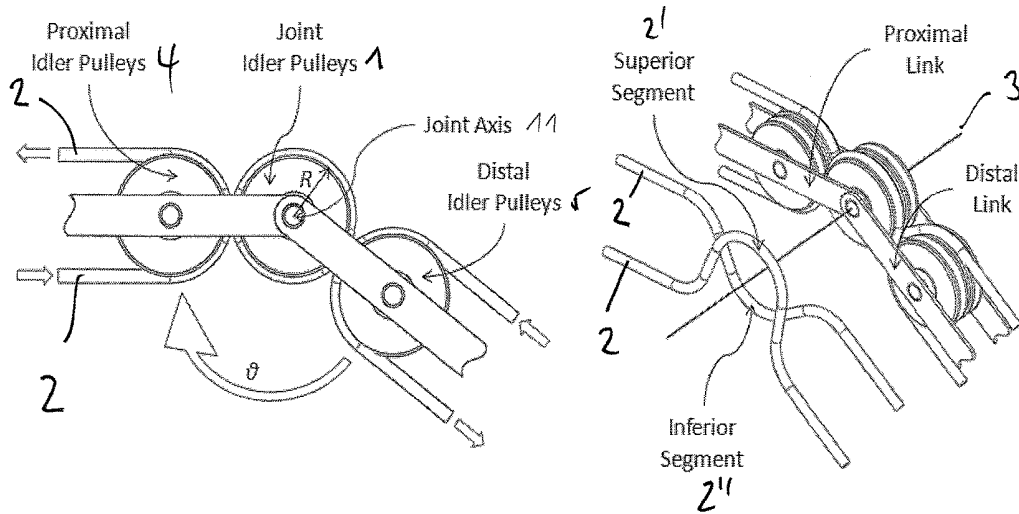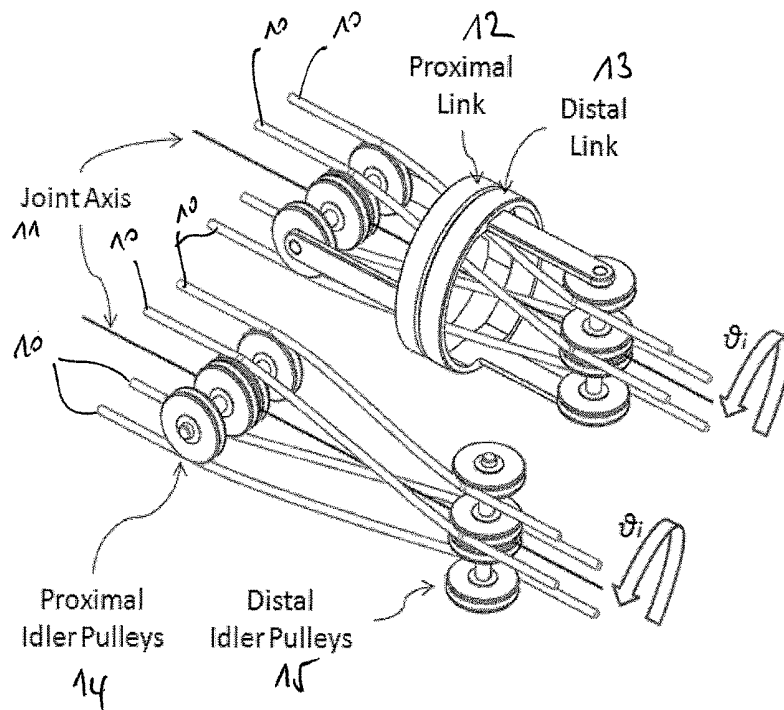
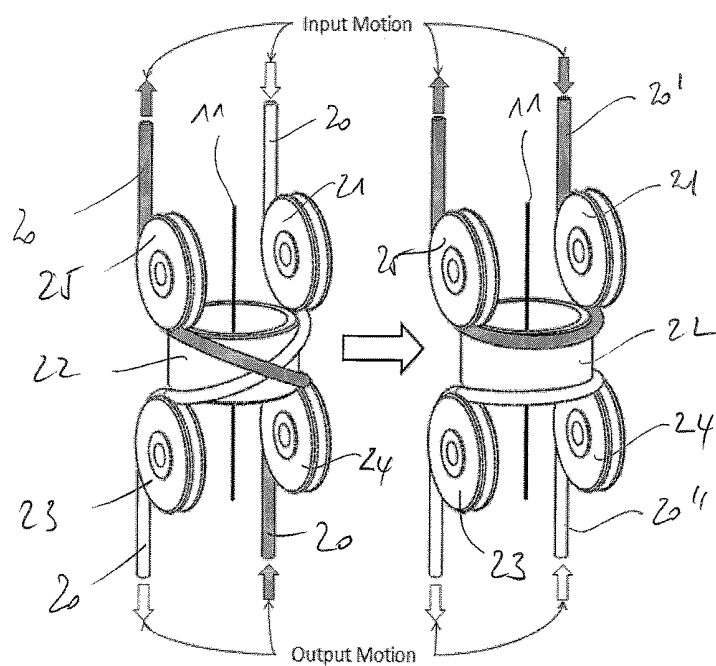**FIGURE 1**

a)   b)

FIGURE 2

FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 6

Proximal
Idler Pulleys

Distal
Idler Pulleys

Joint Axis

Joint
Idler Tubes

FIGURE 7

Cable Bead

Joint
Idler Tube

FIGURE 8

Internal Radial
Bearings   40

Internal
Idler Tube   32

External
Idler Tube   22

Joint Axis   AA

Radial Gap
Between Tubes

FIGURE 9

External
Idler Tube   22

External Miniature
Ball Bearings

Internal
Idler Tube   32

Radial Flanges   43

Joint Axis   AA

(a)   (b)   (c)

FIGURE 10

External Miniature Ball Bearings

Joint Axis

Distal Idler Pulleys

Proximal Idler Pulleys

Joint Idler Tubes

Bead Groves

FIGURE 11

FIGURE 12

FIGURE 13
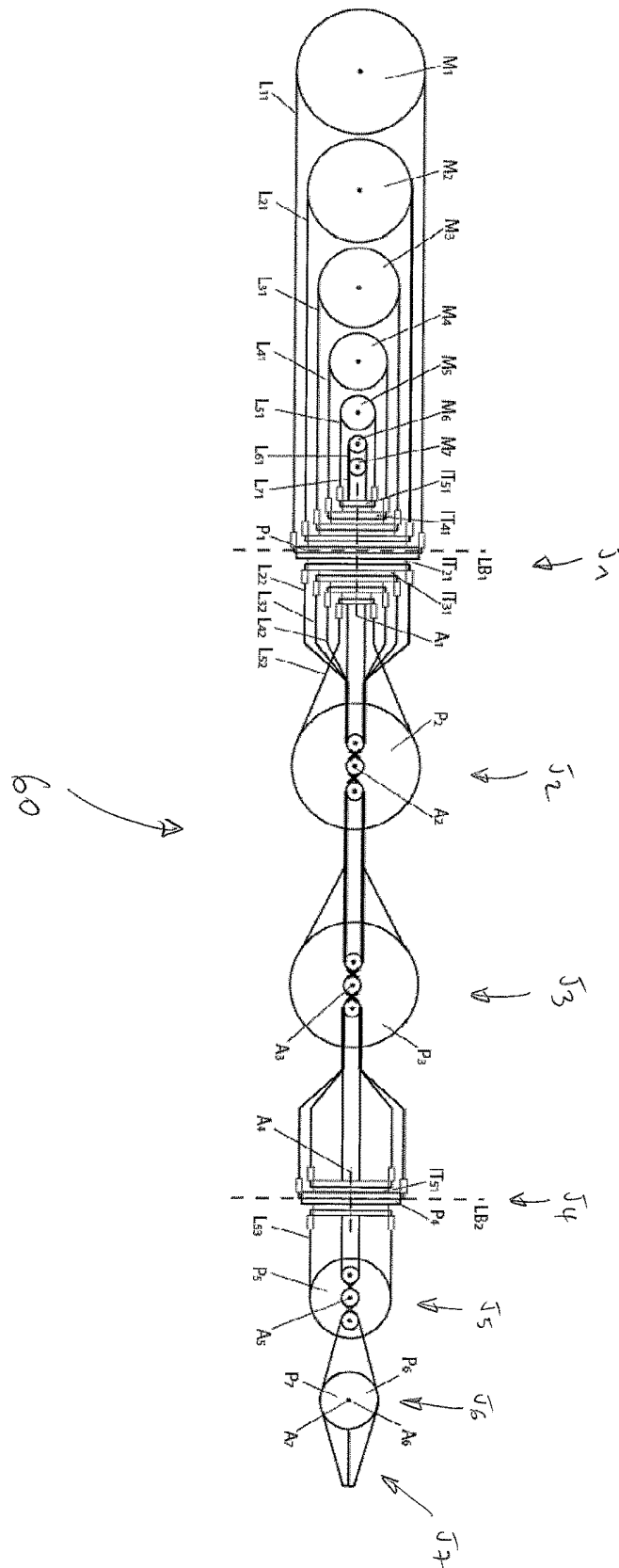
FIGURE 14
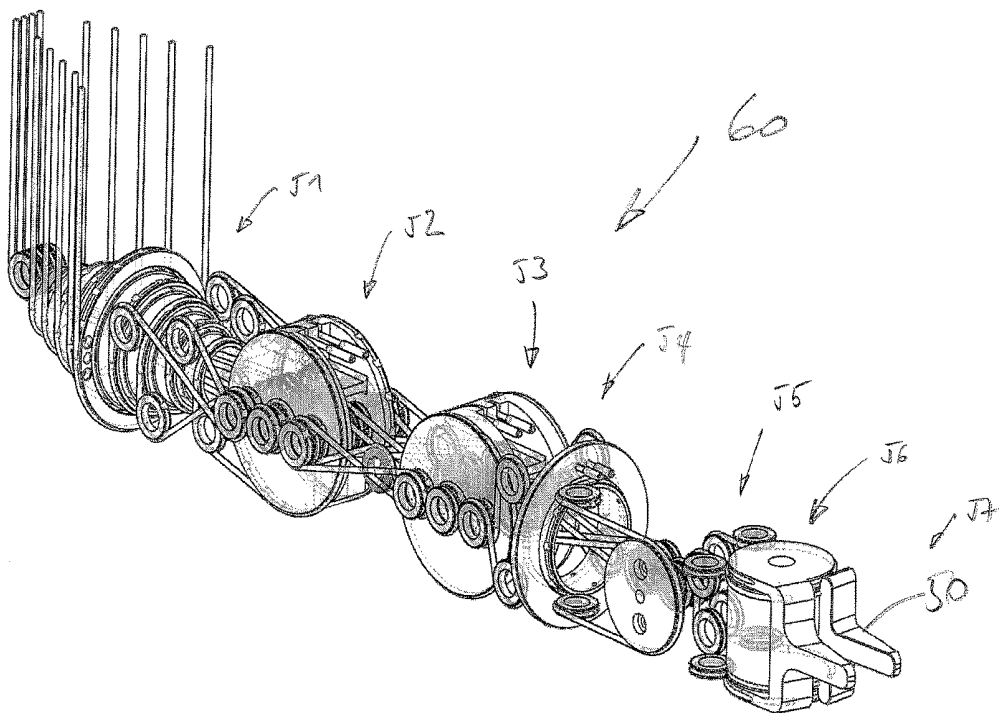
FIGURE 15

