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# Haptic Feedback in a Telepresence System for Endoscopic Heart Surgery

## Abstract

The implementation of telemanipulator systems for cardiac surgery enabled heart surgeons to perform delicate minimally invasive procedures with high precision under stereoscopic view. At present, commercially available systems do not provide force-feedback or Cartesian control for the operating surgeon. The lack of haptic feedback may cause damage to tissue and can cause breaks of suture material. In addition, minimally invasive procedures are very tiring for the surgeon due to the need for visual compensation for the missing force feedback. While a lack of Cartesian control of the end effectors is acceptable for surgeons (because every movement is visually supervised), it prevents research on partial automation. In order to improve this situation, we have built an experimental telemanipulator for endoscopic surgery that provides both force-feedback (in order to improve the feeling of immersion) and Cartesian control as a prerequisite for automation. In this article, we focus on the inclusion of force feedback and its evaluation. We completed our first bimanual system in early 2003 (EndoPAR Endoscopic Partial Autonomous Robot). Each robot arm consists of a standard robot and a surgical instrument, hence providing eight DOF that enable free manipulation via trocar kinematics. Based on the experience with this system, we introduced an improved version in early 2005. The new ARAMIS system (Autonomous Robot Assisted Minimally Invasive Surgery) has four multi-purpose robotic arms mounted on a gantry above the working space. Again, the arms are controlled by two force-feedback devices, and 3D vision is provided. In addition, all surgical instruments have been equipped with strain gauge force sensors that can measure forces along all translational directions of the instrument's shaft. Force-feedback of this system was evaluated in a scenario of robotic heart surgery, which offers an impression very similar to the standard, open procedures with high immersion. It enables the surgeon to palpate arteriosclerosis, to tie surgical knots with real suture material, and to feel the rupture of suture material. Therefore, the hypothesis that haptic feedback in the form of sensory substitution facilitates performance of surgical tasks was evaluated on the experimental platform described in the article (on the EndoPAR version). In addition, a further hypothesis was explored: The high fatigue of surgeons during and after robotic operations may be caused by visual compensation due to the lack of force-feedback (Thompson, J., Ottensmeier, M., & Sheridan, T. 1999. Human Factors in Telesurgery, *Telmed Journal, 5* (2) 129–137.).

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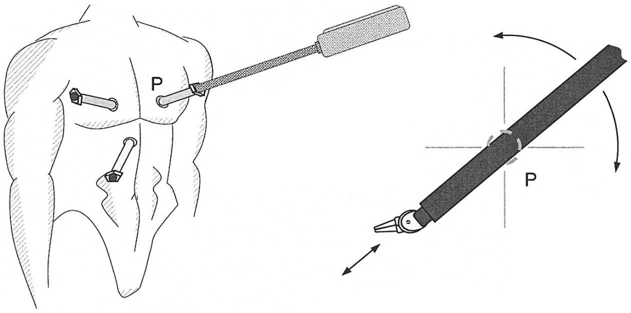



**Figure 1.** *Location of the instrument and camera port.*

## 1 Introduction

Recently, minimally invasive surgery (MIS) has become a promising option for a great number of surgical interventions (such as heart surgery) and has had significant impact on both patients and surgeons. Minimally invasive and endoscopic cardiac surgery not only minimizes the collateral surgical trauma, but it also results in quicker recovery. The length of the hospital stay and the infection rate can be reduced (Morgan et al., 2004). Therefore, patients can profit significantly from this treatment option. On the other hand, surgeons have to cope with increasingly complex working conditions. Since endoscopic surgery is performed through a small port or keyhole in the patient's chest (Figure 1), surgeons must learn to operate with unfamiliar and often awkward surgical instruments. Hence, the techniques of endoscopic surgery have been applied infrequently, particularly in the field of heart surgery. An important step in developing this technology was the introduction of telemanipulation, which was especially designed to enable delicate interventions with high surgical precision. The surgeon no longer controls the instruments directly, but they are controlled by a special device with a Cartesian user interface that surgeons can handle as usual, that is, like instruments for open surgery. They offer as much freedom of movement as the surgeon's own hand would in conventional open surgery, thus providing 6 DOF instead of the 4 DOF that conventional endoscopic instruments have. In addition, they assist the surgeon with motion scaling, tremor filtering, and a stereo vision interface at the input console. Surgeons can now operate using a surgical mechatronic assistant in a comfortable, dextrous, and intuitive manner (Falk, Jacobs, Gummert, & Walther, 2003; Falk, Jacobs, Gummert, Walther, & Mohr, 2003; Falk, Mintz, Grunenfelder, Fann, & Burdon, 2001). Despite the obvious potential advantages of robot-assisted, endoscopic surgery, most researchers and surgeons in this area agree that the lack of haptic feedback is the most important drawback of currently available systems (Mitsuishi, Tomisaki, Yoshidome, Hashizume, & Fujiwara, 2000). The inability of the operator to sense the applied forces causes increased tissue trauma and frequent suture material damage. The systems are telemanipulators with no Cartesian position control (the control loop is implicitly closed by the visual surveilance of the surgeon). Both features are important in order to move the surgeon up in the control hierarchy, that is, to implement "shared control" or "partial autonomy."

