Upgrading Instruments for Robotic Surgery

H. Mayer[1], I. Nágy[1], A. Knoll[1], E.U. Schirmbeck[2] and R. Bauernschmitt[2]
[1]Chair of Robotics and Embedded Systems [2]German Heart Center
Technical University of Munich
{nagy|mayerh|knoll}@in.tum.de, {schirmbeck|bauernschmitt}@dhm.mhn.de

Abstract

During the last decades minimally invasive surgery (MIS) has become an important operation technique and has entered daily practice at most medical sites. Manually performed minimally invasive interventions however suffer from complicated handling due to long instruments and insufficient manipulability inside the body. In addition visual feedback is significantly reduced. These drawbacks were overcome by adoption of robotic systems allowing human-like dexterity and providing a high-quality endoscopic view. Nevertheless those systems themselves have some limitations, like missing force sensory and feedback, and impossibility of cartesian control.
We present in this paper an experimental setup, which we use to tackle both issues. On the one hand we have upgraded surgical instruments (as they are used in robotic surgery) with force feedback capability. On the other hand we have implemented cartesian control for our surgical system and integrated high quality sterescopic view and a simulation environment. With this system we have performed several realistic application examples. Evaluations of these tests have raised necessity for further improvements that will be included into the next version of the instruments.

1 Introduction

Adoption of minimally invasive surgery has had a significant impact on both, patients and surgeons. Patients profit from this new possibility of intervention because of considerably reduced tissue trauma and, on that account, shorter recovery times. On the other hand, minimally invasive operations complicate working conditions for surgeons. They have to cope with an unaccustomed kinematics of surgical instruments, since all operations have to be accomplished through a small port ("keyhole") in the patient's chest. In addition, visual impressions and lighting conditions are limited.
By the application of robotic systems in this field, limitations were partially removed. A sophisticated example for such a system is the *daVinci* workstation (cf. [Guthart and Salisbury, 2000]). It restores full manipulability of the instruments by means of a telemanipulator and provides the surgeon with stereo vision of the operation environment. Another system, which has already been employed for delicate operations, like coronary artery bypass graft, is the *ZEUS* system (cf. [Garcia-Ruiz *et al.*, 1997] and [Boehm *et al.*, 2000]).
Despite the mentioned advantages of robot assisted minimally invasive surgery, all research groups associated with MIS agree about the fact, that the lack of force sensory and force feedback is the severest drawback of currently available systems (cf. [Mitsuishi *et al.*, 2000]). Due to this restriction two major problems arise in such procedures: increased tissue trauma and frequent suture material damage. In order to overcome these hitches, two crucial issues have to be solved. One is inclusion of force sensory and feedback, the other is implementation of full cartesian control of the end effector. The latter is indispensable for calculating exact directions of forces in a known coordinate system. Therefore one of our main research interests is the prototypical construction and evaluation of force sensory/feedback in realistic scenarios of robotic surgery. In particular we focus on instrumental suturing and knot-tying tasks, which are easy to apply when manually executed, but need a lot of experience to be performed via telemanipulation. These tasks, accomplished by human operators, were recorded, and after some processing steps they were autonomously replayed. A key role in this research project is taken by the adjustment of standard minimally invasive instruments (we took the one deployed with the *da Vinci* surgical system) for these challenges.

2 Previous Work

Since the interesting field of robotic surgery has attracted many researchers, there exists a variety of systems with different features implemented by other groups. At the University of California, Berkeley, a robotic system was developed, which has already been used to perform certain surgical tasks like suturing and knot-tying [Cavasoglu *et al.*, 2003]. The Korean Advanced Institute of Science and Technology has developed a micro-telerobot system that also provides force feedback [Kwon *et al.*, 1998]. In Germany two systems for robotic surgery were built at the Research Facility in Karlsruhe [Voges *et al.*, 1997] and at the DLR in Oberpfaffenhofen [Konietschke *et al.*, 2003]. While the first system provides no force feedback, the latter system is equipped with *PHANToM* devices for haptic display. There is also some work available dealing with analysis of knot-tying. At Johns Hopkins University, Kitagawa et al. [Kitagawa *et al.*, 2002] have evaluated occurring forces during knot-tying. They did not measure forces directly at the instruments and during realistic operations, but with a specially designed measurement contrivance. Cao et al. [Cao *et al.*, 1996] have analyzed a variety of surgical tasks (among other things knot tying) and decomposed them into subtasks. They did not include force measurement.

