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Review of Comanipulation Robot in Surgery

Yue Zhan, Xing-guang Duan*, Jian-xi Li

Intelligent Robotics Institute
Beijing Institute of Technology University
5# Nandajie, Zhongguancun, Haidian, Beijing, China
{zhanyue & duanstar &lijianxi}@bit.edu.cn

***Abstract* – Interaction of human and robot (HRI) is the main problem that impacts the development of robot, especially the surgery robot. Comanipulation is a prime solution, with the novel feature of high backdrivability, high precision because of active constrain control. This paper introduces several comanipulation robots in surgery and summarizes the characteristics of each robot. The challenges and opportunities of comanipulation robots in the future are concluded.**

Index Terms* – *Comanipulation, Backdrivability, Active constrain, Registration, Human-robot interaction

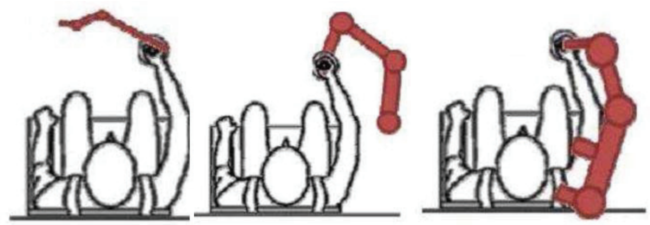
I. INTRODUCTION

Surgical robots have a fast development in recent years with more and more surgical robots used in clinical operation due to the intense research work worldwide. We have seen that these devices and their control can be varied, in order to obtain different features, and sometimes better performances than those obtained through conventional manual practice, in terms of accuracy, repeatability or dexterity. However, the interaction of human and robot which determines whether can exploit the advantages of both human and robot is a main research focus. Comanipulation robots which do not use additional equipment may be the prime solution when remote operation is not needed.

The comanipulation robot is thus any robotic system performing a task, most often in contact with the environment, that can be controlled through direct contact by an operator[1]. It aims to increase the manipulation performances of the operator. The term cobotics is often used to talk about this area. It was invented1, presumably, by J.E. Colgate and M.A. Peshkin, who are also inventors of a patent with the title "Cobots"[2]. It's also called like semiactive robot[3] synergistic robot[4], cooperate robot[5], hands-on robot[6]and collaborative robot[7] by different experts which means the same thing.

Unlike tele-manipulated systems, the devices based on comanipulation assume that the doctor remains close to his/her patient, holding the instruments that perform the gesture. The direct manipulation of the instrument remains in fact the most simple and intuitive way to perform surgery. The robot simply acts like a filter, an active assistance to improve performance and to secure the gesture[8].

Three paradigms of comanipulaor can be seen which are serial comanipulator (see Fig.1 a), parallel comanipulator (see Fig.1 b) and exoskeleton (see Fig.1 c).



a) serial b) parallel c) exoskeleton

Fig. 1 Three paradigms of comanipulator

The serial comanipulator is a system that exhibits mobilities in addition to those of the operator. The mechanism of the comanipulator is thus connected in series with the kinematic chain that consists of the arm and hand of the operator. The parallel comanipulator is a system capable of exerting forces on an instrument in addition to those produced by the operator. The instrument is thus a solid whose proximal part is connected to two parallel kinematic chains (the arm of the operator and the robot), the distal part being in contact with the environment. The active exoskeletons, for instance, are parallel mechanisms with multiple attachment points. They work quite differently compared to parallel comanipulators defined above, but today they have no application in surgical robotics and will not be discussed in this paper.

II. SERIAL COMANIPULATOR

The serial comanipulator is a system that is an approach of surgical instrumentation that aims to increase the dexterity and accuracy of movements performed without moving the surgeon away from the patient or disrupting the operating habits. This is a tool that the operator manually holds at its end called proximal and that can produce a movement of its end called distal, in interaction with the environment.

Micron system (see Fig.2) is a serial comanipulator producing movements intended to compensate for tremors during eye microsurgery operations, designed at the Carnegie Mellon University in the US, which can separate the intentional movements from the parasitic movements.

MCI (motion compensation instrument, see Fig.3) is dedicated to interventions on a beating heart. It features a motorized axis allowing compensation along only 1D of the target organ's movements, for maintaining a distance and/or a constant application of a force between it and the effector, despite the high momentum of heart movements.

