INTEGRATION OF FORCE FEEDBACK IN AN OPEN ROBOT PLATFORM FOR ROBOTIC SURGERY

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Abstract: We present an open robot platform for minimally invasive surgery capable of very sensitive force feedback, which has been developed in very close cooperation with surgeons from cardiac surgery. Forces are measured at the surgical instruments and fed back into the surgeon's hands using multi-dimensional haptic styluses. Integration of force feedback with stereo vision, as offered by the system, will improve accuracy, drastically reduce the time needed for operations and tissue trauma, along with a reduction of stress on the surgeon. This could lead to a wider acceptance of robotic surgery by both, patients and surgeons. The system's software interface and mechanical set-up descriptions are freely available to enable other research groups to participate in the development.

Introduction

During the last decade minimally invasive surgery has become the leading method for many surgical interventions. Unlike open surgery, minimally invasive surgery only needs small incisions in the patient's body. This leads to a drastic reduction of tissue trauma and therefore to shorter recovery times. In the beginning this technique was performed manually with specialised instruments. Today, dedicated robotic systems are applied to assist the surgeon. Commercially available systems like the *daVinci* workstation [1] provides a decoupling of input device and instruments. The surgeon controls the instruments with a master console that is placed separately in the operating room. The instructions are carried out by a tele-manipulator, whose end-effectors perform the operations. This allows for comfortable work and full 6 degree-of-freedom (DOF) control of the instruments. Additionally, vision of the surgeon is improved by means of endoscopic stereo cameras, whose images are displayed at the surgeon's console. This system has a proven record, and many delicate operations have been performed [2..5].

A number of similar systems, both in research and for commercial use have been developed. These include, for example, a robotic system developed at UC Berkeley, which has already been used to perform certain surgical tasks like suturing and knot-tying [6]. The Korean Advanced Institute of Science and Technology has developed a micro-telerobot system that provides force feedback [7]. In Germany the first systems for robotic surgery was built at the Research Facility in Karlsruhe [8] and DLR [9]. While the former system provides no force feedback, the DLR system is equipped with PHANToM™ devices for haptic display.

Despite the advantages the systems offer, there are also needs of surgeons that have not been met. The most crucial issue is the lack of sensitive force feedback combined with delicate and fine instruments [10..12]. This often leads to unpleasant side effects like damaging thread material or even lacerating healthy tissue. It is in particular this shortcoming that results in a fast exhaustion of the operator, because the missing haptic feedback has to be compensated for visually.

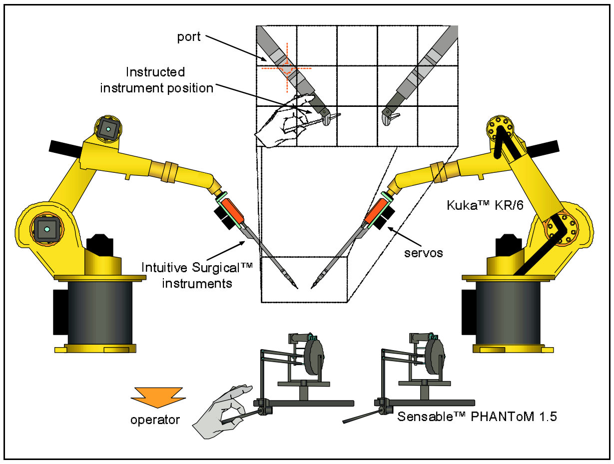

Figure 1: System Set-up

Inclusion of force feedback in medical tele-manipulators is therefore a crucial factor in improving reaction to tissue contact. Our aim is to provide the surgeon with an operation environment very similar to "immediate" instrumental surgery (i.e. the surgeon can always feel forces applied with the instruments). According to [13], the influence of force feedback on operation time seems to be even more profound than it is for visual feedback.

Following this analysis of deficiencies, we developed an open evaluation platform for robotic surgery that was tailored to the needs of sensitive force feedback for delicate operations like bypass operations in cardiac surgery (Fig. 1). Our "robotic surgeon" is not a telemanipulator that is controlled by visual servoing of the surgeon. Instead, it can be directly controlled by sending 6 DOF coordinates to its control unit. This is an important feature for closing control loops in machine learning applications, which can be applied in order to autonomously perform certain recurrent tasks, e.g. automated cutting or knot-tying.

Hardware and Methodology

Hardware Setup: Similar to other systems, 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 shown in Fig. 1, our system has two manipulators, which are controlled by two input devices. Each manipulator is composed of standard industrial robot that bears a standard surgical instrument. 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 also 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 multi-port interface card.

The robot has 6 degrees of freedom. Therefore, with certain restrictions, its flange can reach every position and orientation inside the working space of the robot. 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 and is therefore a redundant manipulator. Position and orientation of the manipulators are controlled by two *PHANToM* devices (Fig. 1). This device is available in different versions with different capabilities. Our version 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.

Force Feedback: The most interesting feature of the PHANToM devices we used, 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. The force sensors were applied directly on the shaft of the instrument. 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 shown in Fig. 2, the sensor gauges are applied at the distal end of the instrument's shaft, i.e. near the gripper. At the top of Fig. 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 readings are blurred with noise, we have applied digital filters to stabilize the results.

