Tutorial

Robotics for telesurgery: second generation Berkeley/UCSF laparoscopic telesurgical workstation and looking towards the future applications

M. Cenk Çavuşoğlu
Winthrop Williams
Frank Tendick and
S. Shankar Sastry

The authors

M. Cenk Çavuşoğlu is based at the Department of Electrical Engineering and Computer Science, Case Western Reserve University, Cleveland, OH, USA.
Winthrop Williams and **S. Shankar Sastry** are based at the Department of Electrical Engineering and Computer Science, University of California, Berkeley, CA, USA.
Frank Tendick is at the Department of Surgery, University of California, San Francisco, CA, USA.

Keywords

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Abstract

Robotic telesurgery is a promising application of robotics to medicine, aiming to enhance the dexterity and sensation of regular and minimally invasive surgery through using millimeter-scale robotic manipulators under the control of the surgeon. In this paper, the telesurgical system will be introduced with discussion of kinematic and control issues and presentation of *in vitro* experimental evaluation results.

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1. Introduction

Medical robotics is an active area of research on the application of computers and robotic technology to surgery, in planning and execution of surgical operations and in training of surgeons. In robotic telesurgery, the goal is to develop robotic tools to augment or replace hand instruments used in surgery. In robotic telesurgery, the robotic tools are not automated robots but teleoperated systems under direct control of the surgeon, therefore giving the name *tele*surgery.

In this paper, the robotic telesurgical workstation (RTW) for laparoscopy developed in a joint project between the Robotics and Intelligent Machines Laboratory of the University of California, Berkeley (UCB) and the Department of Surgery of the University of California, San Francisco (UCSF) is presented. We will introduce the UCB/UCSF RTW, with emphasis on design specifications, with discussion of kinematic and control issues and presentation of *in vitro* experimental evaluation results. The conclusion part will discuss the current and future direction of the medical robotics research being conducted at UCB and UCSF in collaboration with the Department of Electrical Engineering and Computer Science of Case Western Reserve University.

1.1 What is minimally invasive surgery?

Minimally invasive surgery (MIS) is a revolutionary surgical technique (Way *et al.*, 1995). It is minimally invasive in the sense that the surgery is performed with instruments and viewing equipment inserted through small incisions rather than by making a large incision to expose and provide access to the operation site. The main advantage of this technique is the reduced trauma to healthy tissue, which is a leading cause for patients' post-operative pain and long hospital

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stay. The hospital stay and rest periods, and therefore the procedure costs, can be significantly reduced with MIS, but MIS procedures are more demanding on the surgeon, requiring more difficult surgical techniques.

The instruments used in MIS have only 4 DOF through the entry port, preventing the ability to arbitrarily orient the instrument tip. Dexterity is significantly reduced because of the lost DOFs and motion reversal due to the fulcrum effect at the entry point. Force feedback is reduced due to the friction at the air tight trocar and the stiffness of the inflated abdominal wall. There is no tactile sensing on which surgeons highly depend in open surgery to locate arteries and tumors hidden in tissue.

Minimally invasive operations include laparoscopy (abdominal cavity), thoracoscopy (chest cavity), arthroscopy (joints), pelviscopy (pelvis), and angioscopy (blood vessels). The first major laparoscopic surgery, for cholecystectomy (removal of the gall bladder) was performed in 1985 by Mühe in (West) Germany. In less than a decade, there was a quick shift from open surgery to laparoscopic surgery for relatively simple procedures with 67 per cent of cholecystectomies performed laparoscopically in the US in 1993 (Graves, 1993). Adoption of laparoscopic techniques has been slower in more complex procedures, largely because of the greater difficulty due to the surgeon's reduced dexterity and perception.

1.2 Robotic telesurgical system concept

MIS is fundamentally a form of telemanipulation as the surgeon is physically separated from the workspace. Therefore, telerobotics is a natural tool to extend capabilities in MIS. The surgical tools can be replaced with robotic instruments which are under direct control of the surgeon through teleoperation (Figure 1).