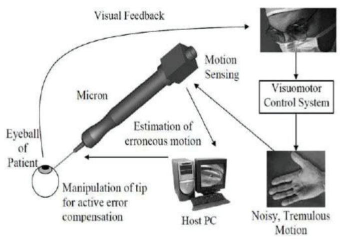


Fig.2 Micron System

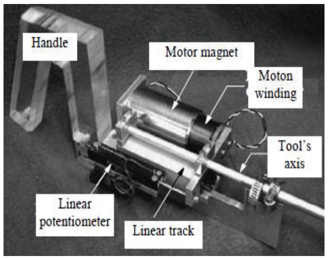


Fig.3 MCI device

MC^2E allows manipulation of a laparoscopic surgery instrument around the insertion point where the trocar is placed. A force sensor is mounted between the trocar and the guidance component of the instrument, so that all forces applied on the instrument, on its distal or proximal part, are measured.

III. PARALLEL COMANIPULATOR

The parallel comannipulator is a system capable of amplifier forces or achieve precious controlled by the operator. There are some commercial platforms or mature researches in parallel comanipulation:

A. *PADyc and Cobot*

PADyC (see Fig.4) stands for Passive Arm with Dynamic Constraints. Its mechanical design enables to constrain the motions of a tool with respect to a preplanned task. for Cardiac Puncturing.

PADyc defines four modes of operation: free mode as a holder; position mode; trajectory mode following a predefined trajectory; region mode for a totally free and unconstrained motion inside the region [9][10]. In order to constrain the motion of the end-effector according to a given task, the conventional actuator of each joint is replaced by a mechanical system that provides four possible functions: both directions, only one direction or no direction at all. Each encoded joint is equipped with a patented mechanism (see Fig.5). It consists of two freewheels mounted in opposition and two electrical motors in order to clutch or unclutch the freewheels independantly. Each motor is electronically constrained to rotate in a single direction.The surgeon is free to propose any direction of motion for the surgical tool attached to the end-effector; the system filters these motions to keep only those which correspond to the pre-planned task.

For each of the freewheels, one part is moved at speed ω_i^+ or ω_i^- by a velocity-controlled motor (which cannot drive the arm) and one is moved at speed ω_i^{op} by the user. Depending on the relative speed ($\omega_i^{op} - \omega_i^{\pm}$), the motion is blocked or not. Thanks to this mechanism, we guarantee that $\omega_i^- < \omega_i < \omega_i^+$ [11][12]. The algorithms allowing computation of the constraint vectors can be generalized in 6-D for a six-degrees-of-freedom robot.

Like PADyC, Cobot[13] is actuated by a human operator (see Fig.6). Cobot very naturally allows the execution of trajectories in space. 'Free motion' and 'motion in a region' modes are not the intrinsic modes and must be achieved through computer control. To allow the user full freedom of motion, the control computer uses a force sensor to detect in which direction the user wishes to move the handle. It then steers the rolling wheel to coincide with the desired direction, much in the way that a castor wheel under the leg of a piece of furniture aligns itself with the desired direction.

B. *Acrobot*

Acrobot means active constraint robot developed by Brain L Davies in Mechatronics in Medicine Laboratory, Department of Mechanical Engineering, London. The surgeon guides the robot by pushing on the force-controlled handle at the tip of the robot, and thus uses his/her superior human senses and understanding of the overall situation to perform the surgery[14], as the surgeon is kept in the control loop. The Acrobot is currently being used in hip or knee replacement[15].

1) Mechanism:

Two generation of Acrobot (see Fig. 7and Fig.8) with different mechanical structures are created. The previous one is a spherical manipulator with three orthogonal axes of motion: yaw, pitch, and extension. It has a relatively small reach (30–50 cm) and range of angles (±30°), which ensures accurate operation with low-powered motors. Consequently, the robot is relatively safe, because potential damage is limited in terms of force and is constrained to a small region. This kinematic structure was adopted so that the mechanical impedance of the axes is low and similar for all axes, allowing the robot to be moved by the surgeon with low force.