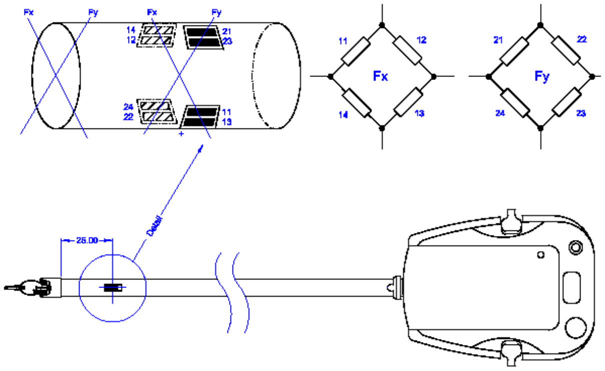

Figure 2: Application of strain gauges to an instrument

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, Fig. 3 top). 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. 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.

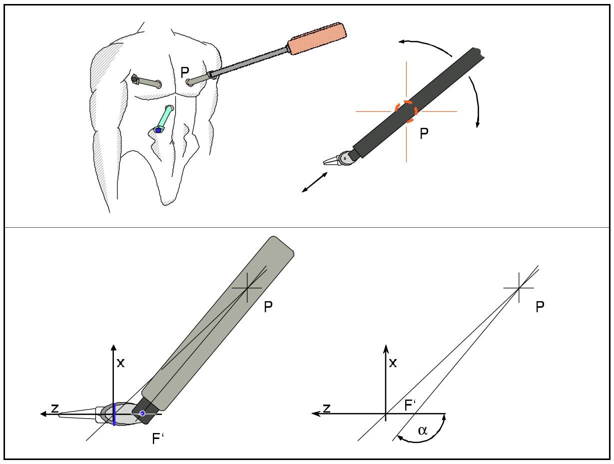

Figure 3: Backward Kinematics with trocar point

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 (e.g. Fig. 3 bottom).

As a result of these considerations, we get the position of the instrument's shaft. As this axis is identical to the flange axis of the robot, we have got the position of the flange. Given this information, we now can determine the backwards kinematics of the robot. This is a standard procedure, whose detailed calculation will be neglected here. As a final result we can implement a mapping from the position of the input stylus to the position of the instrument. That means the surgeon is provided with a direct remote control of the surgical instruments. In order to make navigation easier, we additionally equipped the system with a camera to observe the operation environment. A detailed description of the complex trocar kinematics can be found in [14].

System features: We give only a short list of system features we think to be important. The use of commercially available subsystems (robots, instruments, amplifiers) guarantees reliability and simplifies mass-production at comparable low prices. The robots have a high precision and stiffness. Their good dynamic behaviour could be exploited to perform advanced tasks in motion compensation (e.g. support for beating heart surgery as it was proposed in [15]). The modular character of this setup simplifies the adaptation of the system to technical improvements (e.g. new surgical instruments). Another advantage is the fact that our manipulator is a robot under Cartesian control whose position can be controlled precisely. Finally, the most important feature is the possibility for evaluation of force feedback in combination with endoscopic vision in robotic surgery.

Experimental Results

The original setup of the system, as we have used it for our first evaluations, can be seen in Fig. 4. We have performed several tasks adopted from surgical practice with this system. Our special emphasis was on surgical knot-tying.

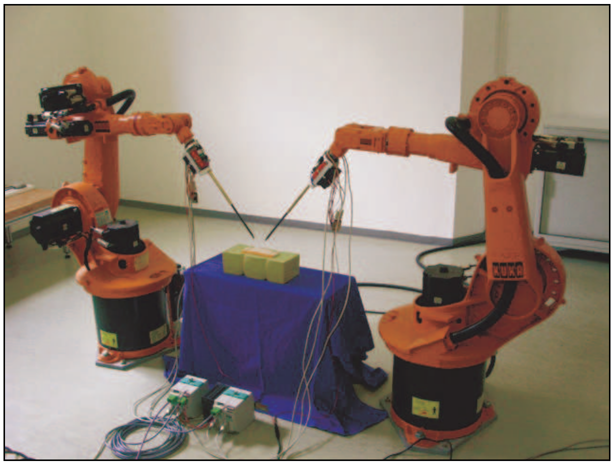

Figure 4: Experimental setup of the system

We successfully have made several different knots on a block of Styrofoam. We experienced some difficulties, because navigation was only based on the image of a single camera. The displayed images are not capable of providing realistic depth information. This experience has also been made by other authors (e.g. [15]). Therefore we are now using a stereo camera. Even with monocular view, knot tying was performed in a time that is acceptable for a first experimental evaluation (approx. one minute per knot). Force feedback has provided very realistic impressions of the environment. Forces were displayed in correct relation and along the right direction of the input device. Haptic feedback has completely prevented destruction of thread material or damaging Styrofoam. Force feedback turned out to be helpful when making contacts of the instruments with manipulated objects. For future evaluation we are planning long-term tests to find out if force feedback can prevent surgeon's fatigue. The current arrangement of input devices, however, is not very comfortable. Therefore we are planning to test different rearrangements of this setup and to develop an own input instrument to replace the stylus pen.

Conclusions

We have presented a novel approach of a robotic system for minimally invasive surgery. It is mainly composed of commercially available subsystems. This has several advantages like precision, reliability and a good dynamic behaviour. The main purpose of the system is evaluation of force feedback. We found out that performance of certain surgical tasks like knot tying will massively profit from this feature. We are planning to prove other advantages, like delayed fatigue in further tests.

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