FIGURE 16

FIGURE 17

Master

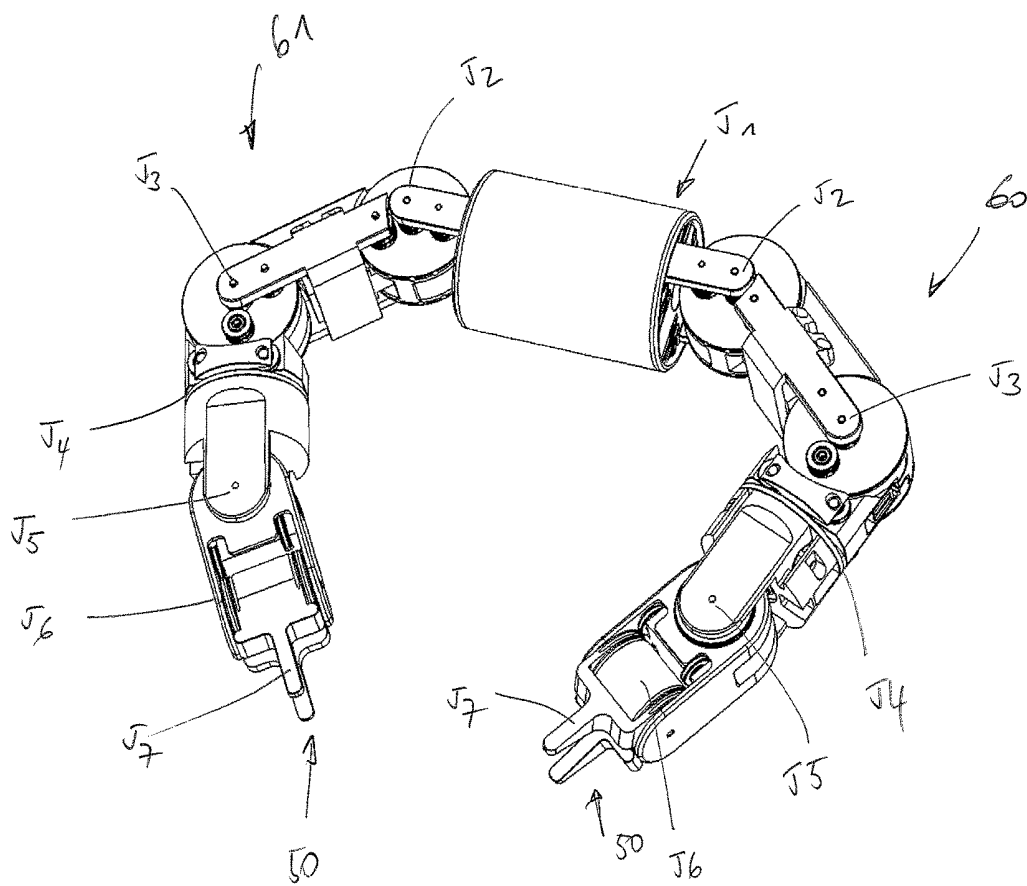Insertion Tube

Slave
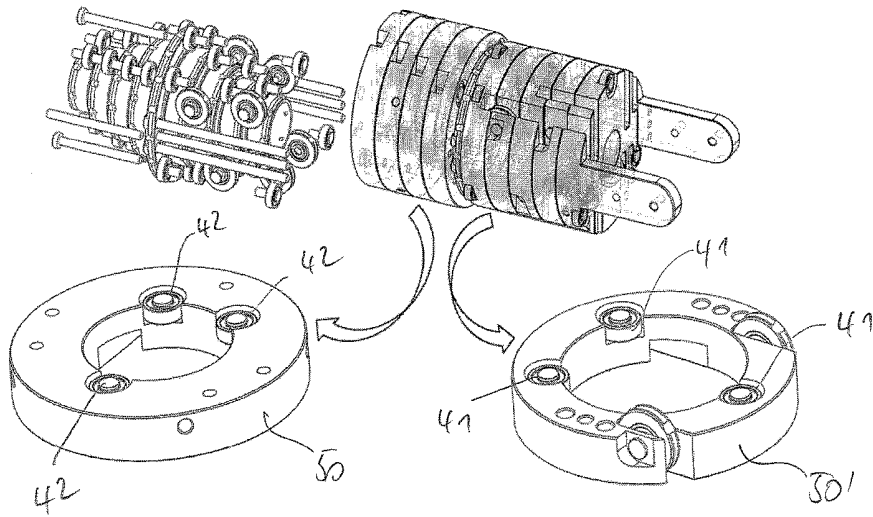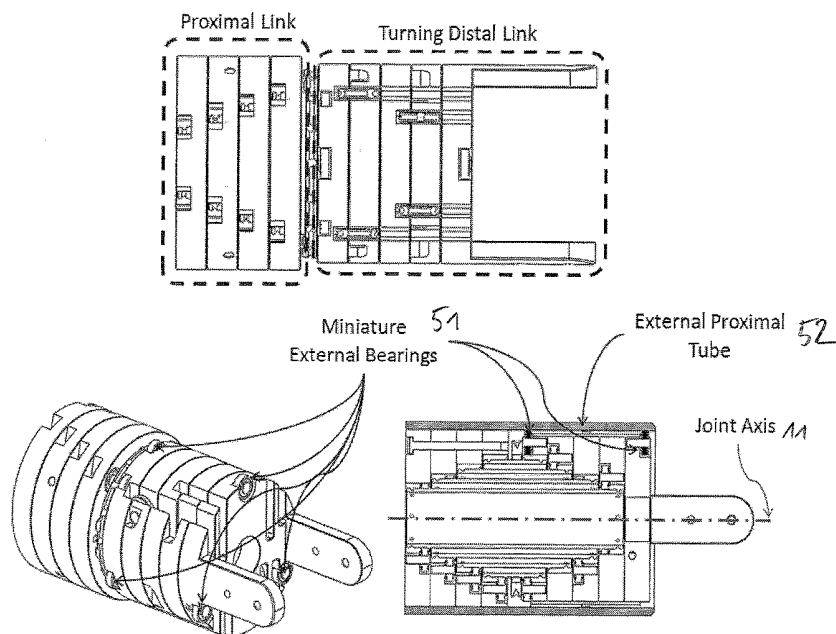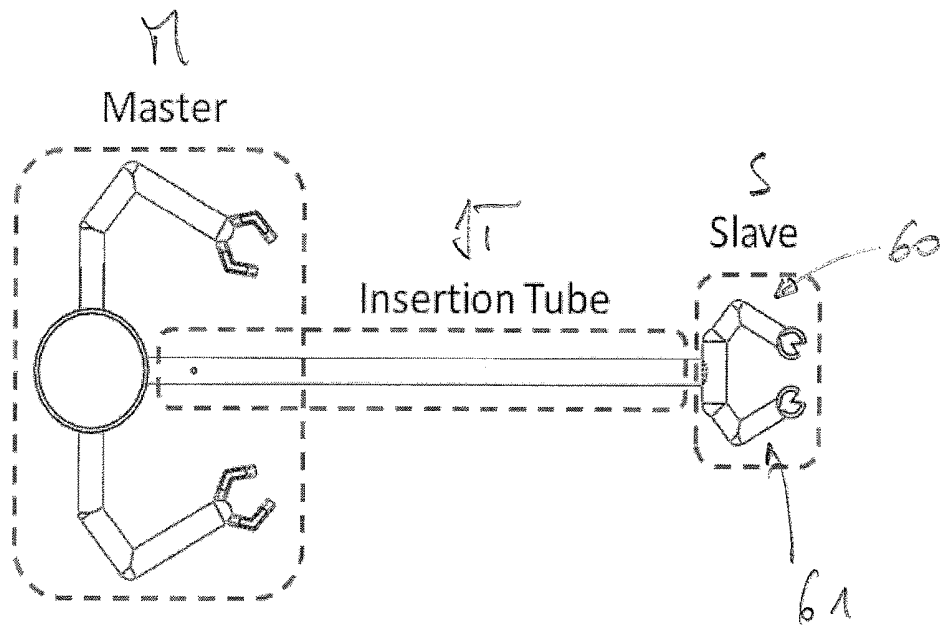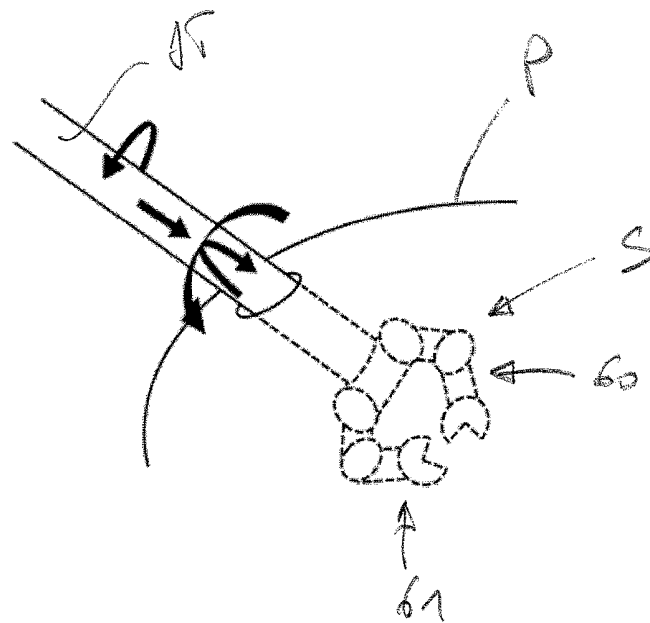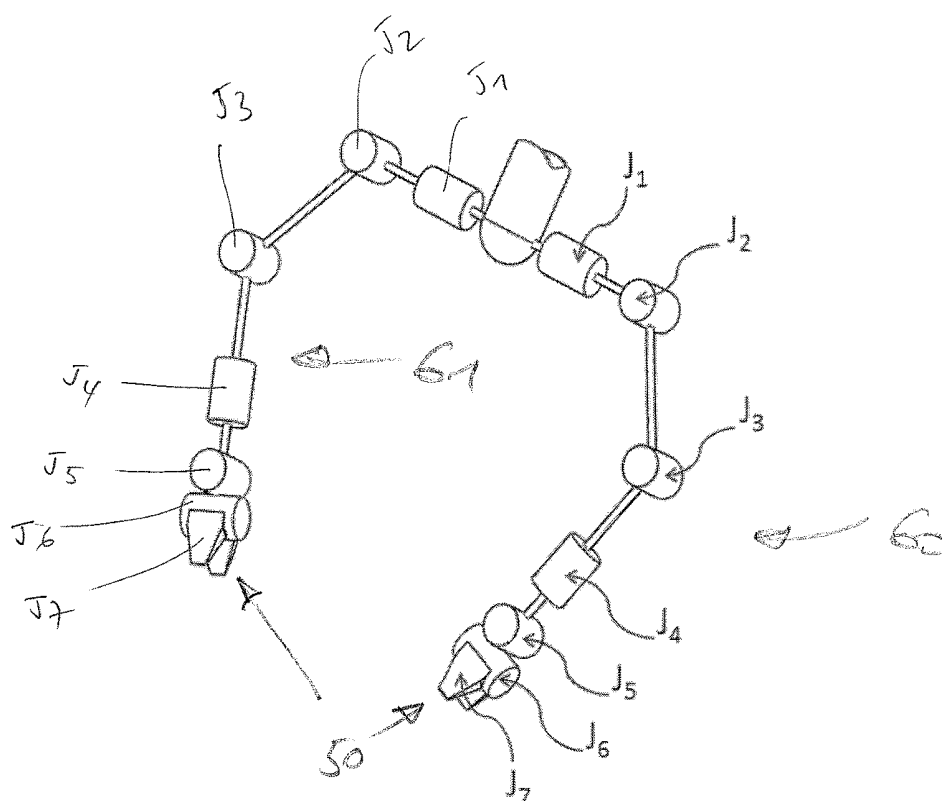
FIGURE 18