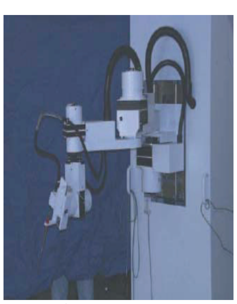


Fig.4 6 DOFs PADyc

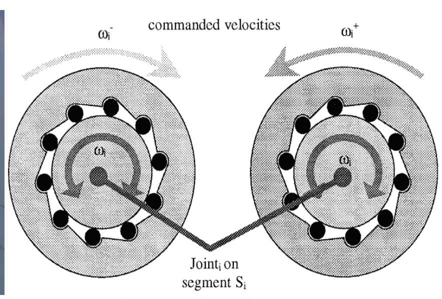


Fig.5 The freewheels mechanism

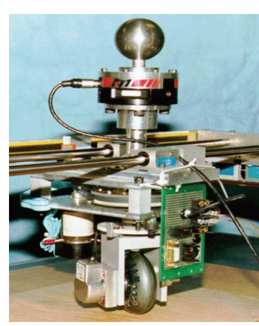


Fig.6 A view of Cobot

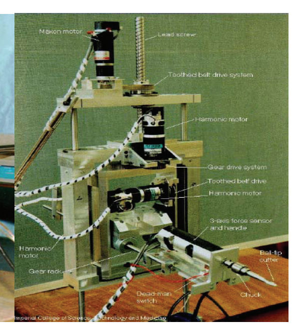


Fig. 7 The previous Acrobot

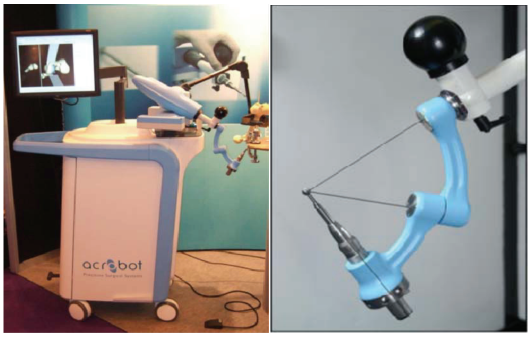


Fig. 8 The Acrobot Sculptor system

The second generation named Acrobot Sculptor utilizes 3 powered axes (pitch, yaw and in/out) to provide location whilst the orientation has a passive linkage that carried the cutter on the end of the arm. This provides a low-cost small robotic system that is light and easy to use. Three axes (pitch, yaw and in/out) are powered, whilst the orientation device that carries the cutter on the end of the arm, is passive and configured to have a common centre of rotation at the centre of the ball cutter as shown in Fig. 8.

2) Registration:

At the start of the operative procedure, it is necessary to register the patient data and pre-operative plan to the current location of the patient and robot. This can be a major source of inaccuracy in the overall procedure. Patient motion monitoring is provided using a mechanical "Microscribe" arm, the tip of which was lightly pinned to the patient's bone[16]. The 6 axes Microscribe arm is passively actuated and had encoders at all joints and a sufficient update-rate that it could monitor patient motion and change the plan and the cutting constraints in real time to maintain the required cutting accuracy. A modified form of Iterative Closest Point (ICP) algorithm was used. To minimize the time and help accuracy this was "bounded" by using the hip centre as a location.

3) Backdrivability:

The handle incorporates a six-axis force sensor, which measures the guiding forces and torques. This force/torque information is used in active constraint control of the robot. Acrobot uses backdrivable motors and transmissions, where conventional robots are usually made strong and stiff at the expense of backdrivability. Good transparency can result due to mechanical sharing of forces between motor and human, made possible by backdrivability and by servo system action aiding the surgeon's desired motion.

4) Active constrain:

The concept of active constraints was first conceived by Professor Brian Davies at Imperial College London as an aid to safety[17]. As the user approaches and then contacts a constraint surface defined in the pre-operative plan, the motors are actuated to gradually increase its resistance until, at the edge of the permitted region, it prevents further motion by the surgeon. This is achieved by a two-level control. Inner loop control gains and demands depend on the d and d_1 are different in the three regions: RI (safe zone), RII (transition zone), and RIII (forbidden zone)[18][19] (see Fig.9).

