Robot Assisted Force Feedback Surgery

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Summary. Minimally invasive surgery characterizes a sophisticated operation technique in which long instruments are inserted into the patient through small incisions. Though providing crucial benefits compared to open surgery (i.e. reduced tissue traumatization) it is also faced with a number of disadvantages. One of the major problems is that the surgeon cannot access the operating field directly and, therefore, can neither palpate tissue nor sense forces. Furthermore, the dexterity of the surgeon is reduced as the instruments have to be pivoted around an invariant point.

To overcome some of the drawbacks, telepresence constitutes a promising approach. The surgical instruments can be equipped with miniaturized force/torque sensors and contact forces can be displayed to the surgeon using a suitable man-machine interface. Furthermore, instruments can be built with additional degrees of freedom at the distal end, providing full dexterity inside the patient's body. Thanks to telepresence the surgeon regains direct access to the operating field, similar to open surgery.

In this chapter a prototypical force reflecting minimally invasive robotic surgery system based on two surgical robots is presented. The robots are equipped with a sensorized scalpel and a stereo laparoscope for visual feedback. The operator console consists of a PHANToM force feedback device and a stereoscopic display. Experimental results of a tissue dissection task revealed significant differences between manual and robot assisted surgery. At the end of the chapter some conclusions based on the experimental evaluation are drawn, showing that both, manual and robotic minimally invasive surgery have specific advantages.

1 Introduction and Motivation

In conventional open surgery the surgeon has full access to the operation area and thus can use all senses for the demanding task of surgery. In contrast to this, in minimally invasive surgery the access is restricted as the surgeon works with long instruments through small incisions.

In this section the peculiarities of manual minimally invasive surgery (MIS) are described and advantages as well as disadvantages are discussed. Subsequently, a short introduction in minimally invasive robotic surgery (MIRS) is given which illustrates the research needs.

1.1 Minimally Invasive Surgery

Minimally invasive surgery is an operation technique which was established in the 1980s. In contrast to conventional, open surgery there is no direct access to the operating field and the surgeon employs long, slender instruments. These are inserted into the patient through narrow incisions which are typically smaller than 10 mm (see Figure 1).
The main advantages of MIS, compared to open surgery, are reduced pain and trauma, shorter hospitalisation, shorter rehabilitation time and cosmetic advantages. However, MIS is faced with at least three major disadvantages [Treat, 1995]: (a) As the surgeon does not have direct access to the operating field the tissue cannot be palpated any more. (b) Because of the relatively high friction in the trocar[3] and due to the torques which are necessary to rotate the instrument around the entry point, the contact forces between instrument and tissue can hardly be sensed. This is especially true when the trocar is placed in the intercostal space (between the ribs). (c) As the instruments have to be pivoted around an invariant fulcrum point (see Figure 1), intuitive direct hand-eye coordination is lost. Furthermore due to kinematic restrictions only four degrees of freedom (DoF) remain inside the body of the patient. Therefore, the surgeon cannot reach any point in the work space at arbitrary orientation. This is a main drawback of MIS, which makes complex tasks like knot tying very time consuming and requires intensive training [Helmy, 2001, Sauerland et al., 2002]. As a consequence MIS did not prevail as desired by patients as well as by surgeons and while most standard cholecystectomies (gall bladder removal) are performed minimally invasively in the industrialised world, MIS is hardly used in any other procedure to this extent.

1.2 Minimally Invasive Robotic Surgery

Robotic and mechatronic systems become a key technology for coping with the drawbacks of manual MIS. Together with telemanipulation techniques they enable a surgeon to regain full access to the operation field. Minimally invasive robotic surgery provides at least five potential advantages: (a) Small force/torque sensors placed near the instrument tip can measure manipulation forces/torques directly and thus, provide kinesthetic feedback when displayed to the surgeon [Seibold and Hirzinger, 2003]. (b) Actuated instruments

[3] The trocar is a surgical instrument, which makes it possible to create incisions in a visceral cavity (i.e. thorax, abdominal cavity) and keep it open with the aid of a tube.

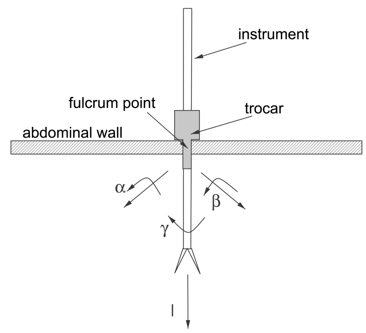


Fig. 1. Schematic exposition of the situation in MIS: The instrument is moved around an invariant fulcrum point. In consequence the surgeon can command only four degrees of freedom (α, β, γ, l) inside the patient's body.

with two additional DoF give back full dexterity inside the human body. (c) The undesired reverse hand motion can be avoided by appropriate control algorithms [Ortmaier and Hirzinger, 2000a]. (d) More accurate movements are possible as the surgeon's hand motion can be scaled down before being transmitted to the robot. Additionally, the surgeon's tremor can be reduced by low-pass filters. (e) Furthermore, autonomous functions such as motion compensation can be realized by MIRS telepresence systems [Ortmaier et al., 2003, Ortmaier, 2003, Nakamura, 2003]. Thus, surgeons could perform new operation techniques like endoscopic minimally invasive bypass surgery on the beating heart [Falk et al., 1999, Boehm et al., 2000].