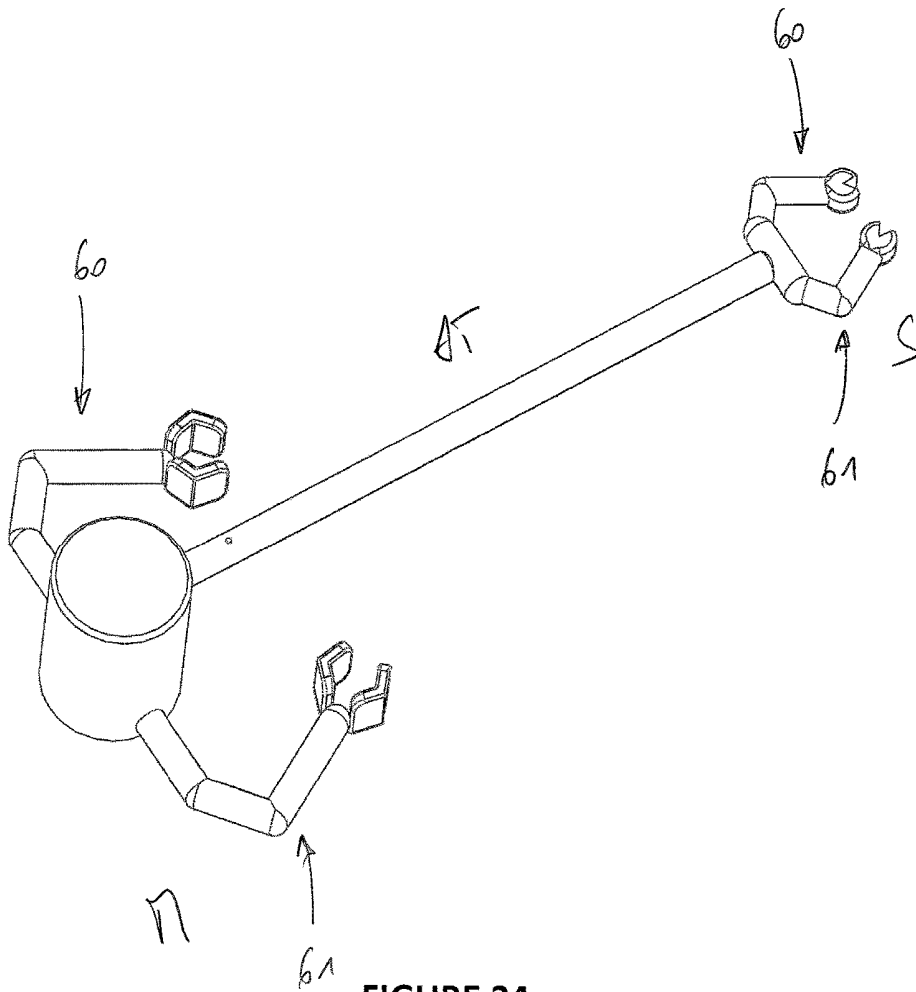FIGURE 19

FIGURE 20
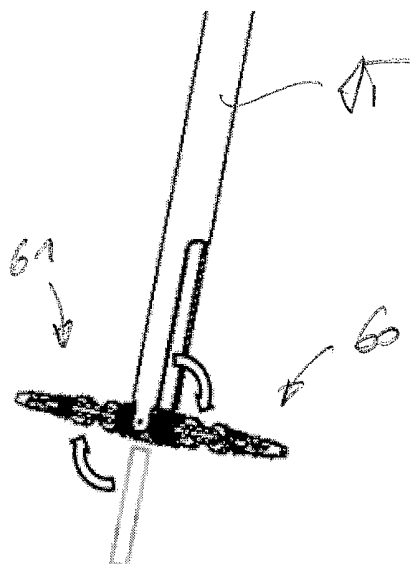
FIGURE 21
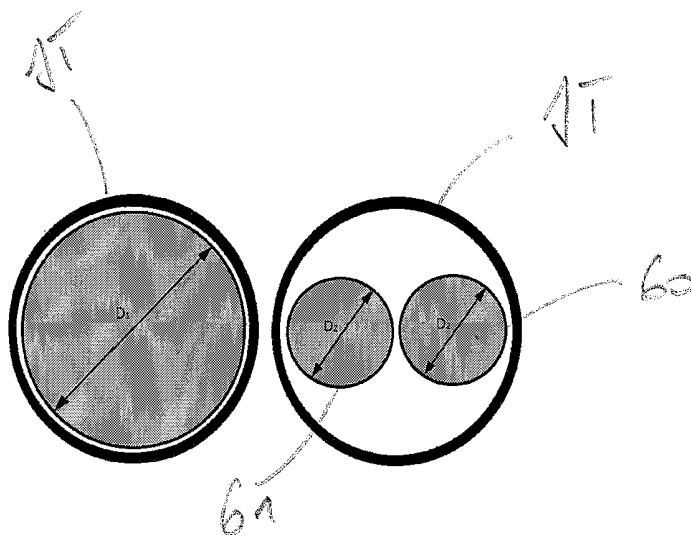
FIGURE 22

FIGURE 23

FIGURE 24

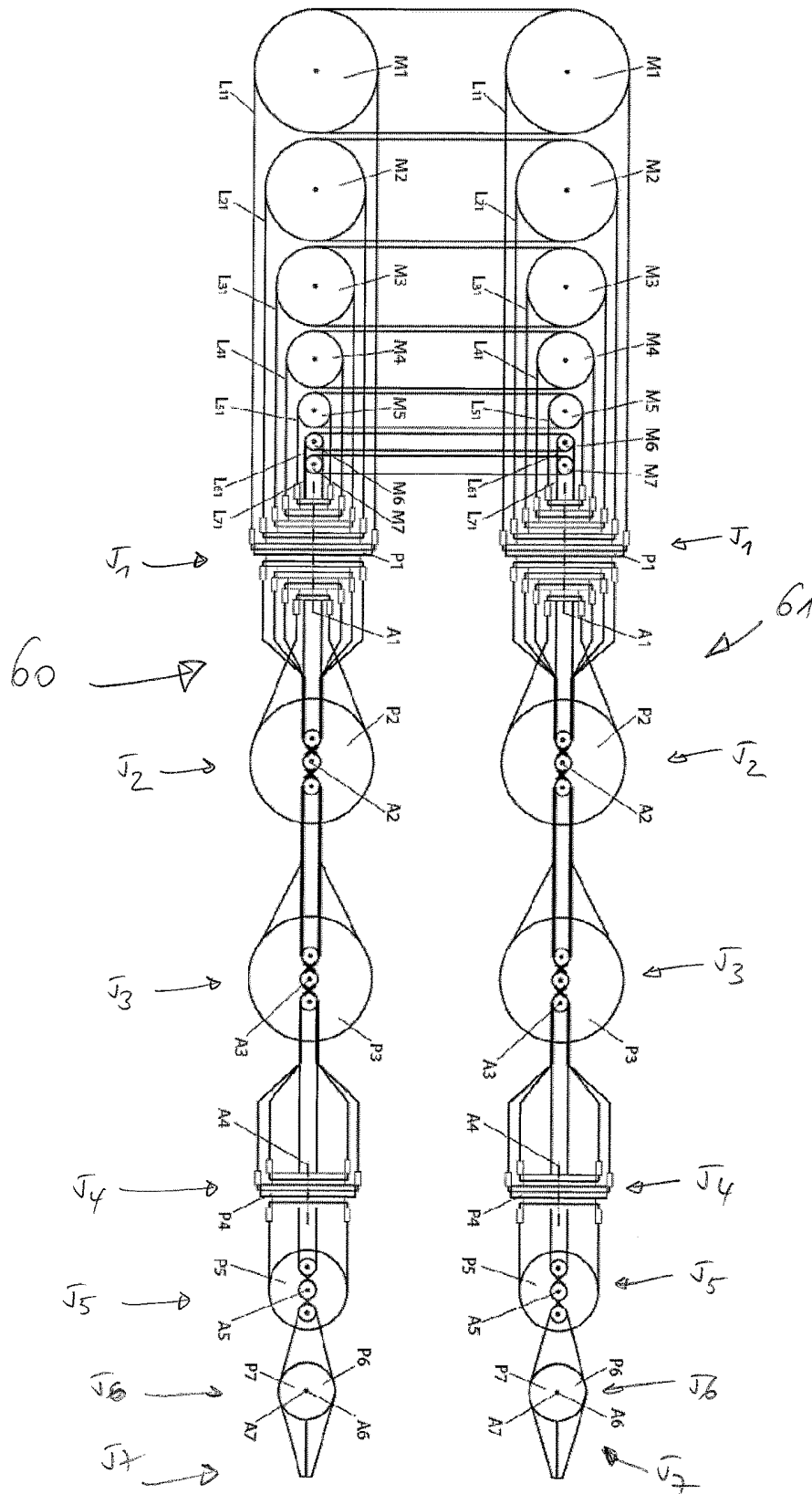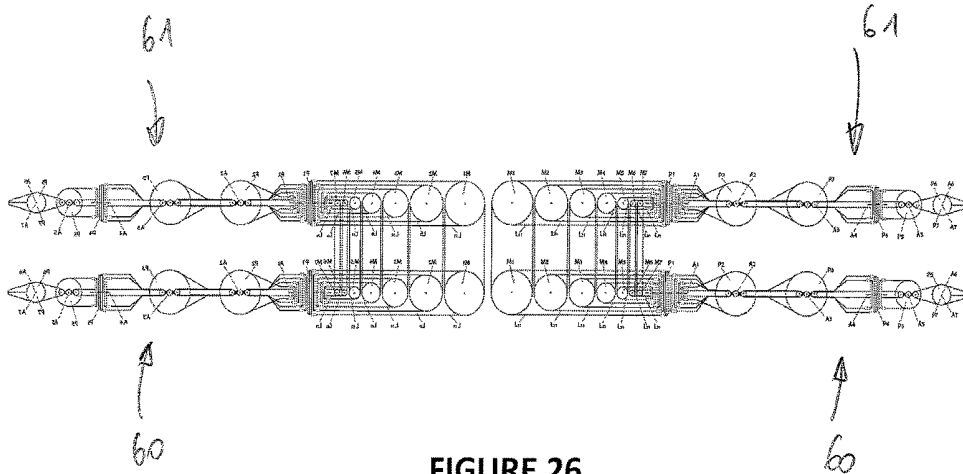FIGURE 25

FIGURE 26
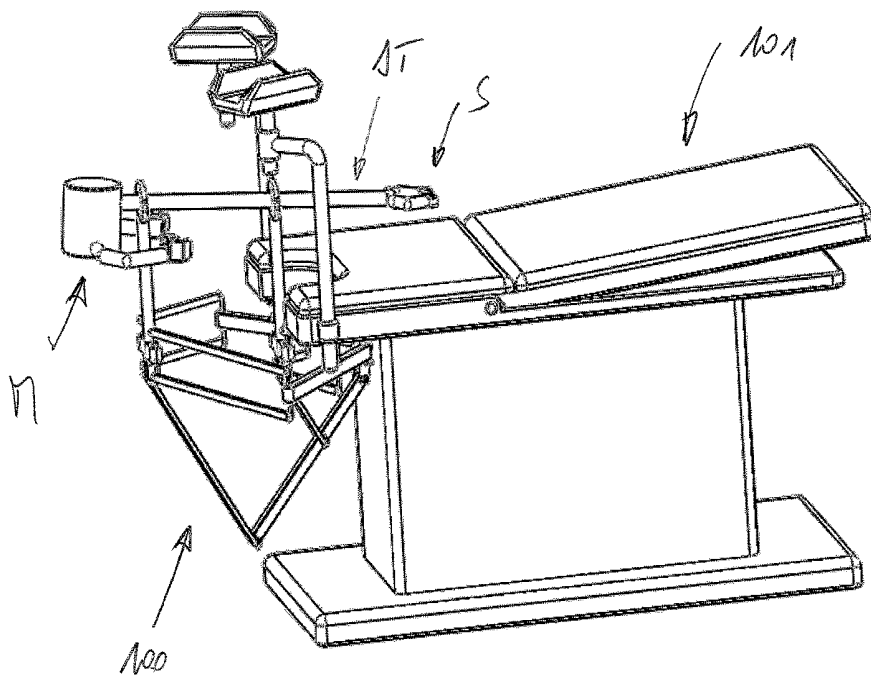

FIGURE 27

1

MECHANICAL MANIPULATOR FOR SURGICAL INSTRUMENTS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of European patent application No 10187088.9 and No 10187097.0, both filed on Oct. 11, 2010, the entire disclosure of which is hereby incorporated herein by reference.

FIELD OF THE INVENTION

The present invention relates to the field of remotely actuated mechanisms and devices for use in surgical procedures within the abdominal cavity, using reduced incisions in the abdominal wall.

BACKGROUND OF THE INVENTION

A major progress in abdominal surgery has occurred during the last decades with the introduction of laparoscopic and minimally invasive techniques. These innovative procedures focused much attention due to their several advantages: smaller abdominal incisions needed, resulting in faster recovery of the patient, improved cosmetics, and shorter stay in the hospital. The safety, efficiency and cost-effectiveness of laparoscopic surgery have subsequently been demonstrated in clinical trials for many routine abdominal operations. However, from the surgeon's point of view, there are still many difficulties in learning and performing such procedures with current laparoscopic equipment, which is non-ergonomic, non-intuitive and missing in adequate stiffness, precision and force feedback.

In order to overcome the disadvantages of traditional minimally invasive surgery (MIS), robot technology has been introduced into the operation room. Although a wide range of diagnostic and therapeutic robotic devices have been developed, the only commercial systems that have already been used in human surgery are the da Vinci System, by Intuitive Surgical, [Guthart2000], and ZEUS, by Computer Motion. Following the fusion between the two companies, the ZEUS robot is no longer produced. The major advantages of these robotic systems are related with the additional degrees of freedom available to the surgeon that allows more complex movements in a limited space, with an increased stiffness. This increased mobility and stiffness has led to short learning curves even for non-laparoscopic surgeons. A major disadvantage of these systems is the high cost of acquisition and maintenance which are actually not affordable for the majority of surgical departments worldwide.

Another drawback of these systems is related with the fact that current surgical robots are voluminous, competing for precious space within the operating room environment and significantly increasing preparation time. Access to the patient is thus impaired and this raises safety concerns. In addition, although robotic systems offer excellent vision and precise tissue manipulation within a defined area, they are limited in operations involving more than one quadrant of the abdomen. Since many gastrointestinal operations involve operating in at least two abdominal quadrants, the repeated disconnection and movement of the robots increase significantly the duration of the surgical procedure.