3 Materials and Methods

Like many other systems for robotic surgery, our setup comprises an operator-side master console for in-output and a patient-side robotic manipulator that directly interacts with the operating environment. As one can see in figure 1, our system consists of two manipulators, which are controlled by two input devices. Each manipulator is composed of a Kuka KR 6/2 robot that bears a surgical instrument from Intuitive Surgical Inc. (deployed as part of the daVinci^{TM} surgical workstation). We have developed an adapter to link the robotic arm with the instrument. The surgical instruments have three degrees of freedom. A micro-gripper at the distal end of the shaft can be rotated and adaptation of pitch and yaw angles is possible. Since the yaw angle of each of the two fingers of the gripper can be controlled separately, it is therefore possible to open and close the gripper. All movable parts of the gripper are driven by steel wires. Their motion is controlled by four driving wheels at the proximal end of the instrument, one four each degree of freedom (two for yaw of the fingers). In order to control the instrument, we have flanged servos to each driving wheel by means of an Oldham coupling. This guarantees instrument movement free of jerk. The servo controllers are connected via serial lines to a multiport card.

The Kuka robot has six degrees of freedom. Since the rotation of the robot's flange and the rotation of the instrument share one axis, our system finally has eight degrees of freedom. This redundancy renders the end effector possible to reach every position and orientation within the working space under restriction of so-called trocar kinematics (see below).

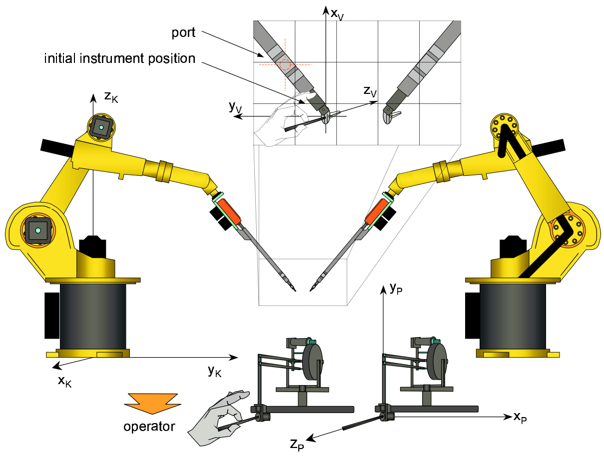

Figure 1: System Overview

Position and orientation of the manipulators are controlled by two PHANToM^{TM} devices from Sensable Inc. (see figure 1). This device is available in different versions with different capabilities. We have chosen the version PHANToM^{TM} Premium 1.5. It has a working space of approx. 20 × 25 × 40 cm, which provides enough space to perform surgical procedures. The user controls a stylus pen that is equipped with a switch that can be used to open and close the micro-grippers.

3.1 Force Feedback

The most interesting feature of the employed PHANToM devices is their capability of displaying forces to the user. Forces are fed back by small servo motors incorporated in the device. They are used to steer the stylus pen in a certain direction. This creates the impression of occurring forces, while the user is holding the pen at a certain posture. Our version of the PHANToM device can display forces in all translational directions, while no torque is fed back. In order to be able to display realistic forces during operation, we have equipped the instruments with force sensors.

Since the shaft of the surgical instrument is made of carbon fibre, force sensors have to be very sensitive and reliable. Therefore we decided to apply strain gauge sensors, which are employed for industrial force registration. As one can see from figure 2, the sensor gauges are applied at the distal end of the instrument's shaft, i.e. near the gripper. At the top of figure 2, one can see the perpendicular arrangement of strain gauges as full bridges. One full bridge of sensors is used for each direction. The signals from the sensors are amplified and transmitted via CAN-bus to a PC system. Since direct sensor reading is flawed with some noise, we have applied a smoothing filter in order to stabilize the results.

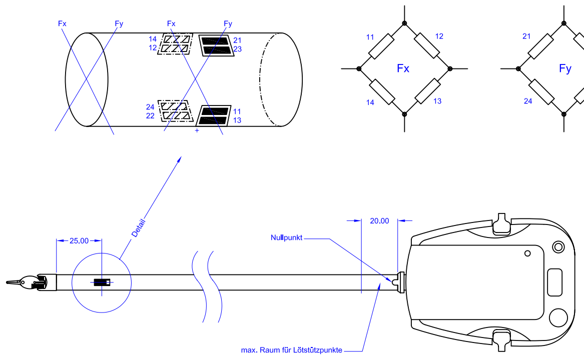

Figure 2: Application of Strain Gauge Sensors

3.2 Trocar Kinematics

The basic idea of minimally invasive surgery is that only small openings have to be made into the surface of the patient's body (so-called keyholes, see figure 3). That means the translational movements of the instruments are essentially restricted by shifts and rotations about these holes. In order to provide the surgeon with a comfortable environment, it is desirable to map the movements of the stylus at the input device directly to instrument motions. Therefore we have to consider the inverse kinematics of our system.