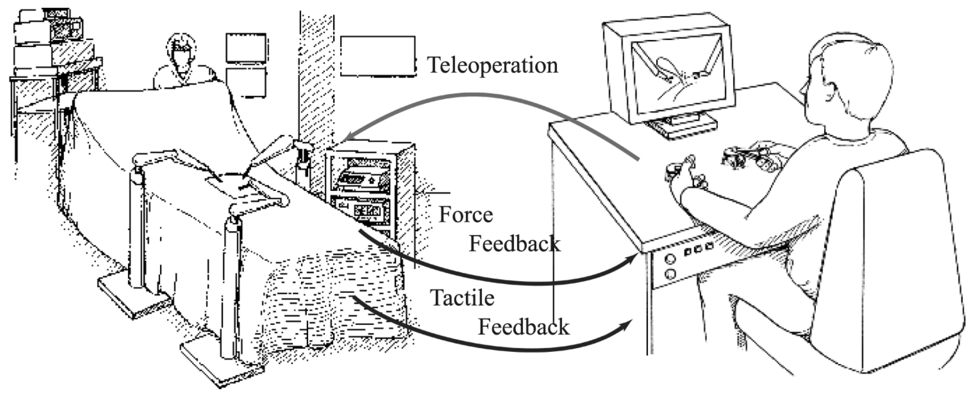
With the telesurgical workstation, the goal is to restore the manipulation and sensation capabilities of the surgeon which were lost due to minimally invasive surgery. A 6 DOF slave manipulator, controlled through a spatially consistent and intuitive master, will restore the dexterity, the force feedback to the master will increase the fidelity of the manipulation, and the tactile feedback will restore the lost tactile sensation.

Other telesurgical systems in the literature for laparoscopic surgery include the telesurgical system for open surgery with 4 DOF manipulators developed at SRI International (Hill *et al.*, 1994) (a laparoscopic version has also been developed), the telerobotic assistant for laparoscopic surgery developed by Taylor *et al.* (1995), the Black Falcon manipulator by Madhani *et al.* (1998), and the telesurgery experiments performed between JPL, California and Polytechnic University of Milan, Italy (Rovetta *et al.*, 1996), and between Nagoya and Tokyo in Japan (Arai *et al.*, 1996). Also, there are two commercial companies, Computer Motion Inc., Goleta, CA, and Intuitive Surgical Inc., Palo Alto, CA, which are developing telesurgical systems intended for minimally invasive cardiac surgery as well as laparoscopy.

It is important to mention at this point that there are other successful medical applications of robotics. These include the ROBODOC system for orthopedic surgery (Taylor *et al.*, 1994), which is an autonomous robotic system to perform total hip replacement surgery, the image guided robotic system for micro-surgery and stereotactic neurosurgery developed by Lavallée *et al.* (1995), the high precision manipulator for micro surgery (eye surgery in particular) developed at NASA Jet Propulsion Laboratory (Schenker *et al.*, 1995), and the image guided planning system for robotic radiotherapy (Tombropoulos *et al.*, 1999). See (Dario *et al.*, 1996; Taylor *et al.*, 1996) for good reviews.

The research problems in the development of a telesurgical system are manipulator design and achieving high fidelity teleoperation. Telesurgical manipulators need to be small, 10 mm or smaller for laparoscopy and 5 mm or smaller for cardiac and fetal surgery, yet have significant workspace and apply forces in the range of several Newtons to be able to manipulate the tissue. At this scale, transmission of sufficient mechanical power is the main challenge. Design of haptic interfaces, 6 DOF, lightweight, high bandwidth manipulators with workspace in the range of several thousand cubic centimetre and with at least 4 DOF, preferably 6 DOF, force feedback, which will serve as master devices, is another active research area.

Figure 1 Telesurgical system concept



Telesurgical tasks require high dexterity and fidelity during manipulation since most of the manipulation is delicate. Therefore, the design requirements for the teleoperation controllers are significantly different from classical teleoperation applications. An important component of the teleoperator design is the quantification of the human operator sensitivity and performance. This is necessary for providing the specifications of the controller as well as measures to evaluate designs. It is also important to have a control design methodology which systematically includes these control design (Çavuşoğlu *et al.*, 2002).

Tactile sensing and display technology is an active research area (Gray and Fearing, 1996; Kontarinis *et al.*, 1995; Moy *et al.*, 2000). Tactile sensors are at a level mature enough for application, however tactile displays are not currently at the necessary scale.