Despite various existing interesting systems and after several years of surgical instrumentation research, surgical robotics is still only at the very beginning of a very prom-

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ising large scale development. One of the major open drawbacks is related to the fact that current robotic instruments are still too bulky and have insufficient dexterity for complex surgical procedures.

Further weaknesses of these systems are related with the stiffness, precision and payload capacity of the micromanipulator units. A large number of conventional and robotic manipulators have been developed [Taylor1999, Cavusoglu1999, Mitsuishi2003, Mayer2004, Guthart2000, Tavakoli2003, Seibold2005, Das1997, Dachs2006, Abbott2007, Ikuta2003, Nakamura2000, Yamashita2005, Arata2005, Salle2004, Kobayashi2002, Dario2000, Peirs2003, Simaan2004, Ikuta2003, Focacci2007, Ishii2007] but their size, dexterity, stiffness, precision and payload capacity are not completely fulfilling the needs for MIS. In some cases, these insufficiencies lead to increased operative time or imprecise performance of several surgical tasks.

Other prior art documents include the following publications: US 2005/0096502, US 2009/0247821, GB 969,899, JP 2008-104620, U.S. Pat. No. 6,197,017, US 2002/0049367, US 2003/0208186, US 2005/0240078, US 2006/0183975, US 2007/0299387, EP 0 595 291, U.S. Pat. No. 6,233,504, US 2004/0236316, US 2004/0253079, US 2008/0058776, US 2008/0314181, US 2009/0198253, WO 03/067341, WO 2004/052171, WO 2005/046500, WO 2007/133065, WO 2008/130235, WO 03/086219, WO 2010/030114, DE 10314827, JP 2004041580, WO 2010/050771, WO 2010/019001, WO 2009/157719, WO 2009/145572, WO 2010/096580, DE 10314828, WO 2010/083480, U.S. Pat. No. 5,599,151, EP 1 254 642, CN 101584594, CN 101732093, U.S. Pat. No. 5,810,716, DE 4303311, US 2008/071208, US 2006/253109, WO 2009/095893, WO 2005/009482, CN 101637402, EP 0 621 009, WO 2009/091497, WO 2006/086663, EP 2 058 090.

SUMMARY OF THE INVENTION

A first aim of the present invention is to improve the known devices and systems.

A further aim of the present invention is to provide a mechanical system, based on a new cable driven mechanical transmission, able to provide sufficient dexterity, stiffness, speed, precision and payload capacity to actuate multi-DOF (degrees of freedom) micro-manipulators. Besides the possibility of being used in several articulated surgical instruments and robotic systems for surgery or other applications involving remote manipulation, it enables the design of a fully mechanical surgical instrument, which offers the advantages of conventional laparoscopy (low cost, tactile feedback, high payload capacity) combined with the advantages of single port surgery (single incision, scarless surgery, navigation through several quadrants of the abdominal cavity) and robotic surgery (greater degrees of freedom, short learning curve, high stiffness, increased intuition).

The unique design of the proposed system provides an intuitive user interface to achieve such enhanced manoeuvrability, allowing each joint of a teleoperated slave system to be driven by controlling the position of a mechanically connected master unit.

The design and performance specifications of this system were driven by surgical task requirements and its use can contribute to increase the performance of abdominal surgical procedures, increasing their reliability.

The mechanical design of micro-mechanical systems can be performed according to many possible concepts and options, even if the kinematical architecture has already

been defined and size and shape specifications imposed. One of the main issues is related with the design of a proper actuation and transmission system. In case of micro-mechanical systems for minimally invasive surgery, and especially for the endoscopic units, this aspect is crucial because the working space and incision dimensions are extremely limited and the high dexterity kinematics and demanding performance constraints are tough design goals to be pursued, since the micro mechanisms should meet highly demanding requirements of stability, precision, force and speed to effectively perform a surgical task. Given that, a special effort was placed in the study and development of a novel mechanical transmission, able to meet all those specified requirements.

The invention concerns a mechanism for remote manipulation comprising:

a. a plurality of movable links; and

b. a plurality of actuated joints placed between the said links, in a serial, parallel or hybrid configuration; and

c. a plurality of joint driven pulleys, placed on each said actuated joint, with the axis co-linear with the axis of the respective joint, actuating different degrees of freedom of the mechanism; and

d. a plurality of actuation pulleys, remotely placed relatively to the movable links of the said mechanism wherein the actuation commands are transmitted to said driven pulleys by means of a cable driven mechanical transmission; and

e. said cable driven mechanical transmission comprising a plurality of driving cables, each coupling an actuation pulley at a proximal location of the mechanism and another one of said joint driven pulley, and wherein at least one of said joints is a co-axial joint where the axis of adjoining links are aligned or in a parallel configuration.

In an embodiment, each said driving cable may comprise a closed loop cable system, transmitting the actuation motion from the said actuation pulleys to the joint driven pulleys.

In an embodiment, each said coaxial joint(s) may comprise an idler tube which is coaxial with the joint axis and which is able to rotate around its axis.

In an embodiment, said closed loop cable may comprise a single ended cable, whose both extremities are linked to said actuated pulley or said joint driven idler pulley or said idler tube for transmission of the controlled motion by contact force.

In an embodiment, said closed loop cable may comprise two ended cables, whose extremities are attached in the said actuated pulleys, said joint driven idler pulleys or said idler tubes.

In an embodiment, at least one of said actuated joints may be of pivot type, where the axis of the said adjoining links are not alignment and the angle between them and changes with the movement of the actuated joint.

In an embodiment each said co-axial joint may comprise one joint idler tube per degree of freedom of the mechanism and each said joint idler tube are co-linear with the axis of the respective said co-axial joint.

In an embodiment, the axis of each said idler tube may keep its co-linear position by means of a set of external ball bearings.

In an embodiment, the axial position of each said idler tube may be kept, in relation to the other idler tubes of the same co-axial joint, by means of the contact between one or more parts of the idler tube, namely radial flanges or

extremities, with external ball bearings or bushing components or any other component of the mechanism.

In an embodiment, the transmission of the actuated motion between the different stages of closed cable loops and the respective joint idler tubes may done through the force generated on the fixation of the cable extremities.

In an embodiment, the transmission of the actuated motion between the different stages of closed loop cables, for the same said closed loop cable system, and the respective said joint idler tubes may be done through the contact force generated between them.

In an embodiment, said contact force may be increased by increasing the number of cable turns around the said joint idler tubes.

In an embodiment, said contact force may be increased by the use of a chain or flexible timing belt element or any other flexible transmission element.

In an embodiment, the chain or flexible element may be a bead chain, comprising a cable with several spherical or other axisymmetric elements, spaced by a constant pitch, along the segments of the cable that contact said joint idler tubes.

In an embodiment, the joint idler tubes, idler pulleys, actuation pulleys and joint driven pulleys may comprise grooves and specially shaped holes to hold said chain or flexible belt element and said spherical or other axisymmetric elements, increasing the transmitted force.

In an embodiment, the actuation pulleys may receive the input control commands.

In an embodiment, the input commands may be given by an operator moving directly the actuated pulleys.

In an embodiment, the input commands may be given by an operator moving a mechanical system that promotes the rotation of the said actuated pulleys.

In an embodiment, the input commands may be given by a plurality of actuators, controlled by electrical signals, to selectively drive the distal part of the mechanism.

In an embodiment, the forces experienced by the distal part of the mechanism are reproduced at the said actuated pulleys to provide force feedback.

In an embodiment, the invention concerns a device comprising a mechanism as defined in the different embodiments defined herein.

In an embodiment, the device is a mechanical teleoperated surgical system, comprising:

a rigid support tube, having two extremities, a distal one, which is inside the patient's body during the surgical procedure, and a proximal one, which is located outside the patient's body; and

a slave articulated unit, coupled to said distal portion of said support tube, composed by two miniature serial manipulators, sharing the same proximal shoulder component, said proximal shoulder component coupled to the said distal portion of the support tube by a rotational joint whose axis is perpendicular to the said support tube's axis, each said miniature serial manipulator comprising a plurality of linkages and joints and a distal griping end-effector element;

a master articulated unit, placed in the distal extremity of the said support tube, composed by two serial manipulators, each one having a plurality of linkages and joints and a distal input handle, with exactly the same kinematics and cable transmission topology of the said slave manipulators, wherein input commands from an operator cause the movement of said slave's end-effectors according to said input commands; and

a cable driven mechanical transmission system, coupled between said master and said slave manipulators, for precisely emulating movement of said master manipulators by said slave manipulators, wherein each driven pulley, actuating a certain degree of freedom, of the said master manipulators is connected to the driven pulley of the said slave manipulator actuating the same degree of freedom; and

a stereoscopic image capture component positioned at the distal end of the guide tube; and

distal surgical instruments, attached to the end-effectors of the slave manipulators.

The surgical instruments may be of any type suitable to be used with the present invention and systems.

In an embodiment, the miniature serial manipulator has an anthropomorphic kinematics, resembling the human arm, said miniature serial manipulator comprising:

a first distal joint, coupled to said distal end of said proximal shoulder component, said first distal joint having a first joint axis substantially co-axial to said proximal shoulder component axis,

a first distal link movably coupled to said first distal joint,

a second distal joint coupled to said first distal joint via said first distal link, said second distal joint having a second joint axis substantially perpendicular and intersecting to said first joint axis,

a second distal link movably coupled to said second distal joint,

a third distal joint coupled to said second distal joint via said second distal link, said third distal joint having a third joint axis substantially parallel to said second joint axis,

a third distal link movably coupled to said third distal joint,

a fourth distal joint coupled to said third distal joint via said third distal link, said fourth distal joint having a fourth joint axis substantially perpendicular and intersecting to said third joint axis,

a fourth distal link movably coupled to said fourth distal joint,

a fifth distal joint coupled to said fourth distal joint via said fourth distal link, said fifth distal joint having a fifth joint axis substantially perpendicular and intersecting to said fourth joint axis,

a fifth distal link movably coupled to said fifth distal joint,

a sixth distal joint coupled to said fifth distal joint via said fifth distal link, said sixth distal joint having a sixth joint axis substantially perpendicular and non-intersecting to said fifth joint axis, said sixth distal joint movably coupled to said at least one end-effector element,

a seventh distal joint coupled to said fifth distal joint via said fifth distal link, said seventh distal joint having a seventh joint axis substantially perpendicular and non-intersecting to said fifth joint axis, said seventh distal joint having a seventh joint axis substantially coincident to said sixth joint axis, said seventh distal joint movably coupled to said a second end-effector element, in such a way that said first and second end effector elements are movable relative to, and independently of, one another,

a plurality of miniaturized driving cables, each coupling an actuation pulley at a proximal location of the support tube and another one of said joint driven pulley, placed on said slave distal joints; and

In an embodiment, a coupling unit, placed at the proximal end of the support tube, mechanically connects the said master and said slave manipulators and their mechanical cable driven transmissions.

In an embodiment, an external manipulator mechanism, fixed relatively to the patient, is able to provide external degrees of freedom to the said support tube in such a way that the said slave unit can be inserted, positioned and moved within the abdominal cavity.

In an embodiment, said sixth distal joint has a sixth joint axis substantially parallel to said fifth distal joint axis, said sixth joint axis further coincident to said seventh joint axis.

In an embodiment, said sixth distal joint has a sixth joint axis substantially perpendicular and intersecting to said fifth distal joint axis, said sixth joint axis further coincident to said seventh joint axis.

In an embodiment, an eighth distal joint is provided between the said second distal joint and said third distal joint wherein said eighth distal joint has a eighth joint axis substantially perpendicular and intersecting to said second distal joint axis and third joint axis.

In an embodiment, the actuation pulleys of the master and slave manipulators are directly connected, in the said coupling unit, with multiple transmission ratios;

In an embodiment, the positioning mechanism further comprises a setup joint which connects the base to an operating room table or to the ground.

In an embodiment, the coupling unit is adapted to releasable connect the support tube to the master unit.

In an embodiment, an external positioning mechanism is provided which has external degrees of freedom of movement that are redundant with the degrees of freedom of movement of the said slave unit, comprises a remote centre of motion mechanism for pivoting the support tube about the incision point.

In an embodiment, said input commands may comprise the operator moving at least one master manipulator input linkage, wherein movement of said input handle corresponds to an analogous scaled increment movement of said slave end-effector.

In an embodiment, the forces experienced by the slave unit during a surgical procedure may be reproduced at the master input handle to provide the operator with force feedback.