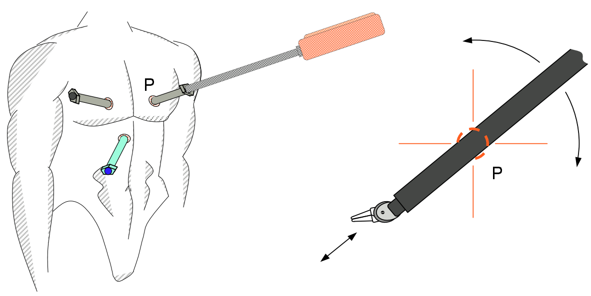

Figure 3: Location of the Instrument and Camera Port

That means we have to find a mapping of an arbitrary posture of the instrument's tip to a position of the motors that control the eight degrees of freedom. The desired position of the instrument is given by the position of the input stylus. It is represented by a homogenous transform matrix. Since the position of the instrument's shaft is restricted by the port (the position of the keyhole), there is only one possibility for aligning the instrument. The angle of the corresponding joints of the instrument can be found by geometric considerations, which are explained in detail in [Mayer *et al.*, 2004].

3.3 Optical System

To enable proper telemanipulation it is indispensable to have a 3D-display providing a distinct vision of the region of interest. In order to allow for such a feature we equipped an additional robot with a 3D endoscopic camera. Like the instruments, this camera can also be moved by means of trocar kinematics and can either be actively controlled by the operator or automatically tracked by the system.
Images taken from the stereo camera system can be displayed via three options. One is a head mounted display (HMD) that is part of our input console. Another possibility is to alternately display left and right images on a CRT-screen. In this case the operator has to wear shutter glasses, which are triggered by the output on the screen. A third option is the projection of the acquired pictures on a silver screen with two video projectors. The projectors have to be equipped with polarizing filters which are orthogonally arranged. Observers have to were glasses with an appropriate polarization for the corresponding eye. Tests have shown, that it is most convenient to work with the shutter system, because the operator is rendered able to see his hands and therefore gets a better hand-eye coordination. That is not possible with the HMD system. Although being an adequate alternative, we had problems with the 3D-projection, because light output of the used projectors was very weak. Therefore we are planning to rerun the test with new video projectors.

3.4 Evaluation of Force Feedback

With the help of this setup we have performed different tasks known from surgical practice and evaluated the impact of force measurement. Our hope is, that haptic feedback contributes to a better performance of systems for robotic surgery by preventing force-induced damages. Examples for such harms are breaking of thread material, ripping tissue and strangulate sutures.

3.5 Winding

The first operation sequence we evaluated was winding thread during knot-tying. Forces are acquired only in the XY–Plane perpendicular to the instrument shaft, as our current setup does not yet allow the measurement of forces along the shaft. Winding thread to form loops