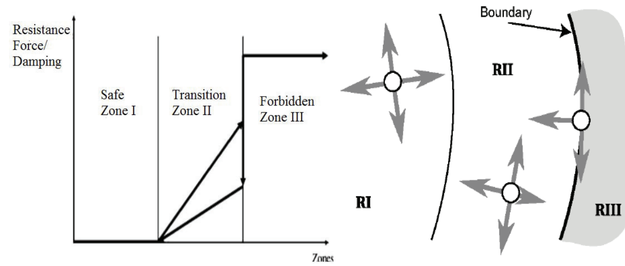


Fig. 9 Active constrain

The simplified formula of resistance $f(\mathrm{d})$ is as follows:

$$f(\mathrm{d}) = \begin{cases} f_{\max} & \text{if } d \le 0 \\ \dfrac{d_1 - d}{d_1} f_{\max} & \text{if } 0 < d < d_1 \\ 0 & \text{if } d_1 \le \mathrm{d} \end{cases} \qquad (1)$$

where $f_{\max}$ is the maximum resistance, d is the distance to the nearest point on the boundary of robot, while d_1 is the distance between RI and RIII.

C. MAKOplasty

MAKOplasty (see Fig.10), which is now owned by Stryker Corp, is proposed to be a semi-active system controlled by the surgeon. It provides both auditory and haptic feedback, limiting milling of the tibia and femur to certain regions. The MAKO system has been focused on UKA[20]; an expansion into acetabular preparation for hip arthroplasty is relatively recent. As of September 2011, the system has been used in more than 10,000 knee arthroplasty procedures[21]. The MAKOplasty Total Hip Application provides accuracy of ± 5 degrees in inclination and version, and ± 2mm to the cup center of rotation to the plan[22].

In order to achieve this function, a new user interactive haptic robotic arm was developed. The design concept of RIO is to enhance the surgeon's skills by providing him with intuitive and interactive tools which increase the safety of the patients, relieve the surgeon's burden to handle the complex surgical environment, and improve surgical outcome. The primary functions of the RIO are measuring the human operator motion in the physical world to explore the virtual and displaying the haptic information to constrain the human motion according to the interacting forces generated in the virtual haptic environments[23].

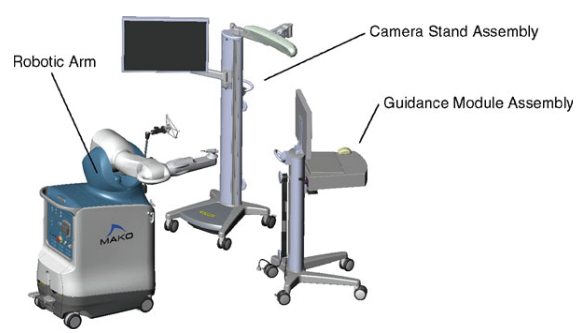


Fig.10 MAKOplasty system

1) Mechanism:

Wire cables attach the drive motor for each joint to the rotational output of each joint through a series of pulleys – to reduce the amount of unsupported cable in the system – and tensioning mechanisms, to remove all back-lash, as shown in Fig.11.

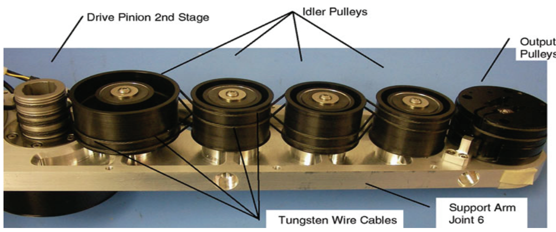


Fig.11 The mechanism of cable drive

2) Registration:

A standard orthopaedic leg holder is used to restrain the leg, combined with bone-mounted trackers to track the bones during the haptic-guided cutting operation. The observed positions by camera of the trackers are used to automatically adjust the position of the haptic environment to compensate for motion of the bony anatomy.

3) Backdrivability:

The use of cable driven systems in the RIO robotic arm provides motion control with low friction and negligible amounts of backlash in the mechanisms.

4) Active constrain:

The back-drivable manipulator permits the surgeon to freely maneuver the cutting tool within the permitted area. Only when moving beyond the desired cutting boundaries will the system push back against the user, creating haptic guidance boundaries that help to keep the surgeon from cutting outside the planned volumes[24].

D. *Surgicobot*

Surgical (see Fig.12) is developed by robotics specialists at the France's centre for atomic energy (CEA) in collaboration with a surgeon from a hospital in Amiens[25] and is applied in laminectomy. Initial tests with Surgicobot have focused on the osteotomy of the lower mandible, a maxillo-facial procedure. It is a textbook case that demonstrates well the advantages of robot-assisted surgery, says Gravez.