In an embodiment, the slave articulate manipulator comprises a serial linkage having a number X of DOFs, and wherein said master input linkage is characterized by a number Y of DOFs where Y is equal to X.

In an embodiment, X comprises 7 slave degrees of freedom of movement and Y comprises 7 master degrees of freedom of movement.

In an embodiment, X comprises 8 slave degrees of freedom of movement and Y comprises 8 master degrees of freedom of movement.

In an embodiment, the rigid support tube has a free internal channel, in which a third surgical instrument may pass, as well as a tool to exchange the gripper distal instruments;

In an embodiment, the third surgical instrument may be flexible, having a distal camera in the tip, or a gripping or a cutting or an ablating end-effector.

In an embodiment, the slave manipulator unit can pivot around the distal extremity of the guide tube by the said proximal shoulder component, being inserted aligned with the tube and then, when already inside the abdominal cavity, being externally actuated to turn into a working configuration, perpendicular to the said positioning tube's axis.

In an embodiment, the magnitude of movements of the slave manipulator unit can is scaled relatively to the movements of the said master manipulator unit.

In an embodiment, the slave articulated unit and said master articulated unit comprise:

a plurality of movable links; and

a plurality of actuated joints, placed, between the said links, in a serial configuration; and

a plurality of joint driven pulleys, placed on each said actuated joint, with the axis collinear with the axis of the respective joint, actuating the different degrees of freedom of the mechanism; and

a plurality of actuation pulleys, remotely placed relatively to the movable links of the said articulated units and transmitting the actuation commands to the said driven pulleys by means of a cable driven mechanical transmission; and

a cable driven mechanical transmission, composed by a plurality of driving cables, each coupling an actuation pulley at a proximal location of the mechanism and another one of said joint driven pulley, placed on said micro-mechanism distal joints.

In an embodiment, each of the driving cable consist of a closed loop cable system, transmitting the actuation form the said actuation pulleys to the joint driven pulleys.

In an embodiment, the closed loop cable system may be composed by multiple sets of stages of closed loop cables, transmitting the actuation commands between them, form the said actuation pulleys to the joint driven pulleys, and keeping a constant total length for all the possible joint configuration of the said mechanism.

In an embodiment, the different closed loop cables of the multiple sets of stages of closed cable loops, transmit the actuation commands between them by a called idler tube, comprising an axisymmetric mechanical component, able to rotate around its axis, which is aligned with the axis of the said co-axial actuated joints.

In an embodiment, the closed loop cable is composed by a single ended cable, whose both extremities are fixed in the said actuated pulley or in the respective said joint driven pulley or in a said idler tube.

In an embodiment, the closed loop cable is composed by a single endless cable, transmitting the controlled motion between said actuated pulleys, said joint driven pulleys and idler tubes by means of contact force.

In an embodiment, the closed loop cable is composed by two ended cables, whose extremities are fixed in both the said actuated pulley and the respective said joint driven pulley or in both the said actuated pulley and an idler tube or in both an idler tube and a said actuated pulley.

In an embodiment, the actuated joints can be of pivot type, where the axis of the said adjoining links are not alignment and the angle between them and changes with the movement of the said actuated joint, and co-axial type, where the axis of adjoining links are aligned or in a parallel configuration.

In an embodiment, the axis of the different idler tubes, for the different degrees of freedom and belonging to the same said co-axial joint, are collinear with the axis of the respective said co-axial joint.

In an embodiment, the axis of each said idler tube is keeps its collinear position by means of the contact with a set of external ball bearings or bushing components or any other component of the mechanism.

In an embodiment, the axial position of each said idler tube is kept, in relation to the other idler tubes of the same co-axial joint, by means of the contact between one or more parts of the idler tube, namely radial flanges or extremities,

with external ball bearings or bushing components or any other component of the mechanism.

In an embodiment, the transmission of the actuated motion between the different stages of closed cable loops and the respective idler tubes is done through the force generated on the fixation of cable's extremities.

In an embodiment, the transmission of the actuated motion between the different stages of closed loop cables, for the same said closed loop cable system, and the respective said idler tubes is done through the contact force generated between them.

In an embodiment, the contact force may be increased by increasing the number of cable turns around the said idler tubes.

In an embodiment, the contact force may be increased by the use of a chain or flexible timing belt element or any other flexible transmission element in the close loop cable system.

In an embodiment, the chain or flexible element is a bead chain, comprising a closed loop cable containing some spherical or other axisymmetric elements, spaced by a constant pitch, along the segments of the cable that can be in contact with the said idler tubes.

DETAILED DESCRIPTION OF THE INVENTION

The present invention will be better understood from the following detailed description and with reference to the drawings which show:

FIG. **1** illustrates two different architectures for remote actuated cable driven systems, a) One actuated pulley per DOF b) Two actuated pulleys per DOF;

FIG. **2** illustrates (a) a Pivot Joint and (b) a Co-axial Joint;

FIG. **3** illustrates a cable rooting along a Pivot Joint, (a) being a 2D view and (b) being a perspective 3D view;

FIG. **4** illustrates the problem of the cable routing along a co-axial joint;

FIG. **5** further illustrates the problem of the cable routing along a co-axial joint;

FIG. **6** illustrates a Co-axial joint Concept Development;

FIG. **7** illustrates a Co-axial joint Concept, for a 2-DOF example;

FIG. **8** illustrates a bead chain turning the idler cylinder;

FIG. **9** illustrates a use of two ball bearings to mount an idler tube;

FIG. **10** illustrates a Radial and axial restriction of the joint idler tubes;

FIG. **11** illustrates a bead chain turning the idler cylinder;

FIG. **12** illustrates a 3D Model of a micro-manipulator according to the invention;

FIG. **13** illustrates a Kinematic Model of the micro-manipulator;

FIG. **14** illustrates cabling schematics of the 7-DOF micro-manipulator;

FIG. **15** illustrates 3D cable layout of the 7-DOF micro-manipulator;

FIG. **16** illustrates component mounting parts;

FIG. **17** illustrates radial and axial restriction of the joint turning distal link;

FIG. **18** illustrates the overall composition of a teleoperated mechanical system according to the invention;

FIG. **19** illustrates the external positioning degrees of freedom;

FIG. **20** illustrates the kinematic model of the micro-manipulators according to the present invention;

FIGS. **21** and **22** illustrate the insertion procedure for the micro-manipulators;

FIG. **23** illustrates a 3D Model of the endoscopic unit;

FIG. **24** illustrates an overview of the fully mechanical master-slave system;

FIG. **25** illustrates a cabling schematics of a sub-teleoperated system;

FIG. **26** illustrates a cabling schematic for the entire teleoperated system according to the present invention and

FIG. **27** illustrates an overview of the entire teleoperated system with the external positioning mechanism.

In order to actuate the joints of a micro-manipulator for MIS, two basic approaches are possible:

(1) placing the actuators within the moving links of the manipulator, or integrating them in the joints directly, without transmission elements; or

(2) placing the actuators on an external location, outside of the patient's body, having the motion transmitted to each joint by means of a complex mechanical transmission.

Internal actuation simplifies the mechanical configuration of the joint, reducing the complexity of the transmission chain. In particular, it has the great advantage that the motion of the joint is kinematically independent with respect to other joints. However, the size of the manipulator links is imposed by the dimension of the actuators and, due to technological power-to-volume limitations of available robotic actuation, it is quite difficult to obtain an anthropomorphic kinematics and the required working performances and dimensions required for an endoscopic system. Furthermore, the motors occupy a rather large space inside the robotic structure, making it difficult to host other elements, like different kind of sensors or internal structural components. Another issue is that, since the mass of the actuators is concentrated inside the manipulator links, the dynamic behaviour of the system and its response bandwidth are reduced.

A further negative aspect is related with the routing of both power and signal cables of the actuators. This issue is more serious for the actuation of distal joints than for the proximal ones, since the cables in distal joints produce a relatively large resistant torque and volume disturbance on the proximal joints.

As a consequence of all those above mentioned disadvantages, the internal actuation of these micro-manipulators was discarded in favour of a remotely actuated solution.

As opposite to internal actuation architectures, in remote actuation the joints are driven by actuators placed outside the moving links. It requires a motion transmission system, which must pass through the joints between the motor and the actuated joint and may bring problems of kinematic and dynamic coupling between the actuated joint and the previous ones.

According to the type of adopted transmission elements, remote actuation systems can be classified as (1) flexible or (2) rigid transmission. This last way of transmission is mainly based on articulated linkages or rolling conjugated profiles (e.g. gear trains) and although may guarantee an increased stiffness of the systems, its implementation in miniature and complex multi-DOF mechanisms is extremely difficult.

On the other hand, flexible transmissions are based on deformable connections that can adapt to variations of configuration by changing the transmission path. They are based on flexible elements with translating motion, subject to tension (more frequently) or tension and compression. Two further subcategories can be identified: pulley-routed flexible elements (tendons, chains, belts) or sheath-routed flexible elements.

In this case, since it was aimed to develop a teleoperated mechanism with good force reflection properties, enabling bilateral force reflection, it was decided to use pulley-routed flexible elements, cables, with ball bearing mounted pulleys, in order to reduce the amount of friction losses along the mechanical transmission.

Remote cable driven actuation can be applied according to different types of organization, depending on the number of actuated pulleys used per joint. In particular, it is possible to recognize two main actuation architectures:

(1) two actuated pulleys per DOF—each one can generate a controlled motion in one direction only and the return motion in the opposite direction must be obtained by an external action, which can be a passive (e.g., a spring) or an active system (e.g., an antagonistic actuator); this is the case of tendon-based transmission systems;

(2) one actuated pulley per DOF—each one can generate a controlled motion in both directions and can be used alone to drive the joint. These two architectures are illustrated in FIG. **1**(a) (one actuated pulley per DOF) and (b) (two actuated pulley per DOF).

Since the second solution requires a higher number of components and brings additional complexity and cost to the mechanical system, the chosen architecture was the one that uses a single actuated pulley per DOF. In this case, the achievable performances are similar in both directions, but particular attention must be paid to backlash. Usually, it is necessary to preload the transmission system. Furthermore, the adoption of a closed loop tendon transmission requires that the overall length of the tendon route must be kept constant, for all the possible configurations of the manipulator.

$$\Delta l=0, \forall q \in W_q$$

In spite of this additional complexity, this actuation scheme has been used, for simple applications, with only a few DOF or low dexterity. However, in a multi-DOF configuration, with high dexterity, reduced dimensions and high payload requirements, several non solved problems arrive from the implementation of this kind of actuation transmission.

In the required kinematic design of high dexterity endoscopic micro-manipulators, two joint configurations may be present, which can be classified as (1) pivot joints or (2) co-axial joints, both being illustrated in FIGS. **2**(a) and (b). The distinction is related to the relative alignment of adjoining links. While in the first kind, the angle, ϑ_{pd}, between the proximal, p, and distal, d, links changes with the movement of the joint, see FIG. **2** a), in the co-axial configuration the proximal joint has an axial rotation movement in relation to the distal one, see FIG. **2** b).

The cable routing method utilized for pivot joints is relatively standard and can be seen in several already developed solutions. As illustrated in FIG. **3**, for this kind of configurations, the cable **2** is wrapped around a pulley **1**, called the "joint idler pulley," which is concentric with the axis of revolution **3** of the joint. To maintain a constant cable length, the cable **2** must remain in contact with the joint idler pulley **1** at all times. In this way, if the joint turns an angle ϑ on the anticlockwise direction, the length of the superior segment **2'**, in contact with the idler pulley, will increase and the inferior segment **2"** will decrease, by the same value, Rϑ, guaranteeing the constant length of the cable closed loop. As said before, each DOF is actuated by two cables, wrapped around a set of two pulleys **1**, passing through the joint. The multi-DOF case, with n DOF, would require a stack of 2n pulleys.

As illustrated in FIG. 3, the joint in addition comprises a set of proximal idler pulleys 4 and a set of distal idler pulleys 5 which guide the cable 2.

However, for the co-axial joints, the cable routing is much more complex. Some solutions to avoid this problem have already been proposed but, to the best of the inventor's knowledge, not for such a small dimension multi-DOF system with such a high dexterity and payload requirements. The problem consists in having an array of cables 10 being twisted about a co-axial axis 11, as shown in FIG. 4, when the proximal link 12 and the distal link 13 rotate relatively, with the two 10 cables actuating the same joint being stretched in the same way, thereby increasing the total length of the closed loop. FIG. 4 also illustrates the proximal idler pulleys 14 and the distal idler pulleys 15.