In order to overcome these deficiencies, two crucial issues have to be solved. One is inclusion of force sensory and feedback, and the other is the implementation of full Cartesian control of the end effector. The latter is indispensable for calculating exact directions of forces in a known coordinate frame. Therefore, one of our main research interests is the 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 very time consuming if performed via telemanipulation. Our working hypothesis was that the handling of telemanipulated surgical systems can be significantly improved by the inclusion of force-feedback. Therefore, we focus below on hardware and software for force-feedback in endoscopic surgery and present an evaluation of its quality.

## 2 Related Work

Telemanipulators for endoscopic surgery are already commercially available. Systems, such as daVinci (Guthart & Salisbury, 2000), offer comfortable user interface and are used in daily practice to perform even delicate operations. However, they offer no force-

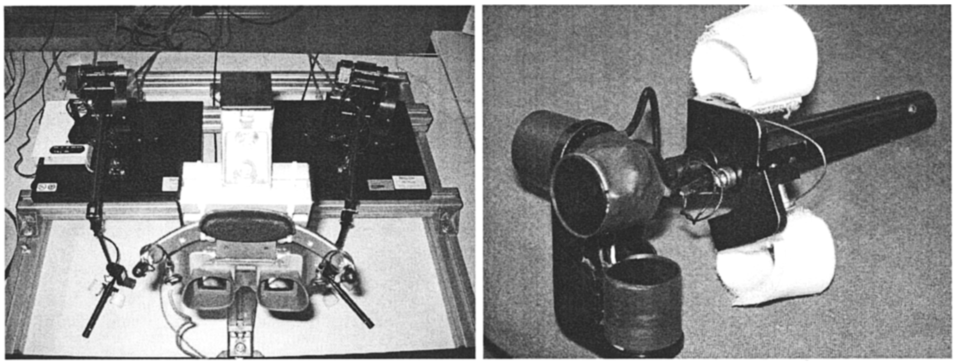


**Figure 2.** *Master console and magnified view of a customized PHANToM stylus.*

feedback and their control loop is closed visually by the surgeon. In addition to these commercial systems, a variety of devices for robotic surgery do exist, implemented by other research groups. At the University of California, Berkeley, a robotic system was developed that has already been used to perform certain surgical tasks, such as suturing and knot-tying (Cavasoglu, Williams, Tendick, & Sastry, 2003). The Korean Advanced Institute of Science and Technology developed a microtelerobot system that provides force-feedback (Kwon, Woo, Song, Kim, & Cho, 1998). In Germany, two systems for robotic surgery were built at the Research Facility in Karlsruhe (Voges, Holler, Neisius, Schurr, & Vollmer, 1997) and at the DLR in Oberpfaffenhofen (Konietschke, Ortmaier, Weiss, & Hirzinger, 2004). While the first system provides no force-feedback, the latter 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, Okamura, Bethea, Gott, and Baumgartner (2002) have evaluated forces occurring during knot-tying. They did not measure forces directly on the instruments or during realistic operations, but with a contrivance that was especially designed for these measurements. Wagner, Vasilyev, Perrin, del Nido, and Howe (2006) have proposed an instrument with force-feedback in order to provide additional modality for ultrasound-guided interventions. Tavakoli, Patel, and Moallem (2005) developed a novel endoscopic instrument with exchangeable head and force-feedback. Their evaluation showed that surgical tasks profit from force feedback, regarding performance time and reduction of fatigue. Cao, MacKenzie, and Payandeh (1996) analyzed a variety of surgical tasks (among other things, knot-tying) and broke them down into subtasks. They did not include force measurement. However, the necessity of haptic feedback in robotic surgery has been discussed controversially by surgeons and haptic engineers (Bethea et al., 2004; Fager, 2004; Hu, Tholey, Desai, & Castellanos, 2002; MacFarlane, Rosen, Hannaford, Pellegrini, & Sinanan, 1999). At the Rensselaer Polytechnic Institute, a robotic system capable of knot-tying was developed (Kang & Wen, 2001), but they mainly focused on force control and have used dedicated instruments for knot-tying. At the German Heart Center in Munich, a daVinci system has been installed. Surgeons often ponder the question of whether performance could be improved if force-feedback is included. Since this problem cannot be evaluated directly within the daVinci system, we decided to take the original instruments and incorporate them into an experimental setup that can be used for evaluation.