Robotic systems for minimally invasive surgery are particularly used in urology, abdominal, and heart surgery. Despite of first encouraging successes (e. g. a completely endoscopic radical prostectomy as described in [Tewari et al., 2003]) the cost benefit ratio of this operation technique is still subject to discussion [Dotzel et al., 2003]. In case of heart surgery, robot assisted interventions are only employed for a small number of highly selected patients [Boyd and Stahl, 2003, Falk et al., 2003b, Novick et al., 2003]. In order to become applicable to a wider range of patients, more sophisticated visualization and navigation techniques [Bergmann et al., 2003] as well as improved manipulator mechanics [Falk et al., 2003a, Jacobs et al., 2003] are necessary. Besides, it is likely that the implementation of force feedback may also yield an important additional benefit in terms of further enhancement and broader application.

2 Related Work

Since the early 1990s more than 35 surgical robotic systems have been developed [Taylor and Stoianovici, 2003]. In the field of minimally invasive robotic surgery especially three commercial systems are to be mentioned: the Zeus system (Computer Motion Inc. [Sackier and Wang, 1995]), the daVinci system (Intuitive Surgical Inc. [Guthart and Salisbury, 2000]), and the Laprotek system (endoVia Medical Inc. [Düpree, 2003]). At the end of 2005 almost 400 installations of the daVinci system are recorded [Intuitive Surgical Inc., 2005]. The Zeus and the Laprotek system were also in clinical use, but both are no longer commercially available. In addition to these systems, the robotic tele-surgical workstation for laparoscopy (University of Berkeley, University of San Francisco; California) has to be pointed out [Cavusoglu et al., 2001]. None of these systems provides kinesthetic feedback and thus prototypical force feedback systems are currently only available at research laboratories. The following paragraphs provide an overview of research activities in the area of telesurgery systems with kinesthetic feedback.

In Korea a group at KAIST (Korea Advanced Institute of Science and Technology) has developed a telepresence system for micro surgical tasks [Kwon et al., 1998]. It is designed for six DoF force/torque reflection at the master console. The slave consists of an industrial six DoF robot for positioning a modified six DoF Stewart platform for micro manipulation. However, it has to be mentioned that the system does not provide full manipulability (i.e. 6 DoF) for laparoscopic surgery due to kinematic restrictions at the fulcrum point. Nevertheless, it is one of the few systems which realizes full force/torque feedback at all.

A further approach for measuring grasping forces is addressed in the work of Hu [Hu et al., 2002]. Here, conventional laparoscopic tools are equipped with strain gauge sensors and the sensed forces are displayed by a PHANToM (SensAble Technologies Inc.), a rather widespread kinesthetic device also used in this work. As this tool is not yet fixed to a robot and as the grip is not actuated, the current setup requires two users: one to actuate the surgical instrument and the second one to feel the grasping forces at the PHANToM. At least two further issues have to be mentioned: First, no contact forces can be measured at present. Second, as the strain gauge sensors are placed at the proximal end the grasping forces are superposed by friction.

A force reflecting master-slave system for minimally invasive surgery is described in [Tavakoli et al., 2003]. In this bilateral system, two modified PHANToMs are used: one serves as force-reflecting master, the other one is equipped with a custom-built instrument and constitutes the slave robot. Master and slave are coupled via a virtual-reality peripheral network. To control the position of the instrument tip an artificial neural network is applied which supports an online adaption to different load conditions at the instrument tip. Unfortunately, the strain gauge sensors are placed at the proximal end, too, so that the measured contact forces are again distorted by the friction between instrument and trocar.

A force controlled laparoscopic surgical robot without distal force sensing is presented in [Zemiti et al., 2004]. A standard force sensor is integrated into a trocar and thus remains outside the patient. This makes it easier to guarantee the required standards of sterilization and requires less effort to miniaturize components. Due to the specific installation of the sensor the measurement is not deteriorated by friction between trocar and instrument. To calculate the contact forces only gravity compensation is necessary. Currently, the robot runs in co-manipulation mode which means that the surgeon and the robot manipulate the same instrument. Initial experimental in vivo and in vitro results are encouraging.

A system for the evaluation of force feedback in MIRS is presented in [Mayer et al., 2004, Schirmbeck et al., 2004]. The usage of commercially available instruments of the daVinci System together with industrial standard robots provides a simple set-up for experiments in MIRS. Only two forces perpendicular to the instruments are measured with strain gauges applied to the outside of the instrument shaft near the wrist. Due to this sensor position, actuation forces for the instrument wrist can not be separated from contact forces. However, friction in the trocar point does not influence the sensor readings. Force display and position command is realized by two PHANToMs. The system is not designed for clinical use since the problem of sterilisability is not adressed and the use of industrial robots in a clinical environment is difficult.