1) Mechanism:

The robot mounted on a bridge support that spans the surgical table is placed above the patient. Surgicobot is a serial robot composed of 6 DOFs, combining a 3 DOFs active arm and a 3 DOFs passive wrist[26]. Therefore, no force sensor is required.

2) Registration:

An optical sensor is attached to the third body of the robot to observe the tool tip and its local environment, as depicted in Fig. 13. The camera is a standard CCD model (Point Grey FL2-08S2M/C Camera). A Laser device (352 nm LasirisTM Green Laser), projecting 49 points on the observed scene, is used as a projector.

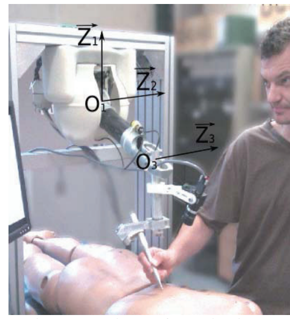


Fig.12 A view of surgicobot

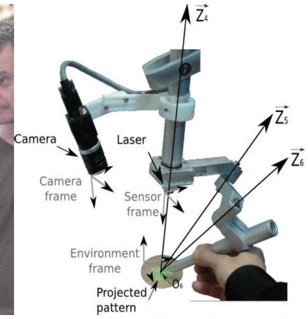


Fig.13 The localizer of surgicobot

3) Backdrivability:

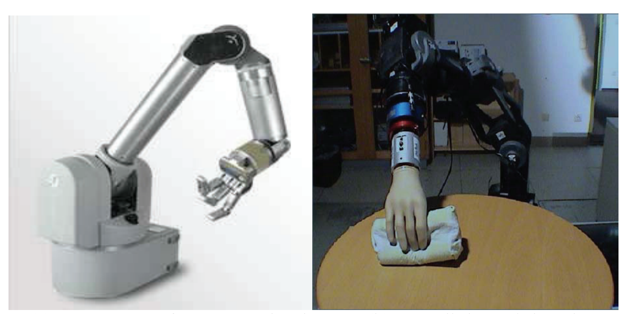
A cable transmission operates a first torque amplification and a one stage gear box operates a second torque amplification. This original combination allows applying large forces while exhibiting very low friction. As a result, Surgicobot is lightweight, compact, powerful and rather backdrivable. Moreover, when the current in the DC motors is null, the milling tool is free of moving along any DOF[27].

4) Active constrain:

Surgicobot is to be programmed in such a way that, above a given surface, the milling tool can be moved freely, whereas the surgeon will not be able of positioning the milling tool below this surface. For a laminectomy procedure, the surface (the limit (b) is sketched in Fig.14) can be designed and registered with the robot according to the pre-define boundary by the surgeon (the limit (a)). The principle of active constrain control is similar to that of Acrobot.

E. *Other robots*

The whole arm manipulator (WAM) (see Fig.16 a) has been further developed and brought to commercial fruition by Barrett Technology, based in Cambridge, Massachusetts[28]. The WAM arm has good backdrivability that enables to intrinsically sense forces over the whole arm by measurement of the torques being applied by the joint drive motors. The MIT engineers have developed an elegant design for a cable-and-cylinder robot transmission system where all basic and wrist axes are driven by 1mm steel cables wrapped around light ceramic-surfaced cylinders[29]. Many researchers research on comanipulation control algorithm based on this platform for the novel feature[30][31][32]. Various control algorithms [33][34][35] are also implemented on similar experiment platform, like DLR light-weight robot (see Fig.16 b)[36].



(a) WAM arm of Barrett technology (b) DLR light-weight robot

Fig.16 Light-weight robot

Robot Of Stereotactic Assistant (ROSA, see Fig.15) is developed by Medtech company in France, which is a commercial robot hitherto distributed in 23 hospitals all over the word and used in stereotactic surgery and SEEG deep electrode implantation. ROSA composed of 6 DOFs, is registered through fixing itself with the head bracket. Although it has backdrivability, ROSA could not intraoperative comanipulate for the strict accuracy requirement of stereotactic. However, it's accessible to operate in comanipulation when registered by laser scanning.

