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A Review of Master–Slave Robotic Systems for Surgery

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Abstract

For decades, men have used robots to overcome their natural limitation in their dealing with the environment. In recent years, robots have been developed to assist surgeons in performing surgeries. Since these robots are meant for surgeons' use, the design and considerations for safety, reliability and human-robot interface become important. One of the most common modes of controlling surgery robots is using a master and slave layout. This paper explores the latest development in the area of master-slave robotic system for surgery

1. Introduction

Although robotics has been widely used in many industries since 1970's, the idea of robots performing surgery on men was not materialized until the late 1990's [1]. This is due to the general perception that robots should be operated away from men for safety reasons.

Humans face several natural limitations that can be overcome by the use of robotics. End effectors and actuators of robots can be made very small allowing complex and agile movements in MIS (minimally invasive surgeries) [2]. Robots can also improve the accuracy and stability of surgeons by scaling large movements made by the surgeons down to micro motion [3]. Surgeon may no longer need to be physically present in performing surgeries, thus promoting teleoperation [4]. These are just some of the advantages on using robotics in surgery. Some of the applications have already been implemented in laparoscopic, thorascopic, endoluminal and arthroscopic interventions [5].

2. Master-Slave Robotic Systems

With the current level of technology, surgery robots are not intended to replace human surgeons. Robots, in general still suffer shortcomings such as the inability to deal with unexpected situations and limited comprehension and interpretation of information. As such, the surgeon, with his perception and decision making skills, is still the main agent taking charge during surgeries. Surgical robots should therefore be viewed as high-end tools that enhance the capabilities of surgeons, and not to replace them

Since the surgeon is in control in most medical robotic systems, an effective human-robot interface has to be present. The interfacing issue becomes more pressing for surgeries where high precision and accuracy are required [6]. Furthermore, surgeons are not specifically used to working with robots. Therefore the design of the interface for surgeons to control the actuate surgery robots has to be intuitive, simple and ergonomic.

One effective mean of providing an intuitive user interface is the use of a master-slave robotic system [7]. The slave robot, in the context of surgery, is the actual robot manipulator that performs the surgery within the patient's body while the master is a device that allows the surgeons to control the slave. This setup is particularly useful if the slave system has many degrees of freedom which require many input parameters simultaneously for smooth handling.

This article focuses on the state of art technology of master-slaves surgical robots. It is not possible to give a comprehensive view on the entire master-slave robots in literature. Instead the authors hope that this review can highlight the many innovative features, differences and state of the art technologies of some of the master-slaves robots mentioned to assist fellow researchers working in or venturing into this field.

da Vinci Surgical System from Intuitive Surgical Inc

The da Vinci robot manipulator provides the 7 DOFs (6 DOF for the positioning and orientation of the end effectors, 1 DOF for grasping) necessary for intuitive manipulation of the tool instrument as shown in Fig 1. Since the slave manipulator has only 4 DOF after passing through the incisions, a 2 DOF wrist is located at the distal end of the manipulator to restore its mobility [8,9].

Intuitive Surgical provides many interchangeable end effectors which can pass through an incision as small as 10 mm wide. The end effectors also contain sensors to provide force feedback to the surgeon [10]. This feature enables the surgeon to feel resistance when the end effectors touch nearby tissue during operation. The da Vinci surgical system employed two medical grade CRT monitors to display the stereo images of the operating sites for the surgeon's view. This highly advanced viewing console allows surgeons to have a 3D image inside a patient body, allowing the surgeon to have natural hand-eye coordination while performing surgery. Additional features that come with the da Vinci master-robotic system are the ability to eliminate the surgeon tremors and motion scaling capability.