The design and realization of a pair of kinesthetic forceps for virtual reality (VR) microsurgery training is described in [Burdet et al., 2004]. The proposed forceps have two actuated DoF and thus, it is possible to rotate around the instrument axis or to open and to close the gripper. To provide full force feedback (i.e. in 6 DoF) the forceps are fixed to a kinesthetic 6 DoF DELTA device [ForceDimension, 2004]. The displayed forces are rendered in real-time by a VR system and so is the visual feedback.

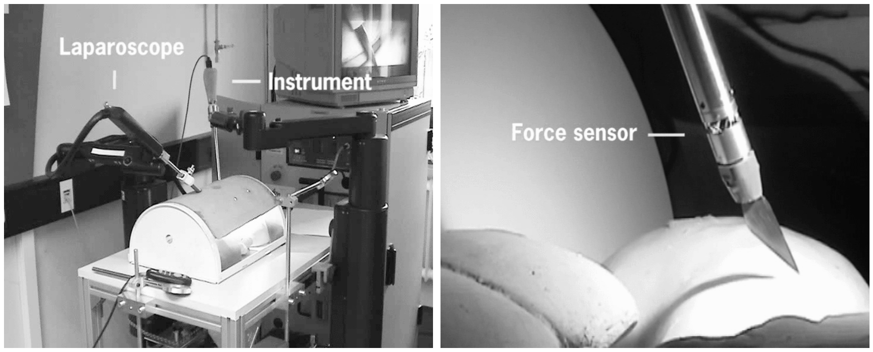
3 Experimental Setup

In the following sections the telesurgery scenario developed at the Institute of Robotics and Mechatronics of the German Aerospace Center (DLR) is presented (for a more detailed description see [Ortmaier, 2003]). The teleoperator supports manipulations in 4 DoF inside the patient and provides visual as well as force/torque sensor data. The remote sensor data are displayed at the operator console.

3.1 Teleoperator

The teleoperator consists of two surgical robots, an Aesop 3000 DS and an Aesop 1000 DS (both from Computer Motion Inc.). While the Aesop 3000 DS is equipped with an operating instrument, the Aesop 1000 DS provides stereo view from the surgical site as it is equipped with a 3D-laparoscope, a rigid endoscope (see Fig. 2, left).

Each of the two robots has four active and two passive joints. The passive joints are equipped with encoders and do neither contain a motor nor a brake.



(a) Teleoperator (b) Sensorized scalpel

Fig. 2. DLR telesurgery scenario: teleoperator and sensorized scalpel.

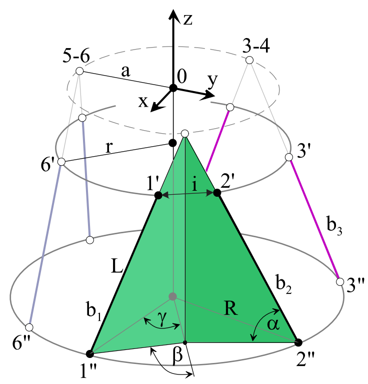
They are necessary to guarantee that no significant forces are exerted at the (a priori unknown) invariant fulcrum point. The camera-robot runs in an automatic mode: As the instrument is equipped with a color mark near the distal end, the surgical instrument can be detected by color segmentation within the stereo camera images of the laparoscope. The camera-robot is then able to follow the instrument automatically. Thus, the surgeon can focus on the operation and is not distracted by unnecessary tasks. For further details on automatic camera guidance see [Wei et al., 1997, Omote et al., 1999].

Surgical Instruments

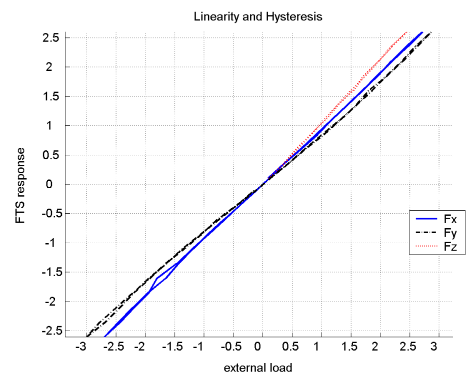
The surgical instrument (see Fig. 2, right) which was developed at DLR is equipped with a miniaturized force/torque sensor (10 mm in diameter) [Seibold and Hirzinger, 2003] and can easily be attached to the robot. The sensor itself is fixed at the distal end of the instrument in order to guarantee a collocated measurement of the contact forces. A force-torque transducer based on a Stewart Platform is well suited for this application. Advantages include high stiffness, adaptable properties, annular shape, and scalability. The geometry and the properties of a Stewart Platform transducer are described completely by the set of variables R, L, α, β and γ shown in Figure 3(a). The parameters L and R denote the link length and base radius respectively. Further geometrical parameters derived thereof are the platform radius r, the radius of the link intersection a and the joint separation at the platform i'.

The characteristic matrix $\mathbf{A} \in \mathbb{R}^{6\times6}$ describing the transformation of link forces $\boldsymbol{F}_{int} = [F_1, F_2, F_3, F_4, F_5, F_6]^T$ to externally applied loads $\boldsymbol{F}_{ext} = [F_x, F_y, F_z, M_x, M_y, M_z]^T$

$$\boldsymbol{F}_{ext} = \boldsymbol{A} \cdot \boldsymbol{F}_{int}, \tag{1}$$



(a) Illustration of geometrical parameters.