2. Description of the system

A RTW has to either improve existing procedures or enable the surgeons to perform operations previously not possible, to justify the cost and overhead of using a non-conventional and complicated tool in surgery. The target tasks chosen in the design of the UCB/UCSF RTW are suturing and knot tying, which are very difficult to perform with existing laparoscopic tools. This is mainly due to the lack of ability to orient the tip of the tools and the difficulties in hand-eye coordination. This makes many advanced abdominal procedures extremely difficult to be performed laparoscopically. Therefore, the design of the system is oriented explicitly towards easy suturing and knot tying.

The current system is a second generation system, designed for extensive operating room testing in animal experiments as well as testing with *ex vivo* tissue and in training box. Its goal is to verify the concept, i.e. to show that using teleoperated 6 DOF slave manipulators, it is possible to improve dexterity and sensation in laparoscopic surgery, and therefore, improve the surgeons' performance and enable them to perform previously impossible surgical operations.

Previous research on medical robotics at UCB includes the development of an endoscopic manipulator (Wendlandt, 1994), early designs of millirobotic manipulators for laparoscopy (Cohn *et al.*, 1995), and the first generation laparoscopic telesurgical workstation (Çavuşoğlu *et al.*, 1999a, b). The first generation prototype was completed in 1997 and tested in *ex vivo* suturing and knot tying experiments.

2.1 Design requirements

The critical piece of the design of the slave manipulator of the RTW is the distal 2 DOF wrist which extends the 4 DOF available through the entry port and therefore gives enough dexterity to perform complex skills, especially suturing and knot tying, in the minimally invasive setting. The slave must be small enough to fit through incisions of typically 10 mm wide, but also be able to apply forces large enough to manipulate tissue and suture. It must have sufficient workspace to span significant regions in the abdominal cavity and suture at almost arbitrary orientations, yet have a wrist short enough in length to work in constrained spaces. System bandwidth should permit natural motions by the surgeon and haptic feedback with sufficient fidelity. Of course, the system must be safe to be used inside a patient.

Performance goals in the design of the millirobot are given in Table I (courtesy Endorobotics Inc.). These values are estimated for a suturing task, force and movement requirements for driving a needle through tissue and tying a knot. The diameter of the instrument is chosen to fit the standard 10 mm and 15 mm diameter trocars. It is preferable not to have larger diameters as it causes greater damage to healthy tissue. For laparoscopic surgery, it is not necessary to go smaller than 10 mm, and use of a 15 mm instrument is acceptable as there are other instruments, for example staplers, that require a 15 mm trocar. Smaller diameters may be necessary or beneficial for other forms of minimally invasive surgery. For example, for minimally invasive cardiac surgery, the instruments need to be able to go through the ribs, also pediatric laparoscopy and fetal surgery require smaller instruments. The wrist-to-gripper length is determined by the clearance between the abdominal wall and the key organs when the abdomen is pressurized. Torque and force requirements are estimated from measurements on instruments performing suturing in an open surgical setting. Two hundred and seventy degrees of roll rotation is required for driving the needle through tissue in a single movement without regrabbing it. Ninety degrees of wrist flexion with 360° of gross rotation is necessary for suturing at the desired orientations. Seven hundred and twenty degrees of gross rotation is desirable for comfortable operation, reducing the need to readjust the instrument. The speed and bandwidth requirements are set to accommodate the bandwidth of intentional hand movements.