This stretch of the different closed loops of cable 10 generates a resistant rotation moment that might be critical for multi-DOF systems. Another source of problems, as seen in FIG. 5, is the misalignment of the cables 10 in relation to the idler pulleys 14, identified by the angle α, caused by this twist, which may cause the disengagement of the cables from the pulleys 14 and the rubbing of the cables 10, generating friction and wear. These problems are especially critical on the proximal joints of the manipulators, due to the high density of cables that actuate the distal joints.

In some applications of micro cable driven manipulators for MIS (minimally invasive surgery), this difficulty is minimised due to the low complexity (low number of internal DOF) of the system and the large ratio between the length of the instrument shaft, h, and the distance between the joint axis and the cables, d. In this way, the misalignment of the cables in relation to the idle pulleys is almost negligible and the change in length of the cables is small, generating a very small resistant rotation moment. In the present case however, due to the high number of internal DOF and the anthropomorphic kinematic configuration, this solution may not be applied.

The developed solution for the present invention is based on the concept shown in FIG. 3, which is adapted to be suitable for co-axial joints. More specifically, the configuration is similar but the two set of proximal and distal idler pulleys are separated by a joint idler pulley to allow the cables, belonging to the same closed loop, to be wrapped around the joint idler pulley, which is now in a perpendicular configuration (rather than a parallel one as illustrated in the embodiment of FIG. 3), aligned with the axis of the joint.

This configuration according to the present invention is illustrated in FIG. 6. In this configuration, the crossing and rubbing of the two cables is evident (see the drawing on the left in FIG. 6) and the way to avoid it resides in dividing the single primitive closed loop in two (as illustrated in the drawing on the right in FIG. 6). By doing this, the single closed loop is divided in two new closed loops, whose relative motion is now transmitted through an axial idler pulley (or tube) see FIG. 6.

More specifically, FIG. 6 shows (on the left side drawing) a first intermediate configuration derived from FIG. 3. In this first intermediate configuration, the cable 20 passes a first proximal idler pulley 21, then over the joint idler pulley 22 (or joint idler tube), a first distal idler pulley 23, goes to the tool to be controlled and comes back to a second distal idler pulley 24, crosses over the joint idler pulley 22 and finally passes a second proximal idler pulley 25. As one can easily see on the drawing of the right side of FIG. 6, the cable 20 crosses over the joint idler pulley 22 which renders this configuration unsuitable for the intended applications. To overcome this problem, the solution is illustrated in the

drawing on the left side of FIG. 6. Specifically, in this configuration, the cable 20 is divided into two loops 20' and 20" which are separated.

The first loop 20' passes the first idler pulley 21 the over the joint idler pulley and back over the second proximal idler pulley 25. The second loop 20" passes the second distal idler pulley 24, then over the joint idler pulley 22 and then over the first idler pulley 23. Accordingly, the motion of the first cable loop 20' may be then transmitted to the second cable loop 20" via the joint idler pulley 22.

As an extension of this concept, to be able to form a multi-DOF system, the joint according to the present invention will be composed by several co-axial idler tubes/pulleys corresponding to the pulley 22 of FIG. 6, with different lengths and different diameters, allowing the hosting of the different sets of proximal and distal idler pulleys for the different closed loops actuating the different joints. FIG. 7 illustrates the basic principle of this extension. For example, one sees in the figure the system as illustrated in FIG. 6 (drawing on the right side) and described above (cables 20', 20", pulleys 21, 23, 24 and joint idler tube 22) and there is accordingly a second similar system for the second DOF. Specifically, basically the second system is similar to the first one with two cable loops 30', 30", proximal idler pulleys 31, 35, distal idler pulleys 33, 34 and a joint idler tube/pulley 32. This pulley 32 has a smaller diameter than the pulley 22 and is concentrical with this pulley 22, aligned along the same axis 11 (the joint axis).

Accordingly, this allows to have two independent actuating systems in the same joint, and the principle may be extended further in order to add additional DOF, the principle being to add the concentrical joint idler tubes/pulleys.

Systems with several stages of endless cables have been used in several mechanical systems where, in order to ensure enough friction to transmit the motion between consecutive closed loops, timing belts have been frequently used. However, for this specific solution, they are not a suitable choice. The main problem is related to the fact that, although timing belts might be used in out-of-plane configurations, in this reduced dimensions application, since the out-of-plane idler pulleys are too close to each other, this kind of configurations are not feasible.

A standard cable could be a solution. However, the friction generated by the cable in contact with the idle pulley and/or tube, for any pair of materials, wouldn't be sufficient and the wear would be excessive. The cable could also be wrapped several times around it, with an exponentially increased friction, but it would promote an unacceptable axial movement of the idler pulley.

Since in this configuration the motion transmission can only be made through half a turn of contact of cable around the joint idler tube/pulley, the friction in the contact is maximized by a specially developed bead chain, which is illustrated in FIG. 8. It is composed by a continuous stiff rope 36 (corresponding to the cables 20', 20", 30', 30" described above) with several spherical beads 37, placed with constant pitch, in the segments of the cable that may be in contact with the joint idler tube 22, 32 as described with reference to FIGS. 6 and 7 above. The bending flexibility, axial symmetry, strength and compactness of this bead chain make it suitable for this application, where high load resistance, no slipping, low volume and right-angle driving are major requirements.

Wire ropes or cables are available in a variety of strengths, constructions, and coatings. Although cable strength generally increases with diameter, the effective minimum bend

radius is decreased. Cable compliance, cost, and construction stretch generally increases with strand count.

During operation, the cable runs in a grooved surface **38**, placed on the extremities of the idler tubes **22**, **32** and the beads seat in sprocket indentations **39**, where the shear force is generated.

As was already explained in the previous section, in a multi-DOF configuration, the primitive closed loop is divided in two new closed loops, whose motion in transmitted through the axial idler tube **22**, **32**, which should be able to rotate independently from other concentrical idler tubes/pulleys which are present in accordance with the embodiment illustrated in FIG. **7**, while keeping its fixed axial position. This could be achieved for example by the use of two internal radial ball bearings **40**, in a standard configuration, as shown in FIG. **9** where the joint idler tubes/pulleys **22**, **32** correspond to the one described above.

However, in a multi-DOF system, the space gap between the concentric joint idler tubes **22**, **32** is not enough to place two ball bearings for each idler tube and so, several (for example preferably six) miniature external ball bearings may be used to guarantee the concentricity of each idler tube. Specifically, one uses six external bearings per joint idler tube/pulley **22**, **32** to ensure a correct and stable positioning. The axial movement is constrained by the contact of two radial flanges with the six bearings as illustrated in FIG. **10**.

More specifically, drawing (a) in FIG. **10** illustrates an axial view of the arrangement of bearings **41**, **42** on the joint idler tube/pulley **22**, **32**. Drawing (b) in FIG. **10** illustrates a front view of the joint arrangement with the bearings **41**, **42** and flanges **43** used to block the lateral motion of the bearings. Drawing (c) in FIG. **10** illustrates a cut and perspective view of the joint arrangement as described.

For an application example with two transmitted degrees of freedom, the layout of the joint using the principles of the present invention described above will look like the one shown in FIG. **11**. More specifically, this embodiment corresponds to the one illustrated in FIG. **7**, using the cable **36** with beads **37** and the joint idler tube **22**, **32** of FIG. **8** with the grooved surface **38**, placed on the extremities of the idler tube **22**, **32** and the beads seat in sprocket indentations **39**. Accordingly, numerical references used in said previous figures apply here to corresponding elements as well as the description.

Making use of the transmission concept previously proposed, the design of several novel mechanical surgical instruments can be implemented. The main goals of these platforms are:

(1) to provide high dexterity within the abdominal cavity,
(2) to provide enough precision and stiffness, enabling the performance of accurate surgical procedures,
(3) to have reduced dimensions and
(4) to have low inertia and friction, allowing good force reflecting properties, increasing the transparency of the teleoperated mechanical system.

As an example of application, FIG. **12** shows the overall composition of a mechanical system such as a manipulator, which is able to provide the desired dexterity to the performance of complicated surgical procedures, like pulling and cutting tissue or eventually suturing. This manipulator has high dexterity, high payload capacity, stiffness and precision, with seven degrees of freedom (six to orientate and to move the distal gripper, i.e. DOF1 to DOF6, and one degree of freedom, DOF7, to actuate the gripper **50**). In order to be as

intuitive to control as possible, the degrees of freedom are designed with an anthropomorphic kinematics, resembling a simplified human arm.

Achieving a kinematic model that matches the one of the human arm is a challenging task, especially in cable-driven devices, where the cables must be routed through joint axes while maintaining constant cable length.

Anthropomorphic joint approximations can be modelled at varying degrees of accuracy and complexity. The level of complexity needed for a suitable representation depends highly on the desired tasks to be performed. For this specific system, since it is aimed to control the position and orientation of the end-effector in the 3D space, the movement of each anthropomorphic micro-manipulator is achieved through the articulation of six single-axis revolute joints plus the gripper **50** actuation.

The manipulator degrees of freedom are labelled from J1 to J7 (as DOF1 to DOF7 illustrated in FIG. **12**), from the proximal to the distal joint, in the order shown in FIG. **13**.

The shoulder abduction—adduction and flexion-extension are then modelled as a composition of two intersecting axes, J_1 and J_2. The elbow flexion-extension is modelled by a single axis parallel to the second shoulder axis, J_3. Forearm prono-supination takes place between the elbow and wrist joints as it does in the physiological mechanism, J_4, while two orthogonal joints, J_5 and J_6, represent the wrist flexion-extension and radial-ulnar deviation. The offset between J_5 and J_6 is due to the physical limitation of having two cable actuated joints with intersecting axis. Finally, the gripper actuation is represented by J_7 and is a result of the actuation of both gripper blades about the same axis.

The resultant kinematics is identical to the Elbow Manipulator, which is considered to be the optimal kinematics for a general 6-DOF revolute joint manipulator.

As illustrated in FIG. **13**, joints J_1 and J_4 are modelled as co-axial joints, and joints J_2, J_3, J_5, J_6 and J_7 are pivot joints.

The cabling topology of the entire manipulator using the principle of the present invention is schematically shown in FIG. **14** which uses the above description of configurations of pivot joints and co-axial joints according to the present invention. The design of the mechanism is such that the closed cable loop systems which control each degree of freedom are moved by the same actuated driven pulley placed in the external part of the body.

Pulleys M_1-M_7 actuate joints J_1-J_7 through a set of cable loops, L_1-L_7, that, depending of the degree of freedom, can have one, two or three stages, separated by the loop break lines, LB_1 and LB_2. A single cable loop runs about multiple idler pulleys, which are placed in proximal and distal positions from the driven pulleys and joint idler tubes.

Since each idler pulley is mounted on a ball bearing, in all the closed loops, with the exception of L_6 and L_7, the cables are perfectly aligned with the idler pulleys, idler tubes and driven pulleys. In this way, the idler pulleys don't suffer any torque, which cause them to tilt about an axis orthogonal to the pulley shaft. Since the single pulley bearings are not designed to handle moments, tilting the pulley forces it to rub on its neighboring pulley, creating additional friction. Also, the bearings themselves are not meant to run tilted, which can create even more friction.

Cable loop L_1 is composed by a single loop stage, L_{11}. Starting from the actuated pulley M_1, L_{11} engages directly the driven pulley P_1, passing by two proximal idler pulleys of joint J_1, and returns back to M_1, where both terminations are fixed.

Cable loop L_2 is composed by two loop stages, L_{21} and L_{22}. Starting from the actuated pulley M_2, L_{21} engages the

idler tube (i.e. the joint idler tube/pulley defined above) IT_{21}, passing by two proximal idler pulleys of J_1, and returns back to M_2, where both terminations are fixed. From IT_{21}, L_{22} passes by two distal idler pulleys of J_1 and engages the driven pulley P_2, where both terminations are fixed.

Cable loop L_3 is composed by two loop stages, L_{31} and L_{32}. Starting from the actuated pulley M_3, L_{31} engages the idler tube (i.e. the joint idler tube/pulley defined above) IT_{31}, passing by two proximal idler pulleys of J_1, and returns back to M_3, where both terminations are fixed. From IT_{31}, L_{32} passes by the two distal idler pulleys of J_1, by the idler pulleys (proximal, joint and distal) of J_2 and engages the driven pulley P_3, where both terminations are fixed.

Cable loop L_4 is composed by two loop stages, L_{41} and L_{42}. Starting from the actuated pulley M_4, L_{41} engages the idler tube (i.e. the joint idler tube/pulley defined above) IT_{41}, passing by two proximal idler pulleys of J_1, and returns back to M_4, where both terminations are fixed. From IT_{41}, L_{42} passes by the two distal idler pulleys of J_1, by the idler pulleys (proximal, joint and distal) of J_2 and J_3 and engages the driven pulley P_4, where both terminations are fixed.