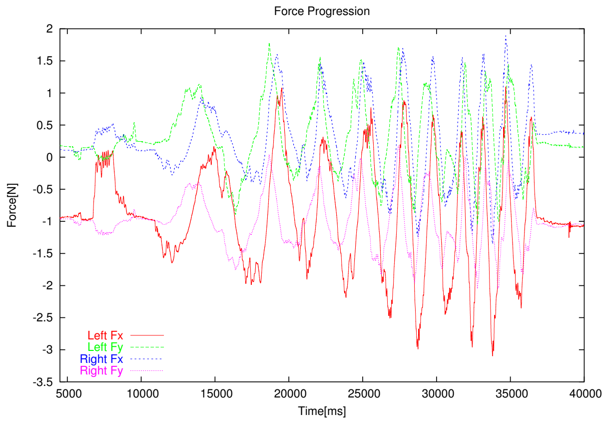

Figure 4: Winding a thread to make loops

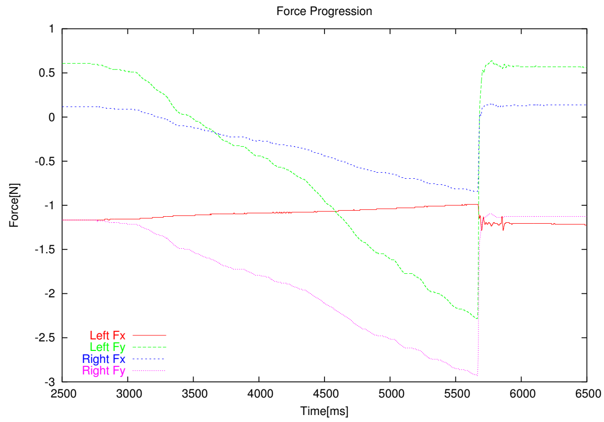

Figure 5: Breaking Ethicon 7/0

is a subtask in instrumental knot-tying (cf. [Cao *et al.*, 1996]), and if executed by a surgeon only very low forces arise, since a human operator easily copes with this task using only visual feedback. However in robot assisted surgery scenarios, high fidelity force sensory is indispensable, as the visual modality is very difficult to interpret. Accordingly, robotic winding can be accomplished only in a force-controlled manner. On the one hand forces are preferably kept constant, on the other hand suture break must be avoided. Fig. 4 shows the force progression during a winding process. The frequency of force peeks in a certain direction grows, as the suture material gets shorter.

3.6 Preventing Suture Material Damage

The tensile strength of absorbable and non-absorbable sutures is critical, both during and after surgical procedures. Having the breaking strengths of all used materials, we are able to prevent suture material damage by limiting the applicable forces to adequate maximal values. Fig. 5 shows the progression of forces while trying to break original surgical suture material, in this case Ethicon PROLENE (7/0, Polypropylen, not absorbable).

3.7 Collision Detection

Avoiding the collision of the instruments in robot assisted minimally invasive surgery is not an easy task. Therefore a symbolic representation of the whole robotic system, including both the instruments and the arms, would be necessary. Furthermore exact position control and a collision detection software subsystem are indispensable. Most setups however do not provide the above mentioned infrastructure. A human operator will easily avoid instrument collisions, but in an autonomous mode other solutions are necessary. A force controlled setup will not prevent collisions, but an early detection can avoid damages of the instruments. Figure 6 shows the forces recorded during an instrument collision. The instrument velocities were within ranges typical to this scenario. We observe, that the highest peak (Y-force component of the left instrument) arises within approximately $35ms$. With a robot arm interpolation of $12ms$ there are nearly 3 interpolation periods to react when such a situation occurs, providing a satisfactory collision interception.

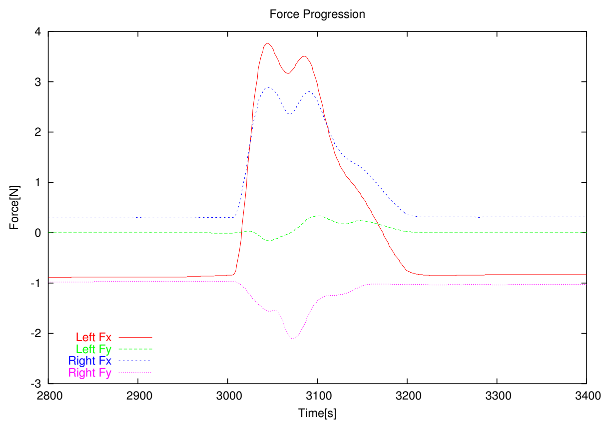

Figure 6: Colliding instruments

3.8 Limitations of Force Sensory

Before incorporating the above mentioned results into our control software, some critical issues still have to be solved. One can be seen above in figures 4 to 6. In these plots force progression does not start at the origin. Unfortunately this is not due to a stable bias, but is due to tension of the wire linkages, when the grippers are closed. This cable tension contributes to a non-neglectible part to the overall force account. Although sensor noise is very low, this phenomenon prevents us from amplifying delicate forces to a sensible level. Currently only relatively high forces (e.g. occurring at collisions and knot-tightening) are perceptible by the user. On the other hand delicate changes in force progression can be measured, but cannot be amplified since they may occur on a high absolute level due to cable tension. Therefore a solution to this issue is highly required.