Table I Performance goals for the millirobot

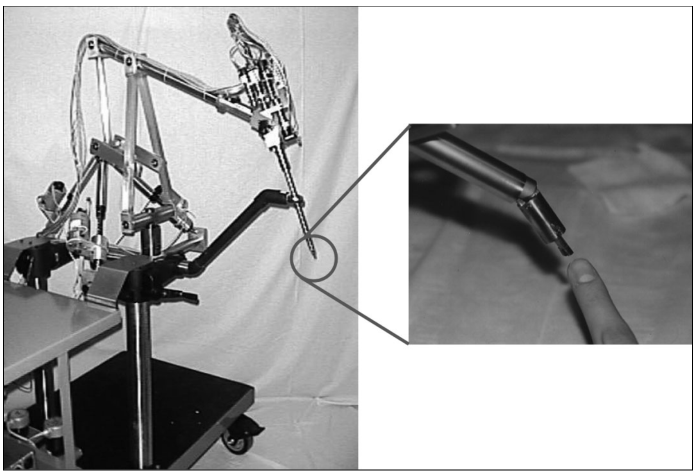
Parameter	Value
Dimension: overall diameter	10-15 mm max
Dimension: wrist joint to grasper	50 mm max
Force: at the point of needle, for driving the needle through tissue	1.5 N min
Torque: about grasper axis, for driving needle (assumes curved needle, 15 mm from grasper to needle tip)	100 N mm min
Torque: wrist flexion (yaw)	300 N mm min
Force: gripping, while driving needle	40 N min
Range of motion: gripper jaw opening	8 mm min
Range of motion: rotation about grasper axis, to drive plus allowance for inclined work surface	270 degrees min
Range of motion: wrist flexion, for driving needle	90 degrees min
Range of motion: wrist pronation	720 degrees min
Speed: grasper, full close in	0.5 s max
Speed: wrist roll	540 degrees/sec min
Speed: wrist flexion	360 degrees/sec min
Bandwidth	5 Hz min
Lifetime	6 months min

2.2 Second generation prototype

The slave manipulator is composed of two parts (Plate 1). The first part is the gross positioning stage located outside the body. It is responsible for positioning the millirobot, which is the second part of the slave robot. The gross stage controls the same 4 DOF as those available in conventional laparoscopic instruments. As the gross stage is located outside the body, there is no tight space limitation. A parallel arrangement is chosen for increased rigidity and a small footprint. Three linear joints, which are connected to the base of the robot with U-joints, control the position of one end of a four-bar linkage. The tool arm and the motors actuating the gross rotation and the millirobot are connected to the opposite end of the four-bar linkage. All four actuators of the gross positioning stage are DC servo motors. In the linear joints, power is transmitted by lead screws connected to the motors. The roll axis through the entry port is tendon driven.

The second part of the slave, the millirobot, is located inside the patient and consequently must be small yet capable of producing a wide range of motion and relatively large forces. To meet these requirements, it has a 2 DOF wrist, with yaw and roll axis rotations, and a gripper (Plate 1). It is 15 mm in diameter.

Plate 1 Slave manipulator of the UCB/UCSF laparoscopic telesurgical workstation. Close-up view of the millirobotic wrist is shown on the right

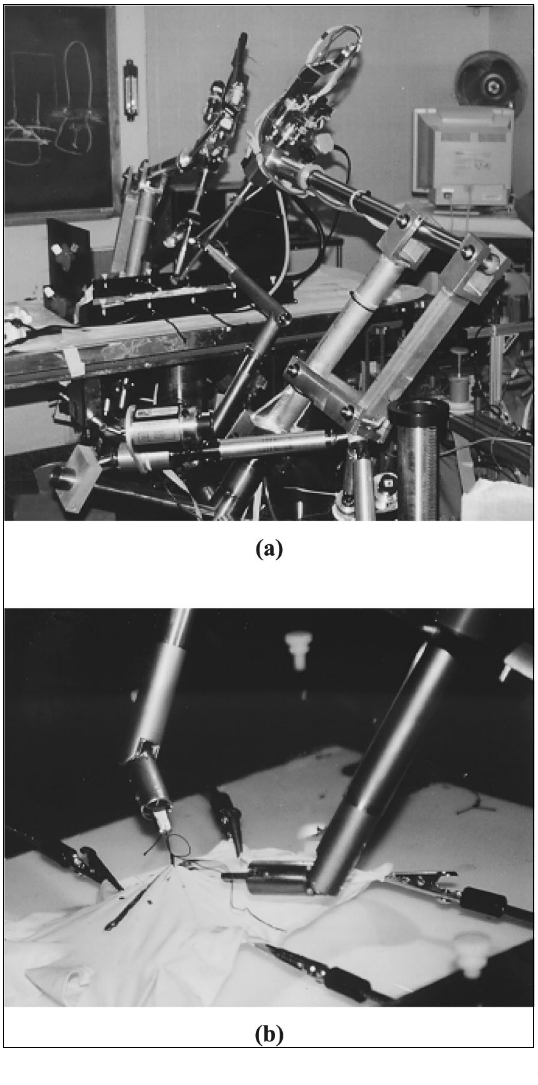


The wrist-to-gripper length is 5 cm. The yaw and roll axes are coupled and actuated with tendons jointed by three DC servo motors located on the end of tool arm outside the body.