## 3 Materials and Methods

Like typical systems for robotic surgery, our setup consists of an operator-side master console (Figure 2) for in-output and a patient-side robotic manipulator that directly interacts with the operating environment.

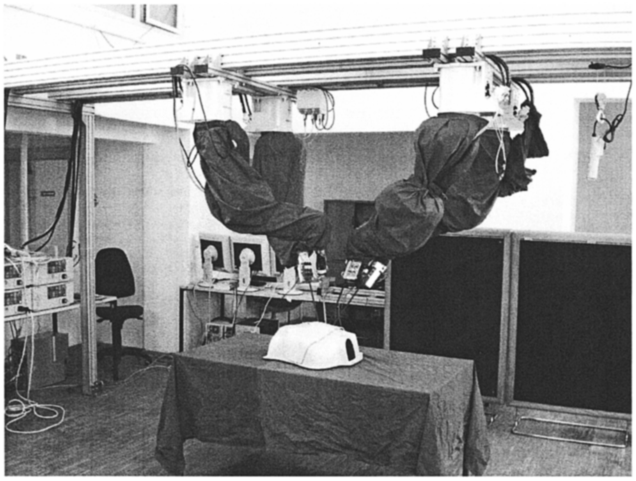
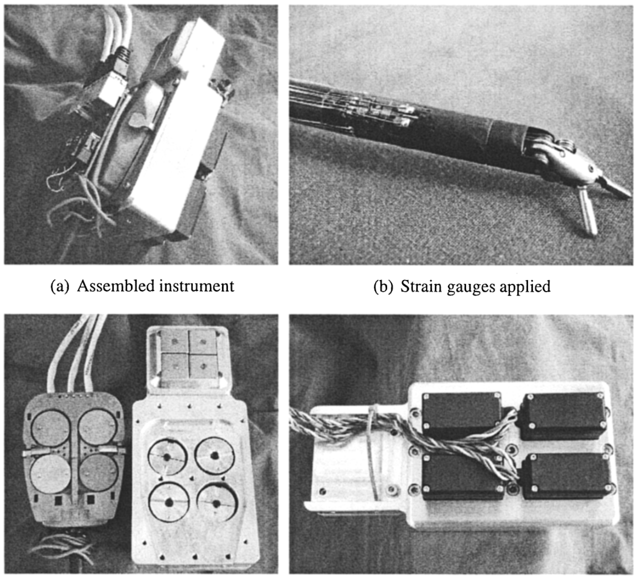


**Figure 3.** *New system ARAMIS with four ceiling mounted robots.*



(a) Assembled instrument (b) Strain gauges applied

(c) Adapter with Oldham coupling (d) Driving servos

**Figure 4.** *Sensorized instrument, magnetic adapter, and servos.*

### 3.1 Robotic Telemanipulator

The ARAMIS system consists of four small robots mounted on the ceiling (Figure 3). The robots have 6 DOF. Since the rotation of the robot's flange and the rotation of the instrument share one axis, our system ultimately ends up having 8 DOF under the restriction of trocar kinematics (Mayer, Nagy, & Knoll, 2004). The crucial part of the master console is two PHANToM haptic interfaces. They are used to control the instruments and to feed back forces. Particular advantages of this setup with multipurpose robots are high precision and stiffness, moderate costs, and an advanced dynamic behavior. The latter could be exploited to perform sophisticated tasks in motion compensation, for example, support for beating heart surgery as it was proposed in Ortmaier, Groeger, Boehm, Falk, and Hirzinger (2005), or compensation for respiratory motion of the ribs.