(b) Transducer response to externally applied forces after calibration.

Fig. 3. Stewart Platform.

is calculated as follows [Sorli and Pastorelli, 1995]:

$$\mathbf{A} = -\frac{1}{2} \cdot \begin{bmatrix} -2n & 2n & \sqrt{3}m + n & \sqrt{3}m - n & -\sqrt{3}m + n & -\sqrt{3}m - n \\ -2m & -2m & m - \sqrt{3}n & m + \sqrt{3}n & m + \sqrt{3}n & m - \sqrt{3}n \\ -2q & -2q & -2q & -2q & -2q & -2q \\ 2aq & 2aq & -aq & -aq & -aq & -aq \\ 0 & 0 & aq\sqrt{3} & aq\sqrt{3} & -aq\sqrt{3} & -aq\sqrt{3} \\ -2an & 2an & -2an & 2an & -2an & 2an \end{bmatrix}, \qquad \begin{array}{l} m = \cos(\alpha)\,\cos(\beta), \\ n = \cos(\alpha)\,\sin(\beta), \\ q = \sin(\alpha). \end{array}$$

To find a sensor geometry that is well conditioned and optimized for the force range expected in a surgical application, the following optimization method is used. The radius of the base R and the link length L are determined by the space available in the instrument. For all geometrically valid combinations (non-intersecting links) of R, L, α, β and γ, $\boldsymbol{A}^{-1}$ is calculated. Various sets of maximally expected external loads $[F_x, F_y, F_z, M_x, M_y, M_z]^T$ are selected, containing loads in the 6 principal directions. Every member of the load set is pre-multiplied by $\boldsymbol{A}^{-1}$, yielding the corresponding set of internal leg forces $[F_1, F_2, F_3, F_4, F_5, F_6]^T$. The variance s^2 of the internal leg force set is a measure of the isotropy of the sensor structure with respect to the external load set. This however is not an isotropy in the classical definition, since the external loads in the principal directions need not to be equal. For the load set $F_{x,y,z} = 20\,\mathrm{N}$, $M_{x,y} = 200\,\mathrm{Nmm}$, $M_z = 100\,\mathrm{Nmm}$ the following parameters were selected as optimal sensor geometry: $R = 4.2\,\mathrm{mm}, L = 3.9\,\mathrm{mm}, \alpha = 57°, \beta = 90°, \gamma = 36°$, yielding a variance of $s^2 = 236\,\mathrm{N}^2$. Using appropriate design of flexural hinges and leg cross-section, properties of the transducer structure are in good agreement with the prediction of the ideal analytical model [Seibold and Hirzinger, 2003].

Fig. 4. Sensorized scalpel with force/torque sensor at tip and electronics.

The force/torque sensor was calibrated by applying known external loads up to 4 N and 100 Nmm. The measurement range is 20 N and 200 Nmm, respectively. Exemplary calibration results are shown in Figure 3(b).

To reduce the influence of noise the electronic measuring equipment is placed inside the instrument shaft. The digital resolution is approximately 9 bits, the sample rate is 800 Hz. Further details on the sensor design are presented in [Seibold and Hirzinger, 2003], see also Figure 4 for details.

On the same basis of a miniaturized force/torque sensor, a new instrument with two additional DoF and an actuated end-effector at the distal end was built (see Fig. 5) [Kübler et al., 2005, Seibold et al., 2004]. Grasping forces at the pair of forceps can be measured. The instrument is currently being tested with respect to position and force measurement accuracy, thermal stability, etc.

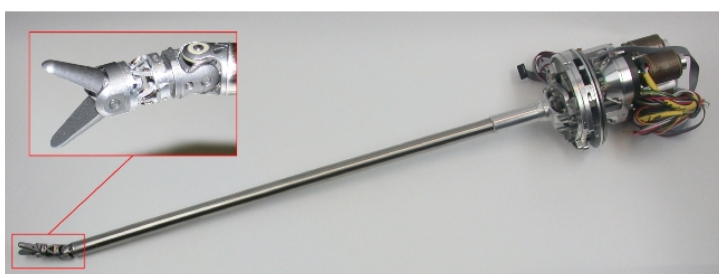


Fig. 5. Sensorized pair of forceps, with force/torque sensor and two additional DoF at distal end as well as drive unit at proximal end.

Robot Control

While the camera-robot runs autonomously, the instrument-robot is teleoperated. This robot is commanded via serial connection (RS 232, 38.4 kbaud). The control software is implemented in C/C++ on a SUN Ultra 60 UPA/PCI. The position control architecture is designed to meet the specific kinematic requirements of an invariant point and considers the passive joints as well (see Fig. 6). The dexterity of the entire system is increased as correct hand-eye coordination is realized. The information flow can be described as follows: The trocar position estimation provides the position $\boldsymbol{t}$ of the entry point which is used together with the joint positions $\boldsymbol{\theta}$ to compute the inverse Jacobian matrix $\boldsymbol{P}^{-1}$. On this basis the simplified dynamics can be calculated, which is a prerequisite for a self-adjusting controller. By a self-adjusting controller (see below) the different joint dynamics can be taken into account resulting in Cartesian dynamic behavior independent of the working position. The controller is described by the transfer functions F_{CX}, F_{CY}, and F_{CZ} which are tuned for the x-, y-, and z-direction separately. The subscript D (see Fig. 6) denotes the desired values, whereas the subscripts p and a indicate the passive and the active joints, respectively. The transfer function $F_D = e^{-\frac{T_d}{2}s}$ represents the delay transfer function caused by the serial connection ($T_d = 22$ ms). The delay time T_d dominates the delay of the communication network between master and slave (TCP/IP via Ethernet) which is less than 1 ms.