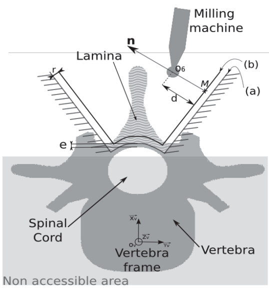


Fig.14 The boundary model

Fig.15 ROSA system

Within the area of surgery, researchers from Johns Hokins University used the LARS robot (Funda et al. 1994) to perform a variety of steady-hand tasks combining hand guiding, active control, and safety constraints in neuroendoscopy and other areas, which was found may take much longer time[37]. Then, they developed the Steady-Hand robot shown in Fig.17. This device was developed for an eye surgery application that requires great accuracy[38]. The robot's controller senses forces exerted by the operator on the tool and by the tool on the environment measured by a sensor, and uses this information in various control modes to provide smooth, tremor-free, precise positional control and force scaling[39][40][41]. Thus, every low frequency force, corresponding to the desired movement, is translated into displacement but every high frequency force corresponding to the tremors is blocked by the system. The result is a more accurate performance of simple gestures, such as the tracking of a straight line or a curve under the microscope[42][43].

There are also some other researches, for example, the programmed breaking[44] like two systems named IMCAS and P-TER based on different technologies have been discussed in Erbse et al.[45] and Davis and Book[46] respectively in early stages. And the localization of force sensors to measure and predict the surgeon's motivation[47] which determine the accuracy of the comanipulation system is conducted.

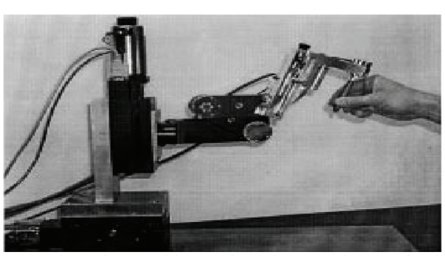


Fig.17 The Johns Hokins University Steady-Hand robot

IV. CONCLUSION

From the different comanipulation robots above, we can conclude in that the main kind of comanipulation in sugery is serial and parallel. In particular, parallel mode is the main kind of comanipilation robot, while serial comanipulation is more about instrument of high flexibility and accuracy. The manipulation robot, taking the advantage of both human and robot, is widely applied in the area of orthopedics for force amplifier and the fine operation such as ophthalmology for precious positional control.

The architecture of robot for backdrivability which is the kernel of parallel comanipulation robot has three main modes: cable transmission, force sensors on the robot and manipulator and the mixed used of them. The mechanism of able transmission preforms well backdrivability. On the contrary, the gear reducer mechanism implements back-drive by measuring and predicting the motion of the surgeon through the sensors mounted on the effector and the comanipulation control algorithm. The registration in the existing parallel comanipulatin robot tends to use additional equipment, like optical navigation or a passive arm with encoders, which will make the system complex and expensive. A real time registration, making a faster progress and better performance of comanipulation robot, need to be developed. Active constrains is an effective way to improve the surgery's accuracy which is almost in the same principle amount the proposed comanipulation robots.

What we can't deny is with the rapid development and popularization of the robot, a safe and flexible interaction in human and robot is inevitable development direction. The same argument applies to surgical robot. The comanipulation robot which has low cost but powerful functions necessary in surgery will be widely used in the next few years.

ACKNOWLEDGMENT

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REFERENCES

[1] Medical robotics[M]. John Wiley & Sons, 2013.
[2] Peshkin M, Colgate J E. Cobots[J]. Industrial Robot: An International Journal, 1999, 26(5): 335-341.
[3] Schneider O, Troccaz J. A six-degree-of-freedom passive arm with dynamic constraints (PADyC) for cardiac surgery application: Preliminary experiments[J]. Computer aided surgery, 2001, 6(6): 340-351. Application: Preliminary Experiments
[4] Davies B. The ACROBOT technology: a model for robotic surgery?[J].
[5] Yen P L, Tsai C H. Cooperative force control of a knee surgical robot for lateral milling of bone[C]//Advanced Robotics and Its Social Impacts, 2007. ARSO 2007. IEEE Workshop on. IEEE, 2007: 1-6.
[6] Ortmaier T, Weiß H, Hagn U, et al. A hands-on-robot for accurate placement of pedicle screws[C]//Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE International Conference on. IEEE, 2006: 4179-4186.
[7] Saito T, Ikeda H. Development of normally closed type of magnetorheological clutch and its application to safe torque control