The da Vinci surgical system has been approved for use by the FDA in 1998 and can be used for more than 500 surgery procedures. More than 200 da Vinci systems are already clinically used throughout the world

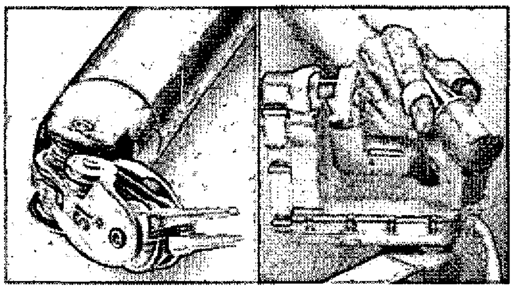

Fig 1: da Vinci's slave and master mechanism adapted from [2]

ZEUS Surgical System from Computer Motion Inc

The main difference between the ZEUS [11,12] system and the da Vinci system lies in the 1 DOF less wrist at the distal end of ZEUS tool bit. Generally a greater number of DOFs will incur more costs and complexity. This is the motivation for developing only 5 DOF for the ZEUS system. In addition to force feedback, anti tremors design and motion scaling capability, the ZEUS surgeon console is capable of understanding and executing voice commands from the surgeons, making the control of the slave more interactive and convenient [13].

The viewing console for the ZEUS system comprises of multiple monitors which can display different views on the surgery as well as patient's vital signs. The master control robot is ergonomically designed and gives surgeon the sensation of controlling the tip of the instrument. ZEUS has also been cleared by FDA in year 2002 and has been used on human patients.

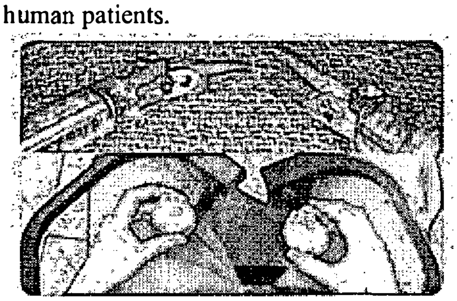

Fig 2: ZEUS's slave and master mechanism adapted from [11]

Robotic telesurgical workstation from UC Berkeley and Department of Surgery of the University of California San Francisco (UCSF),

UC Berkeley and UCSF have developed a prototype robotic system for minimally invasive surgery for telesurgery [14]. The slave robotic manipulator has 4 DOF at the arms, 2 DOF at the wrist and the last degree of freedom is for grasping [15]. Fig 3 shows the layout of the master slave mechanism for this telesurgical workstation.

From the experiment evaluation, one of the greatest drawbacks of the Berkeley telesurgical workstation includes the lack of force feedback in certain DOF from the slave manipulator. With the lack of force feedback, it would be difficult for the surgeon to judge the amount of force that is applied by the slave. This resulted in the damage to the slave's end effectors during the *in vitro* experiment trials.

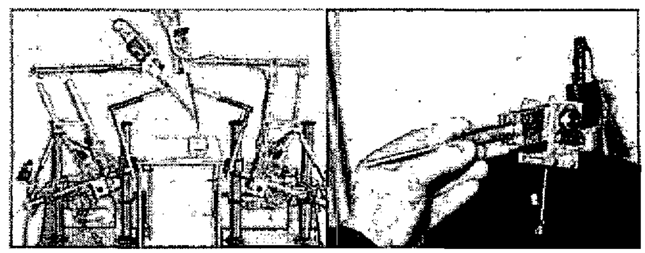

Fig 3: Layout of telesurgical workstation version adapted from [15]

Tele-endoscopic surgical system from University of Tokyo and Kyuushu

A robot capable of microsurgery and teleoperation has been developed by the University of Tokyo and Kyushu [16]. This team paid much attention on ergonomics during the design of the master manipulator such as measuring and studying the motion range of the human body. The master control is designed as though the user is holding onto a pencil and is capable of force feedback.

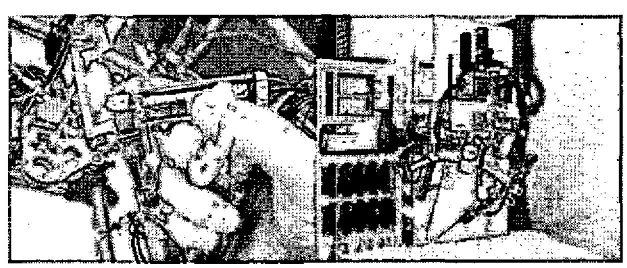

Fig 4: Tele-endoscopic system from Tokyo and Kyushu University adapted from [16]

This SCARA designed slave manipulator is able to control each rotation or translation DOF independently. This allows the robot to maintain the insertion position of the slave manipulator, rendering it safer and its movement more predictable. Much attention was given in designing of the robotic system to deliver 7 DOF force feedback to the surgeon. This means that there is a corresponding sensation to the surgeon for every movement made by the slave manipulator. This allows the surgeon to be safer since he can gauge how much force he had pressed on the patients' tissue.