Cable loop L_5 is composed by three loop stages, L_{51}, L_{52} and L_{53}. Starting from the actuated pulley M_5, L_{51} engages the idler tube (i.e. the joint idler tube/pulley defined above) IT_{51}, passing by the two proximal idler pulleys of J_1, and returns back to M_5, where both terminations are fixed. From idler tube IT_{51}, L_{52}, which is an endless closed loop cable stage, passes by the two distal idler pulleys of J_1, by the idler pulleys (proximal, joint and distal) of J_2 and J_3 and engages the idler tube IT_{52}. From idler tube IT_{52}, L_{53} passes by the two distal idler pulleys of J_4 and engages the driven pulley P_5, where both terminations are fixed.

For each one of the degrees of freedom J_6 and J_7, the cable loops L_6 and L_7 have a single stage, L_{61} and L_{71}. They run from the actuated pulleys M_6 and M_7 until the distal driven pulleys, P_6 and P_7, passing through the idler pulleys of all the proximal pivot joints of the micro-manipulator. On the other hand, when passing by the co-axial joints J_1 and J_4, they are not passing through idler pulleys and are twisted around the joint axis. However, due to extensive length of the loops, between the actuated and driven pulleys, and the short distance between the cables and the axis of rotation, the resulting stretch of the cables is slight, so that the resulting resistance to rotational motion is almost negligible. The resultant misalignment between the cables and the idler pulleys is also within reasonable limits, avoiding the cables to jump out of their path. This twisting of the cables, however, limit the rotation of the instrument shaft to ±180°, at which point the cables will rub on each other, creating friction and wear.

It is important also to note that, since the most demanding force constraint is on the gripping joints, L_6 and L_7 are running in an opposite phase thru the proximal joint idler pulleys, where both coupling torques are canceled.

The references A_1 to A_7 identify the successive joint axis.

FIG. **15** shows a 3D layout of the cabling for each 7-DOF endoscopic micro-manipulator, related to the cabling schematics described before with the joints of FIG. **13**.

To hold in the 3D space all the components of the cabling scheme, like idler pulleys, ball bearings, and positioning pins and screws, special parts were developed, guaranteeing the perfect positioning and support of all the joint components and allowing the routing of the different cables, considering the complex design of FIG. **15**. Special attention was paid to the assembly precision of the mechanism. Since each idler tube is radial and axially positioned by six external miniature bearings (three on each extremity) as

described here above with reference to FIGS. **10** and **11**, their precise positioning is guaranteed by mounting them on a unique base part **50**, **50'**, schematically illustrated in FIG. **16**, whose production process, for example by CNC milling machining, ensures extremely fine tolerances. Both the proximal and distal links of a coaxial joint have a set of base parts **50**, **50'**, which are fixed together by miniature screws, having their alignment guaranteed by positioning pins. In FIG. **16**, the left side drawing shows the assembled joint as described above previously and the right side drawing shows the joint in the base parts **50**, **50'**, in a mounted state.

As explained before, the distal link has an axial rotation movement in relation to the proximal one. Due to the lack of space, this axial rotation and the linear axial movement constraints are guaranteed by six additional miniature ball bearings **51**, which are fixed to the distal set of base parts, in a configuration similar to the one used for the idler tubes, as illustrated in FIG. **17**. In this way, the miniature ball bearings are in direct contact with an external proximal tube **52**, which is fixed to the proximal set of base parts, enabling the precise rotation of the distal set of base parts in relation to the proximal set of parts. The top drawing of FIG. **17** illustrates the joint of FIG. **16** in top view with a proximal link and a turning distal link, the bottom left drawing illustrates the external bearings **51** on the joint and the bottom right drawing illustrates a cut view of the joint in a tube **52**.

In another aspect, the present invention relates to a mechanical system using the cable transmission described herein to form a teleoperated mechanical device as will be described in detail now.

FIG. **18** gives an overview of the endoscopic unit, with two micro manipulators, whose design details were explained previously, placed in an anthropomorphic and teleoperated configuration. Specifically, FIG. **18** illustrates the overall composition of this system which has a total of 14 degrees of freedom (excluding a possible camera system) with a master M, an insertion tube IT for insertion in the patient and a slave S, comprising the micromanipulators which used the cabled system described above.

This Surgical Platform can be divided in three major subsystems, which are designed to work together, achieving a force reflecting teleoperation. The first one is a 14 degree of freedom micro unit comprising two micro-manipulators, the mechanical slave S, with an anthropomorphic kinematics, equipped with an endoscopic camera system, providing triangulation and intuitive hand-eye coordination.

The shaft S which passes into the patient's P body incision is denominated insertion tube, IT, and not only brings the cable driven mechanical transmission from the exterior but also provides the stable fixation and movement of the slave S unit within the abdominal cavity, see FIG. **19** that illustrates the external positioning degrees of freedom on the insertion tube IT and the slave S inside the patient P.

The 3th subsystem comprises a mechanical master interface M, which is directly connected to the slave S through the fully mechanical cable driven transmission, in such a way that a surgeon's hand movements are reproduced in the slave's tip movements. In this way, the two handles of the master unit assume the same spatial orientation and relative position as the slave tips.

As compared with conventional endoscopic instruments, this mechanical manipulator improves the ergonomics for the surgeon, enabling a positioning of his/her hands in a natural orientation to each other, providing improved eye-hand coordination, intuitive manipulation, and an ergonomic posture.

Furthermore, to optimize the manipulation performances, a surgeon has only to control the movements of the instrument tips, without having the need to hold the insertion tube IT in its desired position within the abdominal cavity. Then, the insertion tube IT should be connected to an external positioning mechanism, linked to a fixed external reference (like ground, surgical bed, etc), which should provide the required 4 DOF, see FIG. **19**, to fix and move the endoscopic subsystem inside the body of a patient P. To optimize force transmission and force feedback, the manipulators composing the master-slave system are designed to have light weight, low inertia, high stiffness and low friction in the joints and mechanical transmission. Finally, the endoscopic unit of the system, which enters the patient's body, is completely bio-compatible and might be able to be decoupled from the manipulators and sterilized.

In order to provide the desired mobility needed to perform complicated surgical procedures, like pulling and cutting tissue or eventually suturing, the internal DOFs are given by the two endoscopic micro-manipulators **60**, **61**, which exhibit high dexterity, high payload capacity, stiffness and precision inside the patient's body. In order to be as intuitive to control as possible, the degrees of freedom are designed to resemble a simplified human arm. The stereoscopic camera will be located between the two manipulators **60**, **61**, providing eye-manipulator alignment similar to human eye-hand alignment, and thus enhancing the telepresence and intuitiveness of the system. This aims to give the impression to the surgeon that he/she is operating inside the patient's body with his/her own two hands.

Anthropomorphic joint approximations can be modelled at varying degrees of accuracy and complexity. The level of complexity needed for a suitable representation depends highly on the desired tasks to be performed. For this specific system, since we aim to control the position and orientation of the end-effector in the 3D space, the movement of each anthropomorphic micro-manipulator **60**, **61** is achieved through the articulation of six single-axis revolute joints plus the gripper.

The manipulator **60** degrees of freedom are labelled from 1 to 7, from the proximal to the distal joint, in the order shown in FIG. **20** which corresponds to FIG. **13** above and its description applies correspondingly.

The shoulder abduction-adduction and flexion-extension are then modelled as a composition of two intersecting axes, J1 and J2. The elbow flexion-extension is modelled by a single axis parallel to the second shoulder axis, J3. Forearm prono-supination takes place between the elbow and wrist joints as it does in the physiological mechanism, J4, while two orthogonal joints, J5 and J6, represent the wrist flexion-extension and radial-ulnar deviation. The offset between J5 and J6 is due to the physical limitation of having two cable actuated joints with intersecting axis. Finally, the gripper actuation is represented by J7 and is a result of the actuation of both gripper blades about the same axis. The resultant kinematics is identical to the Elbow Manipulator, which is considered to be the optimal kinematics for a general 6-DOF revolute joint manipulator.

To allow the insertion of the endoscopic micro-manipulators **60**, **61** inside the abdominal cavity, they are first set to a strait position, aligned with the insertion tube IT axis, and then, after being inserted inside the patient's body, they are finally rotated to their anthropomorphic working configuration, this process being illustrated in FIG. **21**.

In this way, the available cross section diameter for each arm manipulator is maximized, for the same insertion tube IT diameter, specially compared with solutions where both

arm manipulators are inserted at the same time, in a parallel configuration, as shown in FIG. **22**. With this configuration, the micro-manipulators diameter can be doubled and their cross section magnified 4 times, enabling a significant increasing in the achieved stiffness of the system.

FIG. **23** represents a 3D Model of the endoscopic unit **60**, **61** which uses the principles of the present invention as described above with cable transmission and degrees of freedom (J1-J7, see the above description).

To reproduce the movements of surgeon's both hands to the corresponding movements at the instrument grippers a fully mechanical master-slave is used, making use of the novel cable driven transmission described before. An overview of the master-slave system is shown in FIG. **24** comprising the master M, the insertion tube IT and the slave S, this typically comprising the endoscopic unit illustrated in FIG. **23** and preceding figures, as described herein.

The system comprises two sub-teleoperated systems working in parallel. In each one of those systems, an endoscopic micro-manipulator, whose design details were explained above, is mechanically connected to another cable driven manipulator, with exactly the same transmission layout, in such a way that, when one of the systems is moved, the other one has a corresponding movement. In other words, the joint spaces of both systems are equivalent:

$$^{M}q=^{S}q, \forall^{M}q \in W_{M_q} \cap ^{M}q \in W_{M_q}$$

This feature can be achieved by directly connecting both master and slave actuated pulleys for each degree of freedom, $^{M}M_i$ and $^{S}M_i$, as shown on FIG. **25** which illustrates the cabling schematics of the system. This is similar to the system described above in relation to FIG. **14** and its description applies correspondingly. Indeed, in FIG. **25**, the same system is illustrated but only doubled to consider both "arms" of the manipulators **60**, **61**.

The cabling schematic for the entire teleoperated system is then represented in FIG. **26**. It corresponds to the system of FIG. **25** which is doubled (one for the slave S and one for the master M) and the description made above in relation to preceding figures (in particular FIGS. **14** and **25**) apply correspondingly here since the overall system works in an identical way.

With this teleoperated system, the ergonomics of the surgeon is visibly improved. He does not have to stand up with his hands in a non ergonomic position, does not have to manipulate long endoscopic instruments with only 4 DOFs and does not have to adapt to the mirroring effect due to the incision in the patient's body. The surgeon can sit comfortably on a chair, with supported elbows, and with his hands positioned in a natural orientation to each other. Placing the endoscopic camera between the two micro-manipulators, aligned with the insertion tube, together with a properly placed of output screen, the surgeon also will be able to manipulate his own viewing direction.

In order to be placed, fixed and moved within the abdominal cavity, the teleoperated system (master M, insertion tube IT and slave S) supported by an external positioning manipulator **100** (see FIG. **27**), which is fixed relatively to an operating table **101**, able to provide external degrees of freedom to the endoscopic micro-manipulators, in such a way that they can be inserted, positioned and moved within the abdominal cavity of a patient.

An example of such an external positioning device **100** illustrated in FIG. **27** is given in PCT/IB2011/053576, the content of which is incorporated by reference in its entirety in the present application.

Although the present invention has been exemplified by an application on a micro-mechanism for performing minimally invasive surgical procedures, it may also be used for other forms of endoscopic surgery as well as open surgery and also in other devices, not limited to medical applications.

The present mechanical system could also be employed for any suitable remote actuated application requiring a dexterous manipulator with high stiffness and quality force feedback. It can be applied in system with different sizes and different kinds of remote actuations, from manual to computer controlled control.

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, for example by way of equivalent means. Also the different embodiments disclosed may be combined together according to circumstances.

REFERENCES

R. Taylor, P. Jensen, L. Whitcomb, A. Barnes, R. Kumar, D. Stoianovici, P. Gupta, Z. X. Wang, E. deJuan, and L. Kavoussi, "A steady-hand robotic system for microsurgical augmentation," Int. J. Robot. Res., vol. 18, no. 12, pp. 1201-1210, 1999.

M. C. Cavusoglu, F. Tendick, M. Cohn, and S. S. Sastry, "A laparoscopic telesurgical workstation," IEEE Trans. Robot. Autom., vol. 15, no. 4, pp. 728-739, August 1999.