system of human-collaborative robot[J]. Journal of Intelligent Material Systems and Structures, 2007, 18(12): 1181-1185.
[8] Jlassi S. Formulation et études des problèmes de commande en co-manipulation robotique[D]. Université Paris Sud-Paris XI, 2013.
[9] Troccaz, J. and Delnondedieu, Y(1996) Semi-active guiding systems in surgery.Atwo-dof prototype of the passive arm with dynamic constraints (PADyC). Mechatronics, 6, 399–421.
[10] Schneider O, Troccaz J, Chavanon O, et al. PADyC: a synergistic robot for cardiac puncturing[C]//Robotics and Automation, 2000. Proceedings. ICRA'00. IEEE International Conference on. IEEE, 2000, 3: 2883-2888.
[11] Troccaz J, Peshkin M, Davies B. Guiding systems for computer-assisted surgery: introducing synergistic devices and discussing the different approaches[J]. Medical Image Analysis, 1998, 2(2): 101-119.
[12] Troccaz J, Delnondedieu Y. Semi-active guiding systems in surgery. A two-dof prototype of the passive arm with dynamic constraints (PADyC)[J]. Mechatronics, 1996, 6(4): 399-421.
[13] Colgate, J. E., Peshkin, M. and Moore, C. (1996) Passive robots and haptic displays based on nonholonomic elements. In Proc. IEEE Int. Conf. on Robotics and Automation
[14] Ho, S. C., Hibberd, R. D. and Davies, B. L. (1995) Robot assisted knee surgery. IEEE Engng Med. Biol., 14, 292–300.
[15] Jakopec, M., Rodriguez, F., Harris, S. et al. The hands-on orthopaedic robot 'Acrobot': early clinical trials of total knee replacement surgery. IEEE Trans. Robotics Automn, 2003, 19(5), 902–911.
[16] Microscribe.(2013) http://www.3d-microscribe.com/
[17] Yen P L, Davies B L. Active constraint control for image-guided robotic surgery[J]. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, 2010, 224(5): 623-631.
[18] Jakopec M, Harris S J, Rodriguez y Baena F, et al. The Acrobot® system for total knee replacement[J]. Industrial Robot: An International Journal, 2003, 30(1): 61-66.
[19] Davies B L, Harris S J, Lin W J, et al. Active compliance in robotic surgery—the use of force control as a dynamic constraint[J]. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, 1997, 211(4): 285-292.
[20] Sinha R K. Outcomes of robotic arm-assisted unicompartmental knee arthroplasty[J]. Am J Orthop, 2009, 38(2 Suppl): 20-2.
[21] Ponnusamy K E, Golish S R. Robotic Surgery in Arthroplasty[J].
[22] The Value of Combined Anteversion in Robotic Arm Guided Total Hip Arthroplasty http://www.makosurgical.com/assets/files/clinical/WP_Value_of_Comb_Anteversion_204412r0
[23] Surgical Robotics: Systems Applications and Visions[M]. Springer Science & Business Media, 2011.
[24] Pearle, D. Kendoff, V. Stueber, V. Mushal, and J. Repicci, "Perioperative management of unicompartmental knee arthroplasty using the mako robotic arm system (makoplasty)," The American journal of orthopedics, vol. 38, no. 2S, pp. 16–19, 2009.
[25] Kochan A. A cobotic solution for surgical applications[J]. Industrial Robot: An International Journal, 2004, 31(6): 478-480.
[26] Françoise V, Sahbani A, Morel G. A comanipulation device for orthopedic surgery that generates geometrical constraints with real-time registration on moving bones[C]//Robotics and Biomimetics (ROBIO), 2011 IEEE International Conference on. IEEE, 2011: 38-43.
[27] Françoise V, Sahbani A, Roby-Brami A, et al. Assistance to bone milling: A tool mounted visual display improves the efficiency of robotic guidance[C]//Engineering in Medicine and Biology Society (EMBC), 2013 35th Annual International Conference of the IEEE. IEEE, 2013: 6252-6256.
[28] Rooks B. The harmonious robot[J]. Industrial Robot: An International Journal, 2006, 33(2): 125-130.
[29] Townsend, W.T. Guertin, J.A. (1999), "Teleoperator slave- WAMdesign methodology", Industrial Robot, Vol. 26 No. 3, pp. 167-77.
[30] Sousa C, Cortesao R, Queirós P. Compliant comanipulation control for medical robotics[C]//Human System Interactions, 2009. HSI'09. 2nd Conference on. IEEE, 2009: 265-271.