We have also developed adapters that are attached to the robotic arms and can be equipped with either an instrument or a stereo endoscope. For security reasons and better handling, we have equipped all flange adapters with magnetic security couplings (Figure 4c). Those will disengage if forces beyond a certain level are exerted that might cause harm to the instruments or chest mockup. Each of the surgical instruments has 3 DOF. A microgripper at the distal end of the shaft can be rotated, and adaptation of pitch and yaw angles is possible. 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 for each degree of freedom (two for the yaw of the fingers). In order to control the joints of the instruments, we have flanged servomotors to each driving wheel by means of an Oldham coupling (Figure 4c). This guarantees instrument movement that is free of jerk. The servocontrollers can be connected via serial lines or a CANbus to a multiport card. The basic idea of endoscopic surgery is that only small openings have to be made into the surface of the patient's body (so-called keyholes, Figure 1). Therefore, translational movements of the instruments are essentially restricted by shifts and rotations within these holes. In order to provide the surgeon with a comfortable user interface, it is desirable to map movements of the stylus of the input device directly onto instrument motions. Considering these requirements, we have implemented the inverse kinematics of our system as shown in Figure 1.

A desired position of the instrument is given by the position of the input stylus. Arbitrary positions of the

**Figure 5.** *Endoscopic stereo camera with customized magnetic adapter.*

instrument's tip are mapped on corresponding positions of the motors that control the 8 DOF. The input data 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), only one possibility for aligning the instrument exists. The angle of the corresponding joints of the instrument can be found by geometric calculations, which are explained in detail in Mayer et al. (2004). In order to speed up this complex computation, the complete inverse kinematics of the robot can be performed on the graphical processing unit (GPU) of a graphics card. In order to prepare this computation, the desired Cartesian positions are transferred to a texture on the graphics card. A so-called fragment shader, which is written in the OpenGL Shading Language and contains the algorithm for inverse kinematics, is applied to the texture. The results (the joint angles of the robot) are transferred to the framebuffer of the card and can be moved back to the CPU. The calculated angles can be directly applied to the robot. Employment of a GPU (NVIDIA GeForce 5200 graphics card) leads to a computation time that is 20 times faster than a modern CPU (Athlon64 2200 MHz).

As mentioned above, the master console (the workstation of the surgeon) consists of custom made modifications of PHANToM force feedback devices (see below).

### 3.2 Optical System

Due to the extremely high-precision requirements in modern minimally-invasive surgery (arteries in heart surgery have a diameter between 1 and 2 mm), it is imperative to provide an accurate 3D view.

Most of the other systems mentioned above come with magnifying three-dimensional endoscopes and appropriate display devices. This is also an essential prerequisite for high accuracy machine vision. The ARAMIS system is equipped with a 3D endoscope providing two separate optical (fiberglass) channels and two synchronized CCD cameras. A magnetic coupling mechanism (Figure 5) allows quick mounting and dismounting without losing the calibration against the rest of the system. We have precisely determined the intrinsic and extrinsic parameters of the camera system in order to achieve the necessary calibration for scene reconstruction. Like the instruments, the endoscopic camera can be moved by means of trocar kinematics and can either be actively controlled by the operator or automatically guided by the system (following the region of interest, i.e., where the instruments are placed). Images taken from the stereo camera system are displayed on a 3D device, which provide differentially-polarized images for right and left eye. Therefore, the surgeon has to wear polarized lenses in order to get a 3D view.

### 3.3 Force Feedback

Positions and orientations of the instruments are controlled by two PHANToM devices (Figure 2). This device is available in different versions with different capabilities. We have chosen the version PHANToM Premium 1.5. It has a working space of approximately $20 \times 25 \times 40$ cm, which is appropriate for performance of surgical procedures. The user controls a stylus pen that is equipped with a switch that can be used to open

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