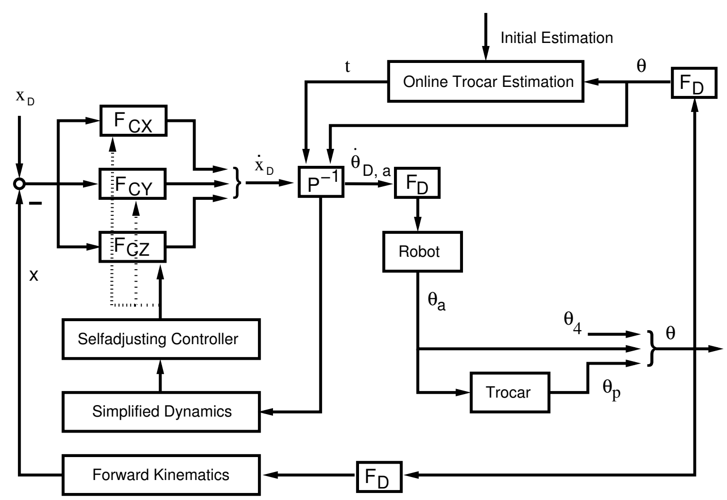


Fig. 6. Teleoperator position control loop.

A self-adjusting controller was chosen, as the Cartesian dynamics of the robot depends on the current configuration. This is due to the fact, that the robot joints have different dynamics which are mapped via the (position dependent) Jacobian into the Cartesian space [Ortmaier and Hirzinger, 2000b]. The control loop for the simplified one degree of freedom case as shown in Figure 7, is considered in the following.

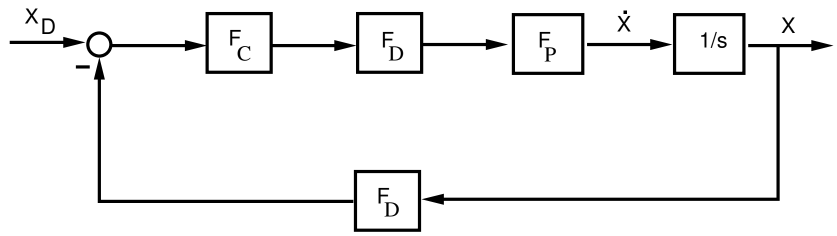


Fig. 7. Closed control loop.

The controller transfer function for each Cartesian DoF of the robot is written as

$$F_C = K\frac{1+T_1 s}{1+T_2 s} \ . \tag{2}$$

The velocity transfer function of the robot for each Cartesian DoF is:

$$F_P = \frac{1}{1+Ts} \quad \text{with} \quad T = T(\boldsymbol{\theta}) \ . \tag{3}$$

Note, that T is not only position dependent but also differs for the Cartesian DoF of the robot. In the following, the equations to tune the parameters for F_C for one DoF are derived. For other DoF the same equations hold.

The gain of the open loop equation is as follows:

$$A = K\frac{\sqrt{1+(wT_1)^2}}{\sqrt{1+(wT_2)^2}}\frac{1}{\sqrt{1+(wT)^2}}\frac{1}{w} = KA^* \ . \tag{4}$$

The corresponding phase is:

$$\phi = \text{atan2}(wT_1, 1) + \text{atan2}(-wT_2, 1) + \text{atan2}(-wT, 1) - \frac{\pi}{2} - wT_D \ . \tag{5}$$

Considering the structure of the controller F_C three parameters have to be determined: K, T_1, and T_2. First $T_2 = kT_s$ is chosen, with T_s being the sample time of the digital implementation, to move the negative part of the phase of $\frac{1}{1+T_2 s}$ as far as possible towards high w. One way to compute T_1 is to choose $T_1 = T$ to compensate the pole of the plant; this works well for $T_D \ll T$ only. An adaption law able to handle the general case is: For a small w_{g1} a desired phase margin ϕ_{R1} (e.g. 80°) is chosen that provides good damping. The necessary phase shift $\Delta\phi_1$ that has to be provided by the controller F_C at w_{g1} can be computed as follows [Natale et al., 1999]:

$$\Delta\phi_1 = -\pi + \frac{\phi_{R1}}{180^\circ}\pi + \frac{\pi}{2} - (-w_{g1}T_D + \text{atan2}(-w_{g1}T, 1)) \ . \tag{6}$$