Using this robotic system, a surgeon successfully performed a cholecystectomy on a pig 150 km away using teleoperation. The measured time delay is approximately 350ms for the visual and auditory information.

ARTEMIS (Advanced Robotics and Telemanipulator System for Minimally Invasive Surgery)

ARTEMIS [17, 18] was developed by Karlsruhe Research Centre in Germany for minimally invasive surgery particularly in the abdominal region. An interesting innovation for ARTEMIS is the 10mm multilink at the end effectors capable of bending more than 180 degrees (See Fig 5). It can position the tip accurately to circumvent organs, vessels or nerve.

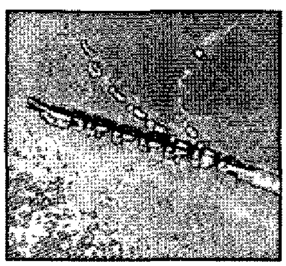

Fig 5:ARTEMIS Multi Link End Effectors adapted from [17]

The master control includes several features such as weight and friction compensation, scaling of motion and force feedback. Several programs have been developed for the use of this system to allow the surgeons to monitor and control the robot. Boundaries can be set using software to prevent the surgeon from engaging sensitive areas specified by the surgeons. A 3D simulator built by Karlruhe research lab itself to offer additional information to the surgeon is displayed on another monitor. Experiments have been performed on animals using the ARTEMIS system and the results gathered seem promising.

Hyper Fingers Robotic System

Developed by Nagoya University, the Hyper Finger [19] robotic system (Fig 6) is used for MIS. Unlike other MIS robotic system, it is bendable and can perform surgeries on hard to reach organs. The end effectors of this robotic system is small enough to pass through a 10 mm incision yet light enough to be mounted on a normal camera tripod stand. Due to its small size and light weight, this make the system highly portable and multiples of it can be used in a single operating theatre.

The slave manipulator has nine DOFs instead of the usual six for other MIS system. This is supposed to allow the surgeon to control the movement of the griper in a smoother fashion. The master manipulator for this robotic system is kinematically similar to the slave manipulator of which the surgeon can control as though it is a pen. *In vivo* experiments on a pig have been performed using this robot system and the surgeons commented on the ease of controls.

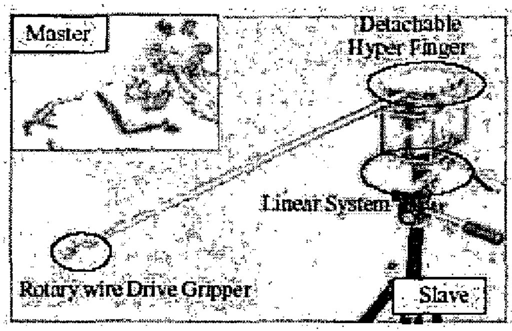

Fig 6: Layout of Hyper Finger robotic system adapted from [19]

Microsurgical Robot for Deep and Narrow Space

Another research project from Nagoya University is a robotic system that can perform surgery in deep and narrow spaces, sometimes without a need for an incision [20]. This robotic system can also reach deep organs which were blocked by other critical organs like the heart or lungs (See Fig 7).

The slave manipulator, with the help of a guide tube, can reach deep and narrow spaces through natural openings like the nasal cavity. One of the reasons why this is achievable is because of the small 3mm diameter end effectors and its flexible body trunk. The actuation of the system is kept smooth with the use of an outer coating for the driving wires which offers lower friction and fixable course for the wires.