[31] Cortesao R, Sousa C, Queirós P. Active impedance control design for human-robot comanipulation[C]//American Control Conference (ACC), 2010. IEEE, 2010: 2805-2810.
[32] Cortesao R, Zenowich B, Araújo R, et al. Robotic comanipulation with active impedance control[C]//ASME-AFM 2009 World Conference on Innovative Virtual Reality. American Society of Mechanical Engineers, 2009: 129-135.
[33] Cagneau B, Morel G, Bellot D, et al. A passive force amplifier[C] Robotics and Automation, 2008. ICRA 2008. IEEE International Conference on. IEEE, 2008: 2079-2084.
[34] Duchaine V, Gosselin C M. General model of human-robot cooperation using a novel velocity based variable impedance control[C]//EuroHaptics Conference, 2007 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 2007. Second Joint. IEEE, 2007: 446-451.
[35] Duchaine V, Gosselin C. Safe, stable and intuitive control for physical human-robot interaction[C]//Robotics and Automation, 2009. ICRA'09. IEEE International Conference on. IEEE, 2009: 3383-3388.
[36] Albu-Schaffer A, Ott C, Frese U, et al. Cartesian impedance control of redundant robots: Recent results with the DLR-light-weight-arms[C]//Robotics and Automation, 2003. Proceedings. ICRA'03. IEEE International Conference on. IEEE, 2003, 3: 3704-3709.
[37] Goradia, T. M., Taylor, R. H., and Auer, L. M. 1997. Robot-assisted minimally invasive neurosurgical procedures: First experimental experience. Proc. of the First Joint Conf. of CVRMed and MRCAS. Grenoble, France: Springer.
[38] Üneri A, Balicki M A, Handa J, et al. New steady-hand eye robot with micro-force sensing for vitreoretinal surgery[C]//Proceedings of the... IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomech atronics. IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics. NIH Public Access, 2010, 2010(26-29): 814.
[39] Gonenc B, Handa J, Gehlbach P, et al. A comparative study for robot assisted vitreoretinal surgery: Micron vs. the Steady-Hand Robot[C]//Robotics and Automation (ICRA), 2013 IEEE International Conference on. IEEE, 2013: 4832-4837.
[40] Mitchell B, Koo J, et al. Development and application of a new steady-hand manipulator for retinal surgery[C]//Robotics and Automation, 2007 IEEE International Conference on. IEEE, 2007: 623-629.
[41] Kragic D, Marayong P, Li M, et al. Human-machine collaborative systems for microsurgical applications[J]. The International Journal of Robotics Research, 2005, 24(9): 731-741.
[42] Kumar R, Jensen P, Taylor R H. Experiments with a steady hand robot in constrained compliant motion and path following[C]//Robot and Human Interaction, 1999. RO-MAN'99. 8th IEEE International Workshop on. IEEE, 1999: 92-97.
[43] Kumar R, Berkelman P, Gupta P, et al. Preliminary experiments in cooperative human/robot force control for robot assisted microsurgical manipulation[C]//Robotics and Automation, 2000. Proceedings. ICRA'00. IEEE International Conference on. IEEE, 2000, 1: 610-617.
[44] Taylor, R. H. et al. (1991) A model-based optimal planning and execution system with active sensing and passive manipulation for augmentation of human precision in computer-integrated surgery. In Proc. 2nd Int. Workshop on Experimental Robotics, Toulouse.
[45] Erbse, S., Radermacher, K., Anton, M., Rau, G., Boeckmann W., Jakse, G. et al. (1997) Development of an automatic surgical holding system based on ergonomic analysis. In Troccaz, J., Grimson, E. and M¨osges, R. (eds), Proc. CVRMed/MRCAS'97, Lecture Notes in Computer Science Series, Vol. 1205, 737–746. Springer-Verlag, Berlin.
[46] Davis H, Book W. Torque control of a redundantly actuated passive manipulator[C]//American Control Conference, 1997. Proceedings of the 1997. IEEE, 1997, 2: 959-963.
[47] Lamy X, Colledani F, Geffard F, et al. Overcoming human force amplification limitations in comanipulation tasks with industrial robot[C]//Intelligent Control and Automation (WCICA), 2010 8th World Congress on. IEEE, 2010: 592-598.