The phase of F_C at w_{g1} is:

$$\angle F_C = \angle \frac{1 + jw_{g1}T_1}{1 + jw_{g1}T_2} \ . \tag{7}$$

Solving Equation 7 for T_1 leads to:

$$T_1 = \frac{\tan(\Delta\phi_1) + T_2 w_{g1}}{w_{g1}(1 - T_2 w_{g1} \tan(\Delta\phi_1))} \ . \tag{8}$$

The last parameter to be calculated is K. A phase-margin ϕ_{R2} for F_{openloop} at the gain crossover-frequency w_{g2} is chosen and Equation 9 is solved for $w = w_{g2}$:

$$\begin{aligned}\Delta\phi_2 &= 0 \\ &= -\pi + \frac{\phi_{R2}}{180^\circ}\pi + \frac{\pi}{2} - (-w_{g2}T_D + \text{atan2}(-w_{g2}T, 1) + \\ &\quad +\text{atan2}(w_{g2}(T_1 - T_2), 1 + T_1 T_2 w_{g2}^2)) \ .\end{aligned} \tag{9}$$

Finally, with Equation 4:

$$K = \frac{1}{A^*(w_{g2})} \ , \tag{10}$$

because w_{g2} is the gain crossover-frequency. As T differs by a large range, but changes slowly, the system can be considered as quasi-linear and the control law is stable.

The automatic control law is configured such that the phase margin of the closed position loop remains between 80° and 60°. This adjustment guarantees a well damped behavior over the entire workspace and reduces the risk of overshooting. The cross-over frequency of the position control loop is about 0.5 Hz, which causes an undesired phase shift between the desired position and the actual position of the robot. The controller is described more detailed [Ortmaier and Hirzinger, 2000a, Ortmaier and Hirzinger, 2000b].

3.2 Operator Console

The operator console (see Fig. 8, left) consists of a stereo display (25 Hz active stereo with shutter glasses[4]) and a PHANToM (SensAble Technologies Inc.). This kinesthetic device provides 6 DoF for position and orientation sensing and uses 3 translational DoF for force feedback. Additionally, the forces can be displayed in the stereo video stream at the TCP of the surgical instrument by means of a 3D arrow (see Fig. 8, right). This enables the surgeon to receive

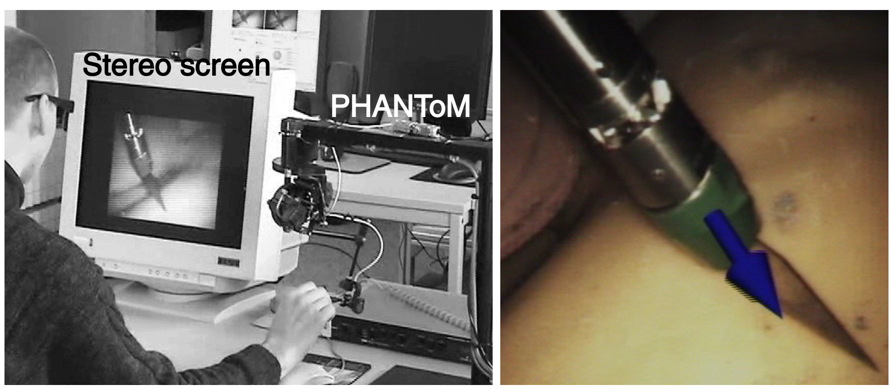
[4] In order to avoid flickering a monitor allowing 50 Hz stereo images was used for the experiments presented in Section 4.

feedback of the manipulation forces, even if no kinesthetic feedback device is available. Furthermore, to provide the surgeon with information on the robot configuration, a robot model can be displayed, thus no additional bandwidth demanding video transmission is necessary.

The position x_P obtained by the PHANToM is scaled by the factor k_S before being sent to the teleoperator. This ensures a correct hand-eye coordination and provides position scaling in order to manipulate the instrument tip more precisely. The roll axis of the instrument is commanded by the last rotational DoF of the PHANToM. The force F_T and the position x_T measured at the end effector (instrument tip) of the teleoperator are transferred to the operator console. Thereby a force F_P is calculated:

$$F_P = k_F F_T + k_C(x_T - k_S x_P) \tag{11}$$

and displayed at the PHANToM. For $k_F = 1$ and $k_C = 0$ the force F_P corresponds to the measured force F_T. By changing the values for k_F the displayed forces are sensed as scaled. The component $k_C(x_T - k_S x_P)$ causes a position coupling between operator and teleoperator, whereby x_P represents the desired position of the instrument tip. This position coupling constitutes a safety feature as it prevents the user to command too fast motions which cannot be executed by the teleoperator. The PHANToM control loop runs with 1 kHz. Further details of the teleoperation concept are presented in [Preusche et al., 2001].



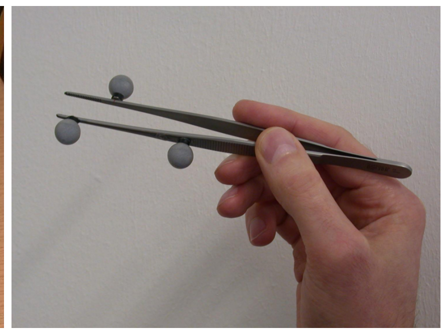
(a) Operator. (b) Visual force feedback.