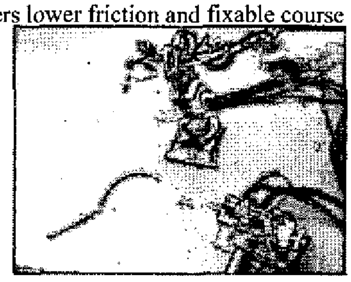

Fig 7: Layout of microsurgical robot system adapted from [20]

The shape of the master resembles a pair of forceps that offers good operability and good control of the slave system. The robotic system allows motion scaling in order to perform microsurgery effectively. Suturing on chicken livers has been successfully performed using this robot system. Although the manipulator manages to reach the deep sites of the body, it requires an additional visual capturing system to be fitted in for monitoring purpose.

RobIn Heart

Developed by Foundation of Cardiac Surgery Development in Zabrze, Poland, Technical University of Lodz and Warsaw University of Technology, RobIn heart was designed to perform MIS, particularly for the heart [21]. Conventional cardiac surgery requires the rib to be taken out which will result in more unnecessary damages to the patient. MIS surgical robots do not face this problem as it can operate on the heart by passing through the gaps between the ribs.

The slave manipulator has 7 DOF for the movement and 1 DOF for actuating the gripper. One additional redundant DOF is located near the wrist of the manipulator to increase maneuverability, avoid obstacle and turn 180 around to operate on the back side of the organ. The arm is made up of parallel mechanism while the wrist is driven by tendons. Special consideration has been taken to prevent the breakdown of the system if one or more tendons break.

Different versions of the master have been built for controlling the slave manipulators such as a modified computer joystick, haptic laparoscopic master robot and keyboard. The haptic laparoscopic master arm is capable of receiving 1 DOF force feedback from the slave. Currently, this robotic system has only been tested on simulations. Animal trials are planned for the future.

NeuroArm

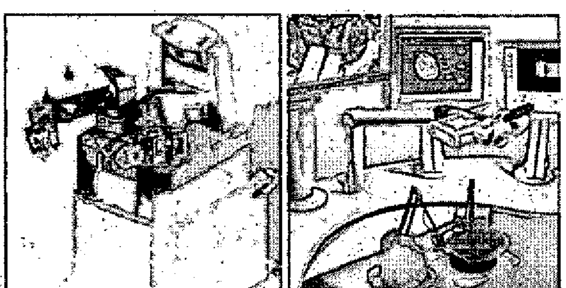

Fig 8: Designer Impression of microsurgical robot system adapted from [22]

The arms of the slave manipulator have 6 DOFs for movement and 1 DOF for the actuation of the end effectors. The mechanism is based on the SCARA configuration as it reduces the number of joints affected by gravity, thus achieving better accuracy. Due to the nature of its usage, the accuracy of the slave manipulator reaches a positional resolution of 30 μm [22]. In addition, this robot is capable of performing surgery under strong magnetic field in an MRI (magnetic resonance imaging) environment. Special attention has also been given to manipulating with soft tissues.

A prototype model has been built and testing has been conducted. It has been reported that the robot will give a more accurate and precise result compared with other traditional methods.

RAM (Robotics Assisted Microsurgery)

This master-slave robot system developed by NASA-JPl and MicroDexterity System, Inc is used to scale down the movement of the surgeon to obtain high precision [23]. The slave manipulator of this robot has a 6 DOF (3 one DOF joint and 1 three DOF joint) robotic arm and is capable of precise movement of up to 10 microns resolution.

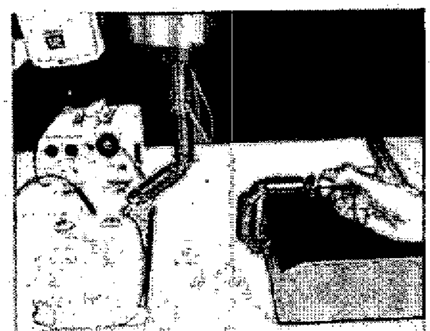

Fig 9: Simulating of Eye Surgery using RAM adapted from [23]

The surgeon controls the end effectors as if holding a pen instead of manipulating it like a wrist. In a simulated surgery as seen in Fig 9, RAM has demonstrated the ability of removing a microscopic 0.015 inch particle from a simulated eyeball.

One area of improvement for this robot could be the introduction of force feedback. This would allow the surgeons to work more safely and effectively.