Plate 2(a) illustrates the positioning of the bimanual system in the operating room. The two slave manipulators are located at the opposite sides of the operating table. Plate 2(b) shows the close-up view of the millirobotic section while tying a knot. Here, it is possible to see the advantage of having the 2 DOF wrist on the slave which makes it possible to have the nice approach angle and the opposing configuration of the two tools.

The master workstation (Plate 3) is composed of a pair of 6 DOF haptic interfaces, each controlling one of the slave manipulators. Commercial 6 DOF force reflecting haptic interfaces (Phantom v1.5, Sensable Technologies Inc., Cambridge, MA) with three actuated DOF are modified to be kinematically similar to the wrist configuration of the slave manipulators. This is to avoid control problems which would arise because of the wrist singularity and relieve the operator from the burden of dealing with unintuitive behavior of the manipulators around the singularity. The master interfaces are also equipped with a stylus handle to give a more dextrous interface for precise manipulation.

Plate 2 (a) Setup of the bimanual system around the operating table, (b) close-up view of the bimanual system tying a knot in the training box



(a)

(b)

Plate 3 Master workstation of the RTW

3. Experimental evaluation results

The experimental evaluation and the workspace analysis of the RTW help us to make the following observations about the current design and suggestions for the next generation system. (The details of the experimental evaluation of the system can be found in Çavuşoğlu (2000)).

- Although we do not currently have any quantitative results comparing 4 versus 6 DOF manipulator configurations, the user comments suggest that having the 2 DOF wrist (which gives a 6 DOF slave manipulator) greatly improves the ability to suture and tie knots. This observation is further substantiated by the results of the experiments with suturing at different suturing surface orientations and incision directions.
- Even if it is possible to suture and tie knots with the current system, the available range of motion is quite restrictive. Especially, the limited range of the roll axis tend to cause difficulties, requiring the user to pay extra attention to the positioning of this joint during initial grabbing of the needle, and forcing

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seldom regrabbing of the needle. Therefore, it is desirable to increase the range of motion for the roll axis, and to some extent the gross rotation. A range of 720° or higher for the roll axis and 1,000° or higher for the gross rotation should be considered as the design goals for the next generation wrist design.
- The yaw axis range needs to be extended to at least 135° for more comfortable suturing at a wider range of suturing surface angles.
- The instrument diameter needs to be reduced below 10 mm for laparoscopic applications, and to 5 mm to accommodate other important minimally invasive applications, such as cardiac surgery.
- The handles on the master interface needs to be redesigned. The existing configuration, with the stylus handle and the gripper button located at the tip of the handle, was described as unnatural and uncomfortable by the surgeons. Actually, this user interface configuration, difficulty in operating the grippers, and the frequent misfirings of the gripper, is the main reason behind the lower than expected performance of the RTW, relative to conventional laparoscopic tools.
- Ability to replace the end effectors is important for using the system during the different phases of an operation to perform tasks other than suturing, such as holding tissue or dissection. These kind of tasks require different end effector designs.
- It is desirable to have an analog gripper for more effective control of the needle, by making it possible to lightly hold the needle and easily reorient it.
- Although the surgeons were able to successfully suture and tie knots without any force feedback, there were more cases when the needle snapped from the suture or the suture itself was damaged during the suturing experiments with the RTW compared to the conventional laparoscopic tools. This was mainly because of the lack of force feedback, since it is very difficult to judge the amount of force applied to the suture, just with visual feedback. Also, in the absence of force feedback, the forces felt by the operator on the handle are purely the functions of the master characteristics, completely independent of what is happening on the slave side. This sometimes results in misleading haptic cues in terms of what is a natural motion of the slave, and what is not. Therefore, it is necessary to have some form of force feedback to the master from the slave side. For having an effective force feedback, it may preferable to be able to place a force/torque sensor on the slave manipulator, which should also be considered during the designing of the third generation slave manipulator.