Fig. 8. DLR telesurgery scenario: operator console.

Additionally to the presented operator station based on a PHANToM two different concepts for the man-machine interface where realized. The new prototypical device to feedback grasping forces shown in the left part of Figure 9 offers a very natural way of force display.

In contrast a user interface where the surgeon moves standard surgical instruments without force feedback was evaluated, too. Optical markers are attached to these instruments and are tracked by stereo cameras (see Figure 9b). Therefore, the current pose of the instruments can be reconstructed. The captured instrument motion is then transmitted to the robot or to a virtual reality simulation. Kinesthetic feedback is not possible with such an approach, but forces can be displayed in the (stereo) video stream by augmented reality techniques (see Fig. 8 in Sec. 3). Evaluating such a system and comparing the results with the setup described above allows for a comparison of different force feedback modalities and man-machine interfaces.

(a) Device to feedback grasping forces.



(b) Tracking of surgical instruments.

Fig. 9. Prototypes for minimally invasive robotic surgery under development.

3.3 Communication

The communication between teleoperator and operator console is established by a TCP/IP protocol via Ethernet. For network transparency a Common Object Request Broker Architecture (CORBA) middle-ware layer is used and thus communication is independent of a certain platform or a specific implementation [COR, 1998]. The implemented architecture provides streams for positions and forces as well as channels for event based commands (e.g. to connect/disconnect master and slave or to open/close a gripper) [Reintsema et al., 1999].

To reduce overall system latency in the experiments, video transmission was realized as a simple local solution. A pair of framegrabbers capture the analog camera signal which is displayed by an OpenGL based visualization using shutter glasses. Advanced solutions for the transmission of compressed videostreams are readily available and, therefore, were not subject to research. The images are not rectified for visualization, since the laparoscope has only minor radial distortion.

4 Force Feedback: An Experimental Evaluation

In order to gain a deeper insight into the importance of force feedback for MIRS systems an experimental evaluation was carried out. The technical setup used here differs slightly from that described in Section 3: the automatic camera guidance was turned off as it was not subject to evaluation. Additionally, an active stereo screen based on shutter glasses with a refresh rate of 100 Hz was integrated into the robotic surgery system. The stereo image itself was updated with 50 Hz, thus flickering was avoided. To realize force feedback, the PHANToM based solution was used as an operator console.

As surgeons spend about 25-35% of their operation time on dissecting tissue [Scott-Conner, 1999] a representative surgical task was realized: An artery that was covered by tissue and that could be recognized as elevation only should be dissected as fast and as un-injured as possible. Although this task is most often carried out by a dissection hook, here, a scalpel was chosen for assessing manipulation errors (i. e. injuries of blood vessels) more exactly. In order to create comparable conditions no organic material was used, but tissue was replaced with modeling material and arteries were substituted by cellular rubber (see Fig. 10). Although the experimental material does not correspond to the visco-elastic characteristics of real tissue the force profiles of the artificial models may be assumed to be similar to natural tissue [Wagner et al., 2002].

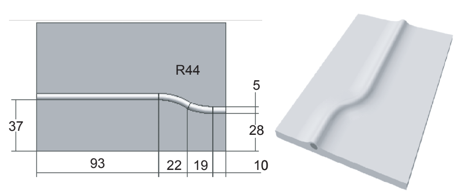


Fig. 10. Experimental scenario: An artificial artery was to be dissected under standardized conditions (dimensions in mm).

Mainly minimally invasive surgeons were recruited as participants. After a sufficient practice session all of the 25 participants were asked to carry out a manual intervention as well as robot assisted interventions with and without force feedback. Learning or fatigue effects were counter-balanced by a Latin

Square Design [Diamond, 2001]. As dependent variables speed as well as accuracy were recorded. Thereby, speed was operationalized by the amount of surface which was dissected within four minutes. To guarantee an objective assessment all items were photographed and the dissected surface was measured in pixel. Accuracy was measured by the extent of injury which was made up of the length, the depth, and the amount of tissue and artery transection. Therefore, all items were judged by three independent raters. According to a scale proposed by [Landis and Koch, 1977] the inter-rater reliability (Cohen's Kappa: 0.82) can be described as almost perfect. In order to explore differences between manual and robot assisted interventions all trials were filmed and an observational video analysis was carried out by three independent raters. As according to [Landis and Koch, 1977] the inter-rater agreement (Cohen's Kappa: 0.72) can be described as substantial the video analysis is assumed to be reliable, too.

In order to explore whether MIS, MIRS without force feedback, and MIRS with force feedback differ, an analysis of variances (ANOVAs) was carried out [Edwards, 1993]. For the speed-variable amount of dissected surface as well as for one of the accuracy-variables, depth of artery transection, significant differences could be detected on a 0.05-level. A Bonferroni Post-Hoc Test revealed that the participants dissected significantly more surface (55.1 %) when the intervention was accomplished manually instead of robot assistedly without force feedback. Within MIRS without force feedback the participants were a little bit faster (9.4 %) compared to MIRS with force feedback though both robot conditions do not differ significantly. To sum up, the surgeons managed the task the fastest manually while robot assisted surgery caused a significant deceleration (see Fig. 11 left).