Microsurgical Telerobot System

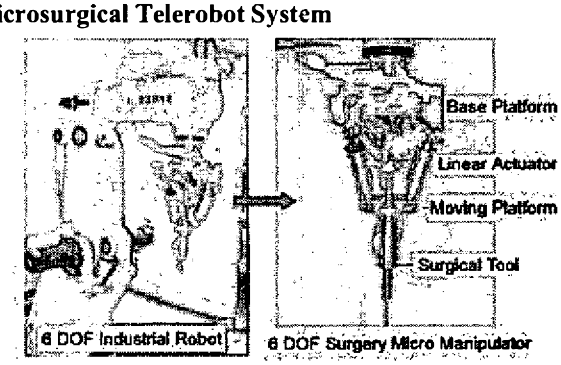

Fig 10: Layout of MicroSurgical slave manipulator adapted from [24]

This robot from KAIST, Seoul, South Korea is another robot for microsurgery such as brain, ophthalmic and microvascular surgeries [24]. It consists of a 6 DOF parallel micromanipulator attached to a 6 DOF industrial robot (See Fig 10). The range of movement for the micromanipulator is limited and thus an industrial robot is required for the rough positioning of the micromanipulator. A parallel micromanipulator is chosen because of its high stiffness and precise positioning in a small space. The micromanipulator is capable of working in a small workspace of 20cm X 20cm X 20cm, with positioning accuracy of at least 50μm.

The master manipulator is also a parallel mechanism and is able to transmit force feedback detected on the slave manipulator. However, control for the master manipulator appears to be difficult and complicated to compute in real time since it involves high order nonlinear equations. The problem is alleviated by the use of three extra encoder sensors at the base platform.

Laparoscopic Robot from Katholieke Universiteit Leuven & University Hospital Gasthuisberg, KULeuven

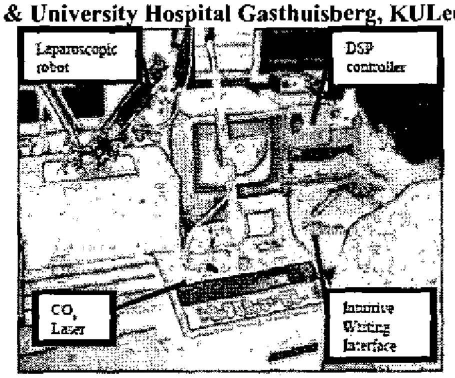

Fig 11: Layout of laser laparoscopic robotic systems adapted from [25]

This robotic system is used for laser laparoscopy, a process popularly used for endometriosis treatment [25].

This interesting robotic system uses the ability of the operator to sketch or write on paper to define the task at hand. Its unique control system is appropriately named as WYDIWYC (What You Draw Is What You Cut).

The slave manipulator is modified from the prototype manufactured by KARL STORZ GmbH & Co, a 4 DOF manipulator with a CO_2 laser attached to it. The master handle for this robotic system consists of a digitizer tablet and a wireless pen with 2 buttons (See Fig 11). The user, seeing the position and orientation of the laser on the TV, only needs to draw out the position on where the laser needs to cut. For safety reasons, the robots will only move if the pen has touched the designated writing pad. This results in a simple interface that requires a very short learning curve. A possible means of further improving the system is by enabling the surgeon to draw directly on the visual display provided instead of on the writing pad.

Although this robotic system is not ready for clinical test yet, users have shown the capability of using the lasers to burn out 3mm X 3mm letters on an apple in a simple lab experiment.

4. Conclusion

A comprehensive review of master-slave surgical robotic systems has been presented in the paper. Table 1 shows a summary comparing the different attributes of the various systems presented. It is evident that such robotic systems are, slowly but surely, making their way into operating theatres in hospitals all over the world. In recent years, they have also gained the acceptance of both surgeons and patients since they do offer certain practiced advantages. The authors hope that this review would serve as a starting point for other researchers who might venture into this exciting field of medical robotics.