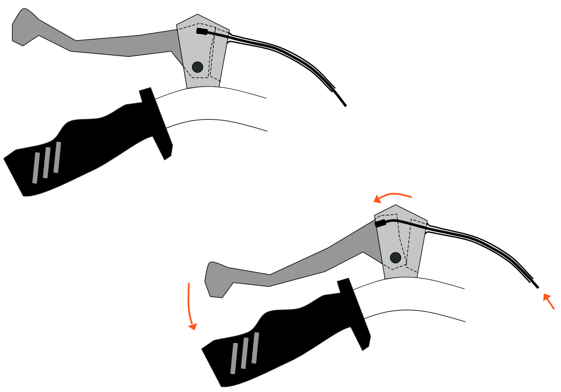

Figure 7: Principle of a Bycicle Brake

One possible remedy, which we will evaluate in the near future, is decoupling force transmission from the instrument shaft. This will be done by a similar construction as one can find in bicycle brakes (see figure 7). When the brake lever is pulled, force is transmitted via a steel wire which is enveloped by a flexible, but incompressible tube. Theoretically no force is applied on the handle bars. In fact it is even possible to transmit breaking forces if the handle bar is cut off.
This idea can be transferred to our instruments. A piece of the instrument is cut out where forces should be measured. This part is replaced by a solid aluminum cylinder. Forces are rerouted about this cylinder by means of enveloped linkages (see figure 8). Now force sensors can be placed on the aluminum cylinder without disturbing measurements by unwanted cable tension.

Another issue that also leads to cable tension is the adjustment of the actuation servos for the instruments. Since steel wires inside the instruments expand after a while, it is necessary to readjust the alignment of the driving wheels of the servos. This is an intricate procedure that often leads to an inappropriate cable tension. Therefore we are planning to replace this construction by a new actuation system based on linear stepping motors (see figure 9). Each linear motor directly exerts forces on one of the instrument's steel wires. Motors are axially

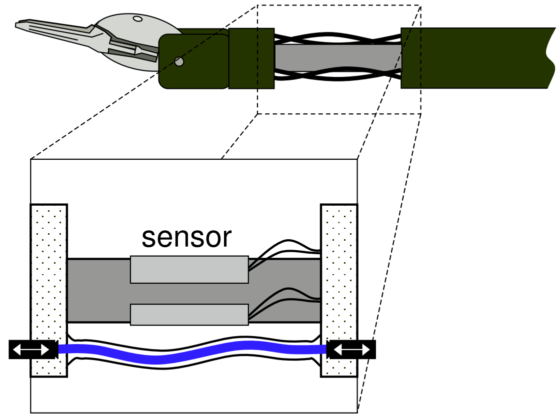

Figure 8: Reroute Forces with Enveloped Linkages

relocatable against each other. Therefore it is easy to adjust the initial posture of the instruments with setscrews. In addition these screws can be combined with springs to absorb suddenly occurring cable tension.

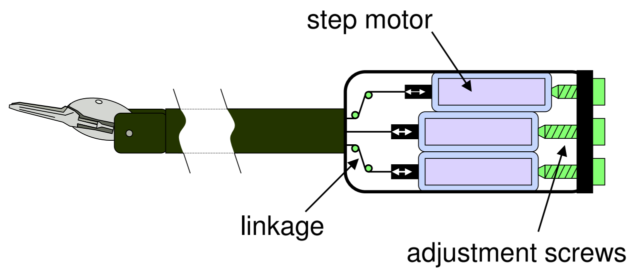

Figure 9: Actuation System with Stepping Motors

4 Partial Autonomy

Regardless of the above mentioned issues we have successfully performed several knot-tying tasks with our system and recorded both, force progression and the corresponding trajectories (described by position and orientation of the instruments).
Our first experiment was replay of a previously recorded knot-tying task. Since our system features a high repeat accuracy, this procedure was performed very reliable. The only prerequisite is positioning the needle at a known place. Since we leave the needle placement to the surgeon and we know the geometry of our system, we can always exactly locate the corresponding position. Due to exact kinematics, execution of up to double speed has raised no difficulties. As our objective is not restricted to acceleration, we also want to generate optimized trajectories with respect to smoothness and path planning. Therefore we have applied spline approximation to the

raw data (see figure 10) . This results in a symbolic representation of the trajectory in the form of a parametric space-curve. Before applying the generated curve to the real system, collision avoidance has to be guaranteed, since overmodified paths can contingently result in instrument collision.