In addition to the experiments and analysis performed, functional capabilities of the RTW needs to be further evaluated by performing complete procedures in animal experiments. Animal experiments will also help to evaluate the ergonomics of the slave manipulator setup. Finally studying the learning curve for the RTW will give important insights into the usability of the system.

4. Future

One main future thrust of the research on robotic telesurgery needs to be the design of new manipulators for smaller scale procedures such as cardiac surgery and fetal surgery. It may be possible to go to the scale for some cardiac applications with the existing technology, i.e. with tendons, but for smaller scale it is necessary to have novel actuators and mechanical designs.

Continuation of the research on high fidelity teleoperation is important, because it is necessary to have a methodology to guide the design of manipulators at smaller scale. An interesting research problem here is looking at the mechanical design of teleoperation systems from a control point of view, to reveal the requirements on the mechanical design for better controllability and higher achievable closed loop performance.

4.1 Intelligent robotic tools for off-pump coronary artery bypass graft surgery

Our major research trust in the near future is the development of a system for surgery on the beating heart. This effort will be in the form of collaborative research project between

UCB, UCSF, and Case Western Reserve University.

In Coronary Artery Bypass Graft surgery (CABG) a detour (bypass) is created for the blood to flow around a blockage in a coronary artery. Currently, 85-90 per cent of CABG surgeries are done on-pump, using a cardiopulmonary bypass machine (also known as heart-lung machine), allowing the surgeon to stop the heart in order to perform fine cutting and suturing needed. The remaining 10-15 per cent are performed with the heart still beating (off-pump), enabled by a stabilizing arm, that forcibly constrains a section of the heart. Due to the complications resulting from using cardiopulmonary bypass machine, performing CABG off-pump is highly desirable. However, current off-pump CABG technology is crude, effectively stabilizing the side or back of the heart remains challenging, and off-pump stabilization is inadequate for all but the largest diameter target vessels. Telesurgical robotics technology provides a superior alternative to perform off-pump CABG. Using active relative motion canceling (ARMC), cameras and teleoperated surgical tools mounted on robotic instruments can actively track the heart motion, allowing the surgeon to operate on the beating heart as if it is stationary. Since this method does not rely on passive constraining of the heart, using millimeter scale robotic manipulators it would be possible to operate on the side and back surfaces of the heart as well as the front surface.

Developing robotic tools with ARMC to perform beating heart CABG surgery involves several interesting research problems. For such a system, tracking of the motion of the heart is critical. Effective tracking requires modeling the heart behavior to estimate the expected motion based on mechanical and biological signals, such as EKG and blood pressure. Another important component is the sensing system. For performance and safety reasons, it is necessary to develop a multi-modal and redundant sensing system for measuring heart motion and biological signals. Model based fusion of the information from these multiple sources is an important research component. It is also necessary to build a manipulator with sufficient bandwidth and redundancy to track the motion, yet provide sufficient dexterity to be able to perform surgery. A macro-micro manipulator design would be required, where the macro motion stage will track the motion of the heart and the micro motion stage will be used for fine manipulation.

References

Arai, F., Tanimoto, M., Fukuda, T., Shimojima, K., Matsuura, H. and Negoro, M. (1996), "Multimedia tele-surgery using high speed optical fiber network and its applications to intravascular neurosurgery – system configuration and computer networked implementation", *Proceedings of the IEEE International Conference on Robotics and Automation*, Vol. 1, pp. 878-83.

Çavuşoğlu, M.C. (2000), *Telesurgery and Surgical Simulation: Design, Modeling, and Evaluation of Haptic Interfaces to Real and Virtual Surgical Environments.* PhD thesis. University of California, Berkeley.

Çavuşoğlu, M.C., Sherman, A. and Tendick, F. (2002), "Design of bilateral teleoperation controllers for haptic exploration and telemanipulation of soft environments", *IEEE Transactions on Robotics and Automation*, Vol. 18 No. 4 (in press).

Çavuşoğlu, M.C., Cohn, M., Tendick, F. and Sastry, S.S. (1999a), "Laparoscopic telesurgical workstation", *Video Proceedings of the IEEE International Conference on Robotics and Automation* (ICRA 1999).

Çavuşoğlu, M.C., Tendick, F., Cohn, M. and Sastry, S.S. (1999b), "A laparoscopic telesurgical workstation", *IEEE Transactions on Robotics and Automation*, Vol. 15 No. 4, pp. 728-39.