Name of System	DOF (Not inclusive of gripper)	Force Reflection	Purpose	Motion Scaling	Teleoperation	Size of incisions (MIS)
da Vinci	6	Yes	MIS	Yes	Yes	10 mm
ZEUS	5	Yes	MIS	Yes	Yes	10 mm
Telemanipulator	6	Yes	MIS	Not Stated	Yes	3.5-5 mm
Tele-endoscopic	6	Yes	MIS	Yes	Yes	10 mm
ARTEMIS	6	Yes	MIS	Yes	Yes	10 mm
Hyper Finger	8	No	MIS	Not Stated	Yes	10 mm
Microsurgical robot	6	No	MIS	Yes	Yes	3 mm
RobIn Heart	7	Yes	MIS	Yes	Not Stated	10 mm
NeuroArm	6	Yes	MIS	Yes	Yes	Not Stated
RAM	6	No	Micro Surgery	Yes	No	NA
KAIST's Telerobot	6	Yes	Micro Surgery	Yes	Yes	NA
Laparoscopic robot	4	No	Laser Laparoscopy	Yes	Yes	Not Stated

Table 1: Summary of attributes of robotic systems

References

[1] Davies, B.; *A review of robotics in surgery*; Proceedings of Institute of Mechanical Engineering 1999, 214: 129-40

[2] Intuitive Surgical Inc. http://www.intuitivesurgical.com/

[3] Hunter I.W., Lafontaine S., Nielsen, P.M.F., Hunter, P.J., Hollerbach, J.M.; *Manipulation and dynamic mechanical testing of microscopic objects using a tele-micro-robot system;* Robotics and Automation, 1989. Proceedings 1989 IEEE International Conference on ,14-19 May 1989; Pages:1553 - 1558 vol.3

[4] Butner, S.E., Ghodoussi, M.; *Transforming a surgical robot for human telesurgery;* Robotics and Automation, IEEE Transactions on ,Volume: 19 ,Issue: 5 ,Oct. 2003 Pages:818 – 824

[5] Taylor, R.H., Lavallee, S., Burdea, G.C., Mosges, E.R.; *Computer Integrated Surgery Technology and Clinical Applications*; Cambridge, MA: MIT Press, 1996

[6] Taylor, R.H., Lavallee, S., Burdea, G., Mosges R., Sheridan, T.; *Human factors in telesurgery;* Computer- Integrated Surgery, Cambridge, MA: MIT Press, 1996, pp223-230

[7] Bergamasco, M., Dario, P., Sabatini, A.; *Advanced interfaces for teleoperated biomedical robots;* Engineering in Medicine and Biology Society, 1989. Images of the Twenty-First Century. Proceedings of the Annual International Conference of the IEEE Engineering in,9-12 Nov. 1989; Pages:912 - 913 vol.3

[8] Guthart, G.S., Salisbury, J.K., Jr.; *The Intuitive^{TM} telesurgery system: overview and application;* Robotics and Automation, 2000. Proceedings. ICRA '00. IEEE International Conference on ,Volume: 1 ,24-28 April 2000 Pages:618 - 621 vol.1

[9] Madhani, A.J., Niemeyer, G., Salisbury, J.K., Jr.; *The Black Falcon: a teleoperated surgical instrument for minimally invasive surgery;* Intelligent Robots and Systems, 1998. Proceedings 1998 IEEE/RSJ International Conference on,Volume: 2 ,13-17 Oct. 1998 Pages:936 - 944 vol.2

[10] Salisbury K. J, Madhani A. J; *Force-reflecting surgical instrument and positioning mechanism for preforming minally invasive surgery with enhanced dexterity and sensitivity*, Patent number: CA2255692, 1997-11-27

[11] Computer Motion Inc http://computermotion.wwwa.com/productsandsolutions/products/zeus/index.cfm

[12] Sanchez Dan, Svanidze Oleg, Uecker Darrin, Wang Y.L.; Wright James; *Microwrist system for surgical procedures;* Patent number: WO03049596, 2003-06-19

[13] Uecker Darrin, Wilson Jeff, Jordan Charles, Laby Keith, Wanf Y.L., Wright James; Ghodoussi Modjtaba; *Method and apparatus for performing minimally invasive surgical procedures,* Patent number: WO0051486; 2000-09-08