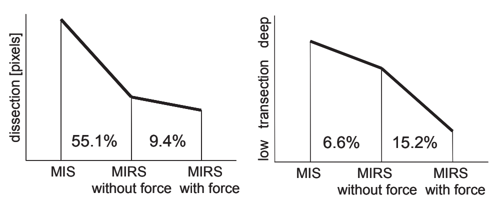


Fig. 11. Manual versus robot assisted interventions: While MIS was accomplished much faster (left), significantly less injury occurred during 'MIRS with force feedack' (right).

The results are reverse when the accuracy-variable is regarded (see Fig. 11 right): In average the deepest artery transection occurred when the task was executed manually. While during MIRS without force feedback the task was performed a little bit more carefully (6.6 %) compared to a manual intervention, artery transection could be reduced only significantly (15.2 %) when force feedback was available. To sum up, the surgeons managed the task the most precise when force feedback was available.

At a first glance the results may be associated with a speed-accuracy trade-off. It may be argued that during robotic interventions a more accurate result was to be observed only due to the fact that the surgeons worked slower and not because of the availability of force feedback. This assumption cannot be held for two reasons: First, the extent of injuries was related to the dissected surface and thus the ANOVA-calculations are not based on absolute, but on relative, standardized values. Second, further interesting insights are gained by the video analysis: When manual and robot assisted interventions are compared, a t-Test reveales that significantly more cutting operations appeared within MIRS (see Fig. 12). As it is obvious that the risk of injury increases especially during cutting, the fact that within MIRS significantly less injury occurred can only be explained by the availability of force feedback.

The video analysis provides also insight concerning the training demands of robot assisted surgery. Irrespective of whether the task was performed manually or robot assistedly the same techniques, 'scraping', 'lifting', and 'cutting', were applied (see Fig. 12). Though both conditions differ quantitatively there are no qualitative different operations. A remarkable difference is only apparent when the dynamic of movement is considered: During MIS the surgeons tended to operate more often length- as well as crosswise to the artery. Besides, the direction was changed more frequently and the participants tended to move more often back and forth compared to MIRS. In consequence, robot assisted surgery does not afford new operating techniques but requires a more continuous working style which has to be trained by experienced surgeons.

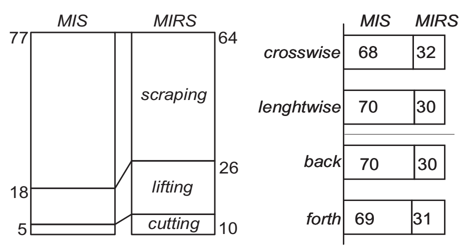


Fig. 12. Operating techniques (left) and dynamic of movements (right) within MIS and MIRS (in %). The following definitions apply: crosswise and lengthwise refer to the artery direction, back and forth are related to person's view direction. Irrespective of whether the task was performed manually or robot assisted the same techniques were applied (scraping, lifting, cutting).

5 Conclusions

In this Section the results of Section 4 are discussed in terms of research objectives. Though the results were gained within a specific experimental environment some general conclusions for designing MIRS systems may be drawn.

Manual and robot assisted minimally invasive surgery techniques turned out to have certain advantages as well as disadvantages: Whenever it is essential to reduce operation time a manual technique seems to be most suitable, whenever any unnecessary traumatization is to be avoided a robot assisted technique with force feedback will be more appropriate.

Though all in all the participants tended to work more carefully within the robot surgery setting, a significant reduction of injuries was to be observed only when force feedback was available. While this fact is comprehensible it is less obvious why at the same time operating time doubles; especially when it is considered that the robot surgery stands out by a more intuitive hand-eye coordination. This observation is probably due to the low bandwidth in the position control loop of the robot (see Sec. 3). This fact causes a phase shift between the desired position and the current position of the instrument. Consequently, the users tended to work slower to guarantee an accurate positioning of the instrument (see Fig. 11). Nevertheless, despite of this possible drawback the present force reflecting setup reduces unintentional injuries successfully.

In general, evaluation results depend on the experimental system under consideration. Therefore, in order to derive a more general conclusion, further enhancement of the components used for the MIRS system is desirable.

To increase the bandwidth of the telesurgery system (i. e. to reduce the time delay between the surgeon's commands and the motion of the robots) an increased dynamics of the surgical robot and a shorter communication delay between surgical robot and operator console are needed. Therefore, a new kinematically redundant surgical robot with fast dynamics and high sample rate (3 kHz) was developed [Ortmaier et al., 2006].

To provide full dexterity inside the patient the latest DLR instruments (see Fig. 5) are designed to integrate a miniaturized force/torque sensor as well as to provide two additional DoF and an actuated pair of forceps at the distal end. Suitable user interfaces for commanding such MIRS systems are also under development (see Fig. 9).

New operation techniques like automatic camera guidance [Wei et al., 1997, Omote et al., 1999] or motion compensation for surgery on the beating heart [Ortmaier et al., 2005, Nakamura et al., 2001, Ginhoux et al., 2004] will be available in the future. This will spread minimally invasive surgery procedures drastically, and, thus, contribute to further reduce patient trauma.

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