M. Mitsuishi, J. Arata, K. Tanaka, M. Miyamoto, T. Yoshidome, S. Iwata, S. Warisawa, and M. Hashizume, "Development of a remote minimally invasive surgical system with operational environment transmission capability," in Proc. 2003 IEEE Int. Conf. Robot. Autom., Taipei, Taiwan, pp. 2663-2670.

H. Mayer, I. Nagy, A. Knoll, E. U. Schirmbeck, and R. Bauernschmitt, "The Endo[PA]R system for minimally invasive robotic surgery," in Proc. 2004 IEEE/RSJ Int. Conf. Intell. Robots Syst., Sendai, Japan, pp. 3637-3642.

G. Guthart and J. Salisbury, "The intuitive telesurgery system: Overview and application," in Proc. 2000 IEEE Int. Conf. Robot. Autom., San Francisco, Calif., pp. 618-621.

M. Tavakoli, R. V. Patel, and M. Moallem, "A force reflective master-slave system for minimally invasive surgery," in Proc. 2003 IEEE/RSJ Int. Conf. Intell. Robots Syst., Las Vegas, Nev., pp. 3077-3082.

U. Seibold, B. Kubler, and G. Hirzinger, "Prototype of instrument for minimally invasive surgery with 6-axis force sensing capability," in Proc. 2005 IEEE Int. Conf. Robot. Autom., Barcelona, Spain, pp. 496-501.

H. Das, T. Ohm, C. Boswell, R. Steele, G. Rodriguez, S. Charles, and D. Istrate, "Dexterity-enhanced telerobotic microsurgery," in Proc. 8th Int. Conf. Adv. Robot., 1997, pp. 5-10.

G. W. Dachs and W. J. Peine, "A novel surgical robot design: Minimizing the operating envelope within the sterile field," in P^{ro}c. 28th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc., New York, 2006, pp. 1505-1508.

D. J. Abbott, C. Becke, R. I. Rothstein, and W. J. Peine, "Design of an endoluminal NOTES robotic system," in Proc. 2007 IEEE/RSJ Int. Conf. Intell. Robots Syst., San Diego, Calif., pp. 410-416.

K. Ikuta, K. Yamamoto, and K. Sasaki, "Development of remote microsurgery robot and new surgical procedure for deep and narrow space," in Proc. 2003 IEEE Int. Conf. Robot. Autom., Taipei, Taiwan, pp. 1103-1108.

R. Nakamura et al., "Multi-DOF forceps manipulator system for laparoscopic surgery-mechanism miniaturized & evaluation of new interface," in Proc. 4th Int. Conf. Med. Image Comput. Comput.-Assist. Interv., 2000, pp. 606-613.

H. Yamashita, A. Iimura, E. Aoki, T. Suzuki, T. Nakazawa, E. Kobayashi, M. Hashizume, I. Sakuma, and T. Dohi, "Development of endoscopic forceps manipulator using multi-slider linkage mechanisms," presented at the 1st Asian Symp. Comput.-Aided Surg.—Robot. Image-Guided Surg., Tsukuba, Japan, 2005.

J. Arata, M. Mitsuishi, S. Warisawa, and M. Hashizume, "Development of a dexterous minimally-invasive surgical system with augumented force feedback capability," in Proc. 2005 IEEE/RSJ Int. Conf. Intell. Robots Syst., pp. 3207-3212.

D. Salle, P. Bidaud, and G. Morel, "Optimal design of high dexterity modular MIS instrument for coronary artery bypass grafting," in Proc. 2004 IEEE Int. Conf. Robot. Autom., New Orleans, La., pp. 1276-1281.

Y. Kobayashi, S. Chiyoda, K. Watabe, M. Okada, and Y. Nakamura, "Small occupancy robotic mechanisms for endoscopic surgery," in Proc. Int. Conf. Med. Comput. Comput.-Assist. Interv., 2002, pp. 75-82.

P. Dario, M. C. Carrozza, M. Marcacci, S. D'Attanasio, B. Magnami, O. Tonet, and G. Megali, "A novel mechatronic tool for computer-assisted arthroscopy," IEEE Trans. Inf. Technol. Biomed., vol. 4, no. 1, pp. 15-29, March 2000.

J. Peirs, D. Reynaerts, H. V. Brussel, G. D. Genem, and H.-W. Tang, "Design of an advanced tool guiding system for robotic surgery," in Proc. 2003 IEEE Int. Conf. Robot. Autom., Taipei, Taiwan, pp. 2651-2656.

N. Simaan, R. Taylor, and P. Flint, "A dexterous system for laryngeal surgery: Multi-backbone bending snake-like slaves for teleoperated dexterous surgical tool manipulation," in Proc. 2004 IEEE Int. Conf. Robot. Autom., New Orleans, La., pp. 351-357.

K. Ikuta, T. Hasegawa, and S. Daifu, "Hyper redundant miniature manipulator 'hyper finger' for remoteminimally invasive surgery in deep area," in Proc. 2003 IEEE Int. Conf. Robot. Autom., Taipei, Taiwan, pp. 1098-1102.

F. Focacci, M. Piccigallo, O. Tonet, G. Megali, A. Pietrabissa, and P. Dario, "Lightweight hand-held robot for laparoscopic surgery," in Proc. 2007 IEEE Int. Conf. Robot. Autom., Rome, Italy, pp. 599-604.

C. Ishii and K. Kobayashi, "Development of a new bending mechanism and its application to robotic forceps manipulator," in Proc. 2007 IEEE Int. Conf. Robot. Autom., Rome, Italy, pp. 238-243.

The invention claimed is:

1. A mechanical teleoperated surgical device for surgical procedure, the device comprising:

a support tube having a distal region and a proximal region;

a slave unit disposed at the distal region of the support tube, the slave unit comprising:

a plurality of slave links interconnected by a plurality of slave joints;

a plurality of slave driven pulleys coupled to the plurality of slave joints, each of the plurality of slave driven pulleys configured to actuate a degree of freedom; and

a plurality of slave actuation pulleys configured to actuate the plurality of slave driven pulleys;

an end-effector connected to a distal end of the slave unit;

a master unit disposed at the proximal region of the support tube, the master unit comprising:

a plurality of master links interconnected by a plurality of master joints;

a plurality of master driven pulleys coupled to the plurality of master joints, each of the plurality of master driven pulleys configured to actuate a degree of freedom and connected to each of the plurality of slave driven pulleys configured to actuate a same degree of freedom; and

a plurality of master actuation pulleys configured to actuate the plurality of master driven pulleys, the plurality of master actuation pulleys directly connected to the plurality of slave acutation pulleys;

a handle connected to the master unit for operating the mechanical teleoperated surgical device;

a cable driven transmission system coupled between the slave unit and the master unit, the cable driven transmission system comprising a plurality of cables, each of the plurality of cables coupling the plurality of master and slave actuation pulleys and respective plurality of master and slave driven pulleys such that contact force applied on the handle transmits motion between the slave and master units via the cable driven transmission system to move the end-effector at a predetermined selected ratio relative to movement at the handle responsive to the contact force applied thereon; and

an external positioning mechanism coupled to the support tube and configured to provide the support tube movement in four degrees-of-freedom about an incision point.

2. The mechanical teleoperated surgical device of claim 1, wherein the cable driven transmission system is configured such that each of the plurality of slave links of the slave unit and each of the corresponding plurality of master links of the master unit move substantially parallel to each other when the mechanical teleoperated surgical device is operated.

3. The mechanical teleoperated surgical device of claim 2, wherein the end-effector comprises at least three articulated end-effector links interconnected by end-effector joints and wherein the handle comprises at least three articulated handle links interconnected by handle joints.

4. The mechanical teleoperated surgical device of claim 3, wherein a kinematic model of a chain formed by the at least three articulated end-effector links and end-effector joints of the end-effector is identical to a kinematic model of a chain formed by at least three articulated handle links and handle joints of the handle.

5. The mechanical teleoperated surgical device of claim 4, wherein the cable driven transmission system is configured such that each of the at least three articulated end-effector links and each of the at least three articulated handle links move substantially parallel to each other when the mechanical teleoperated surgical device is operated.

6. The mechanical teleoperated surgical device of claim 4, wherein the predetermined selected ratio between the handle and the end-effector corresponds to a ratio between a length of each handle links and a length of each of the at least three articulated end-effector links.

7. The mechanical teleoperated surgical device of claim 1, wherein the mechanical teleoperated surgical device is configured to move in seven degrees-of-freedom.

8. The mechanical teleoperated surgical device of claim 1, wherein the force applied on the handle transmits motion between the slave and master units via a first set of the plurality of cables coupling the plurality of slave actuation pulleys and respective plurality of slave driven pulleys to move the end effector in a first degree-of-freedom, and

wherein the force applied on the handle transmits motion between the slave and master units via a second set of the plurality of cables coupling the plurality of slave actuation pulleys and respective plurality of slave driven pulleys to move the end-effector in a second degree-of-freedom.

9. The mechanical teleoperated surgical device of claim 8, wherein the force applied on the handle transmits motion between the slave and master units via a third set of the plurality of cables coupling the plurality of slave actuation pulleys and respective plurality of slave driven pulleys to move the end-effector in a third degree-of-freedom.

10. The mechanical teleoperated surgical device of claim 8, wherein the mechanical teleoperated surgical device is configured to move in seven degrees-of-freedom.

11. The mechanical teleoperated surgical device of claim 1, wherein each of the slave and master units has an anthropomorphic kinematic model, resembling a simplified kinematics of a human arm.

12. The mechanical teleoperated surgical device of claim 1, wherein at least one of the joints of the master and slave units is of pivot type, where a longitudinal axis of two adjoining links are not aligned and an angle between them changes with a movement of the joint, and wherein at least one of the joints of the master and slave units is of co-axial type, where a longitudinal axis of two adjoining links are aligned or are in a parallel configuration.

13. The mechanical teleoperated surgical device of claim 1, wherein the plurality of cables coupling the plurality of slave actuation pulleys and respective plurality of slave driven pulleys comprises at least one transmission loop of flexible and/or rigid elements mounted to transmit a motion from each of the plurality of master driven pulleys of the master unit to the plurality of slave driven pulleys of the slave unit configured to actuate the same degree of freedom.

14. The mechanical teleoperated surgical device of claim 13, wherein the at least one transmission loop is in the form of cable(s), belt(s) or chain(s).

15. The mechanical teleoperated surgical device of claim 14, wherein each of the plurality of slave and master joints of respective slave and master units comprises at least one co-linear joint idler tube, through which motion is transmitted between proximal and distal transmission loops of the at least one transmission loop.

16. The mechanical teleoperated surgical device of claim 13, wherein each of the plurality of slave and master joints of respective slave and master units comprises at least one co-linear joint idler tube, through which motion is transmitted between proximal and distal transmission loops of the at least one transmission loop.

17. The mechanical teleoperated surgical device of claim 1, wherein the master unit and/or slave unit is connected to the support tube by a coupling unit, which allows the structural connection/disconnection of the master and/or slave units and the cable driven transmission system.

18. The mechanical teleoperated surgical device of claim 1, wherein each of the master and slave units can be locked in a stationary configuration when a surgeon is not holding the handle and when the device is in an active position.

19. The mechanical teleoperated surgical device of claim 1, wherein each of the slave and master units comprises two

slave manipulators and two master manipulators, respectively, each of the two master manipulators configured to be operated independently from the other.

20. The mechanical teleoperated surgical device of claim 1, further comprising an adjustable articulated supporting structure to insert, position and move the slave unit within an abdominal cavity of a patient, allowing passage of the support tube through an incision realized on the patient.

21. The mechanical teleoperated surgical device of claim 1, wherein the support tube has an internal channel adapted to receive a surgical instrument and/or an endoscopic camera.

22. The mechanical teleoperated surgical device of claim 1, wherein a kinematic model of a chain formed by the plurality of slave links and slave joints of the slave unit is identical to a kinematic model of a chain formed by the plurality of master links and master joints of the master unit.

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摘要(译)

一种新型机械系统，基于新型电缆驱动机械传动，能够提供足够的灵活性，刚度，速度，精度和有效载荷能力，以驱动多自由度微操纵器。除了用于手术或其他涉及远程操作的应用的多种关节外科手术器械和机器人系统的可能性之外，它还能够设计新型全机械手术器械，其提供传统腹腔镜检查的优点（低成本，触觉反馈，高有效载荷能力）结合单口手术（单切口，无瘢痕手术，通过腹腔的几个象限导航）和机器人手术（更大的自由度，短学习曲线，高刚度，高精度，增加直觉）的优点。所提出的系统的独特设计提供了直观的用户界面以实现这种增强的可操作性，允许通过控制机械连接的主单元的位置来驱动远程操作的从属系统的每个关节。