[14] Cavusoglu, M.C., Tendick, F., Cohn, M., Sastry, S.S.; *A laparoscopic telesurgical workstation;* Robotics and Automation, IEEE Transactions on ,Volume: 15 , Issue: 4 ,Aug. 1999 Pages:728 – 739

[15] Cavusoglu, M.C., Williams, W., Tendick, F., Sastry, .S.; *Robotics for Telesurgery: Second Generation Berkeley/UCSF Laparoscopic Telesurgical Workstation and Looking towards the Future Applications;* In the Proceedings of the 39th Allerton Conference on Communication, Control and Computing, Monticello, IL, October 3-5, 2001. http://robotics.eecs.berkeley.edu/medical/laparobot.html

[16] Mitsuishi, M., Arata, J.; Tanaka, K., Miyamoto, M., Yoshidome, T., Iwata, S., Hashizume, M., Warisawa, S.; *Development of a remote minimally-invasive surgical system with operational environment transmission capability;* Robotics and Automation, 2003. Proceedings. ICRA '03. IEEE International Conference on ,Volume: 2 , 14-19 Sept. 2003, Pages:2663 - 2670 vol.2

[17] Hermann, R.; *ARTEMIS. A telemanipulator for cardiac surgery;* European Journal of Cardio-Thoracic Surgery, Volume 16, Supplement 2, 1 November 1999, Pages S106-S111

[18] Schurr, M.O., Buess, G., Neisius, B., Voges, U.; *Robotics and telemanipulation technologies for endoscopic surgery, a review of the ARTEMIS project;* Surgery Endoscopy, Volume 14 number 4, April 2000, Pages 375-381

[19] Ikuta, K., Hasegawa, T.. Daifu, S.; *Hyper redundant miniature manipulator "Hyper Finger" for remote minimally invasive surgery in deep area;* Robotics and Automation, 2003. Proceedings. ICRA '03. IEEE International Conference on ,Volume: 1 ,14-19 Sept. 2003. Pages:1098 - 1102 vol.1

[20] Ikuta, K., Yamamoto, K., Sasaki, K.; *Development of remote microsurgery robot and new surgical procedure for deep and narrow space;* Robotics and Automation, 2003. Proceedings. ICRA '03. IEEE International Conference on ,Volume: 1, 14-19 Sept. 2003, Pages:1103 - 1108 vol.1

[21] Nawrat, Z., Podsedkowski, L., Mianowski, K., Wroblewski, P., Kostka, P., Baczynski, M., Malota, Z., Granosik, G., Jezierski, E., Wroblewska, A., Religa, Z.; *RobIn Heart in 2002 - actual state of Polish Cardio-Robot;* Robot Motion and Control, 2002. RoMoCo '02. Proceedings of the Third International Workshop on, 9-11 Nov. 2002 Pages:33 – 38

[22] Calgary Health Trust, Fundraising brochures for NeuroArm; http://www.cbi.ucalgary.ca/CHT%20neuroArm_sep10.pdf

[23] Charles, S., Das, H., Ohm, T., Boswell, C., Rodriguez, G., Steele, R., Istrate, D.; *Dexterity-enhanced Telerobotic Microsurgery;* Proceedings of the 8th International Conference on Advanced Robotics; 1997. p. 5–10. Available from: http://robotics.jpl.nasa.gov/tasks/rams/icar97.pdf

[24] Dong-Soo Kwon, Se Kyong Song; *A Microsurgical telerobot system with a 6-DOF Haptic device;* Proceedings of the 2000 International Symposium on Mechatronics and Intelligent Mechanical System for 21 Century, Kyong Sang Nam-Do, Korea, pp. 65-71, 2000. http://robot.kaist.ac.kr/~songsk/paper/isim2000.pdf

[25] Tang, H.W., Van Brussel, H., Reynaerts, D., Vander Sloten, J., Koninckx, P.R.; *A laparoscopic robot with intuitive interface for gynecological laser laparoscopy;* Robotics and Automation, 2003. Proceedings. ICRA '03. IEEE International Conference on , Volume: 2 , 14-19 Sept. 2003, Pages:2646 - 2650 vol.2