Cohn, M., Crawford, L.S., Wendlandt, J.M. and Sastry, S.S. (1995), "Surgical applications of millirobots", *Journal of Robotics Systems*, Vol. 12 No. 6, pp. 401-16.

Dario, P., Guglielmelli, E., Allotta, B. and Carrozza, M.C. (1996), "Robotics for medical applications", *IEEE Robotics and Automation Magazine*, Vol. 3 No. 3, pp. 44-56.

Graves, E. (1993), *Vital and Health Statistics*, Data from the National Health Survey No. 122, U.S. Department of Health and Human Services, Hyattsville, MD.

Gray, B.L. and Fearing, R.S. (1996), "A surface micromachined microtactile sensor array", *Proceedings of the IEEE International Conference on Robotics and Automation*, Vol. 1, pp. 1-6.

Hill, J.W., Green, P.S., Jensen, J.F., Gorfu, Y. and Shah, A.S. (1994), "Telepresence surgery demonstration system", *Proceedings of the IEEE International Conference on Robotics and Automation*, pp. 2302-7.

Kontarinis, D.A., Son, J.S., Peine, W. and Howe, R.D. (1995), "A tactile shape sensing and display system for teleoperated manipulation", *Proceedings of the IEEE International Conference on Robotics and Automation* (ICRA'95), Vol. 1, pp. 641-6.

Lavallée, S., Troccaz, J., Gaborit, L., Cinquin, P., Benabid, A.L. and Hoffmann, D. (1995), "Image guided operating robot: a clinical application in stereotactic neurosurgery", in Taylor, R.H., Lavallée, S., Burdea, G. and Mösges, R. (Eds), *Computer Integrated Surgery: Technology and Clinical Applications*, MIT Press.

Madhani, A.J., Niemeyer, G. and Salisbury, J.K. (1998), "The black falcon: a teleoperated surgical instrument for minimally invasive surgery", *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems* (IROS'98) Vol. 2, pp. 936-44.

Moy, G., Wagner, C. and Fearing, R.S. (2000), "A compliant tactile display for teletaction", *Proceedings of the IEEE International Conference on Robotics and Automation* (ICRA 2000).

Rovetta, A., Sala, R., Wen, X. and Togno, A. (1996), "Remote control in telerobotic surgery", *IEEE Transactions on Systems, Man, and Cybernetics – Part A: Systems and Humans*, Vol. 26 No. 4, pp. 438-43.

Schenker, P.S., Das, H. and Ohm, T.R. (1995), "A new robot for high dexterity microsurgery", in Ayache, N. (Ed.), *Computer Vision, Virtual Reality and Robotics in Medicine. First International Conference, CVRMed'95. Proceedings*, Springer-Verlag, Berlin, Germany, pp. 115-22.

Way, L.W.; Bhoyrul, S.; Mori, T. (Eds) (1996), *Computer-Integrated Surgery: Technology and Clinical Applications*, MIT Press, Cambridge, MA.

Taylor, R.H., Funda, J., Eldridge, B., Gomory, S., Gruben, K., LaRose, D., Talamini, M., Kavoussi, L. and Anderson, J. (1995), "A telerobotics assistant for laparoscopic surgery", *IEEE Engineering in Medicine and Biology Magazine*, Vol. 14 No. 3, pp. 279-88.

Taylor, R.H., Mittelstadt, B.D., Paul, H.A., Hanson, W. and Kazanzides, P. et al., (1994), "An image-directed robotics system for precise orthopaedic surgery", *IEEE Transactions on Robotics and Automation*, Vol. 10 No. 3, pp. 261-75.

Tombropoulos, R.Z., Adler, J.R. and Latombe, J.C. (1999), "Carabeamer: a treatment planner for a robotic radiosurgical system with general kinematics", *Medical Image Analysis*, Vol. 3 No. 3.

Way, L.W.; Bhoyrul, S.; Mori, T. (Eds) (1995), *Fundamentals of Laparoscopic Surgery*, Churchill, Livingstone.

Wendlandt, J. (1994), Milli robotics for endoscopy. Memo M94/7, UC Berkley ERL, January 1994.