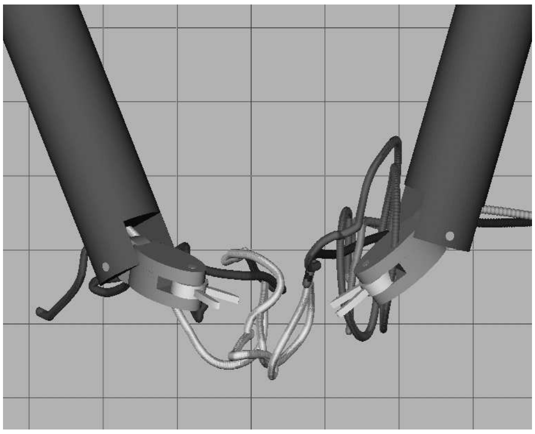

Figure 10: Spline Approximated Trajectory (Knot-Tying)

5 Conclusion

We have presented a novel approach of a robotic system for minimally invasive surgery. The main purposes of the system are evaluation of force feedback and machine learning. We found out that performance of certain surgical tasks like knot-tying will profit from this feature. Experiments have shown that haptic feedback can be employed to prevent the surgeon from potentially harmful mistakes. Tension of thread material and tissue parts can be measured and displayed in order to restrict force application to a tolerable amplitude. Collision of instruments can be detected and intercepted by real-time force evaluation. Forces are measured at the surgical instruments and feeded back into the surgeon's hands using multi-dimensional haptic styluses. For future evaluation we are planning to improve the setup of our instruments and then incorporate the results of force evaluation into our control software. Currently we are also working on a simulation environment that can be used to model haptic interaction with a tissue model. This can be applied for off-line evaluation of critical tasks.

References

[Guthart and Salisbury, 2000] G. S. Guthart, J. K. Salisbury: The *Intuitive*^{TM} Telesurgery System: Overview and Application, IEEE ICRA, San Francisco, CA, April 2000.

[Garcia-Ruiz *et al.*, 1997] A. Garcia-Ruiz, N. G. Smedira, et al.: Robotic surgical instruments for dexterity enhancement in thoracoscopic coronary artery bypass graft, J Laparoendosc Adv Surg Tech 7(5), pp. 277-283, 1997.

[Boehm *et al.*, 2000] D. H. Boehm, H. Reichenspurner, et al.: Clinical use of a computer-enhanced surgical robotic system for endoscopic coronary artery bypass grafting on the beating heart, Thorac Cardiov Surg 48, pp. 198-202, 2000.

[Konietschke *et al.*, 2003] R. Konietschke et al.: Optimal Design of a Medical Robot for Minimally Invasive Surgery, *2. Jahrestagung der Deutschen Gesellschaft fuer Computer- und Roboterassistierte Chirurgie (CURAC)*, Nuernberg, Germany, 2003.

[Kwon *et al.*, 1998] D. Kwon et al.: Microsurgical Telerobot System, *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 945-950, 1998

[Voges *et al.*, 1997] U. Voges et al., Evaluation of ARTEMIS: the Advanced Robotics and Telemanipulator System for Minimally Invasive Surgery, *Proceedings IARP 2nd Workshop on Medical Robotics*, pp. 137-148

[Cavasoglu *et al.*, 2003] M. Cavasoglu et al.: Robotics for Telesurgery: Second Generation Berkeley/UCSF Laparoscopic Telesurgical Workstation and Looking towards the Future Applications, *Industrial Robot, Special Issues on Medical Robotics*, Vol. 30, no. 1, 2003

[Ottensmeier *et al.*, 1999] J. Thompson, M. Ottensmeier and T. Sheridan: Human factors in telesurgery: effects of time delay and asynchrony in video and control feedback with local manipulative assistance, Telemed Journal 5(2), pp. 129-137, 1999

[Kitagawa *et al.*, 2002] M. Kitagawa, A. M. Okamura et al.: Analysis of Suture Manipulation Forces for Teleoperation with Force Feedback, Technical Report, Johns Hopkins University, Baltimore MD, USA, 2002

[Cao *et al.*, 1996] C. Cao, C. MacKenzie and S. Payandeh: Task and motion analyses in endoscopic surgery, Proceedings ASME Dynamic Systems and Control Division, pp. 583-590, Atlanta, USA, 1996

[Mitsuishi *et al.*, 2000] M. Mitsuishi, S. Tomisaki et al.: Tele-micro-surgery system with intelligent user interface, IEEE International Conference on Robotics and Automation, pp. 1607-1614 San Francisco, CA, April 2000.

[Mayer *et al.*, 2004] H. Mayer, I. Nágy and A. Knoll: Kinematics and Modelling of a System for Robotic Surgery, Proceedings on Advances in Robot Kinematics, pp. 181-190 Sestri Levante, Italy, June 2004.