ORIGINAL ARTICLE

Towards robotic heart surgery: Introduction of autonomous procedures into an experimental surgical telemanipulator system

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Abstract
The introduction of telemanipulator systems into cardiac surgery enabled the heart surgeon to perform minimally invasive procedures with high precision and stereoscopic view. For further improvement and especially for inclusion of autonomous action sequences, implementation of force-feedback is necessary. The aim of our study was to provide a robotic scenario giving the surgeon an impression very similar to open procedures (high immersion) and to enable autonomous surgical knot tying with delicate suture material. In this experimental set-up the feasibility of autonomous surgical knot tying is demonstrated for the first time using stereoscopic view and force feedback.

Keywords: robotic heart surgery, autonomous action sequences, knot tying, force feedback

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INTRODUCTION

The introduction of minimally invasive surgery has had a significant impact on patients and surgeons: patients profit from this new possibility of intervention because of considerably reduced tissue trauma and shorter recovery times. In contrast, minimally invasive operations aggravate the working conditions for surgeons. They have to cope with unaccustomed kinematics of surgical instruments, since all operations have to be accomplished through a small port in the patient's chest. In addition, visual impressions and lighting conditions are limited. By implementation of telemanipulated systems, limitations were partially removed. A sophisticated example is the daVinci® Surgical System [1]. Even in challenging surgical procedures like coronary artery bypass grafting the endoscopic and telemanipulated technique was established [2, 3]. It restores full control of the instruments by means of a telemanipulator and provides stereo vision of the operation environment to the surgeon. Despite the advantages of robot assisted minimally invasive surgery [4] the lack of force sensory and force feedback is one severe drawback of currently available systems [5]. Especially for the introduction of autonomous skills like knot-tying, recorded and reproduced forces are indispensable [6, 7]. Due to this restriction two major problems arise in such procedures: increased tissue trauma and frequent suture material damage. In order to overcome these problems two crucial issues have to be solved: the inclusion of force sensing and feedback, and the implementation of full Cartesian control of the end effector, which is essential for calculating the exact directions of forces in a known coordinate system. Therefore one of the main research interests is the prototypical construction and evaluation of force and sensory feedback in realistic scenarios of robotic heart surgery to implement autonomous knot tying. In particular we focus on instrumental (in comparison with conventional manually performed) suturing and knot-tying tasks, being easy to apply when manually executed, but requiring a lot of experience to be performed via telemanipulation. These tasks, accomplished by human operators, were recorded and after processing some steps they were autonomously replayed.

MATERIALS AND METHODS

Similar to other systems for robotic surgery, our set-up 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 Figure 1, the system consists of two surgical manipulators, which are controlled by two input devices. Each manipulator is composed of a KUKA KR 6/2 robot that carries a surgical instrument from Intuitive Surgical Inc. Furthermore we developed an adapter to link the robotic arm with the instrument.

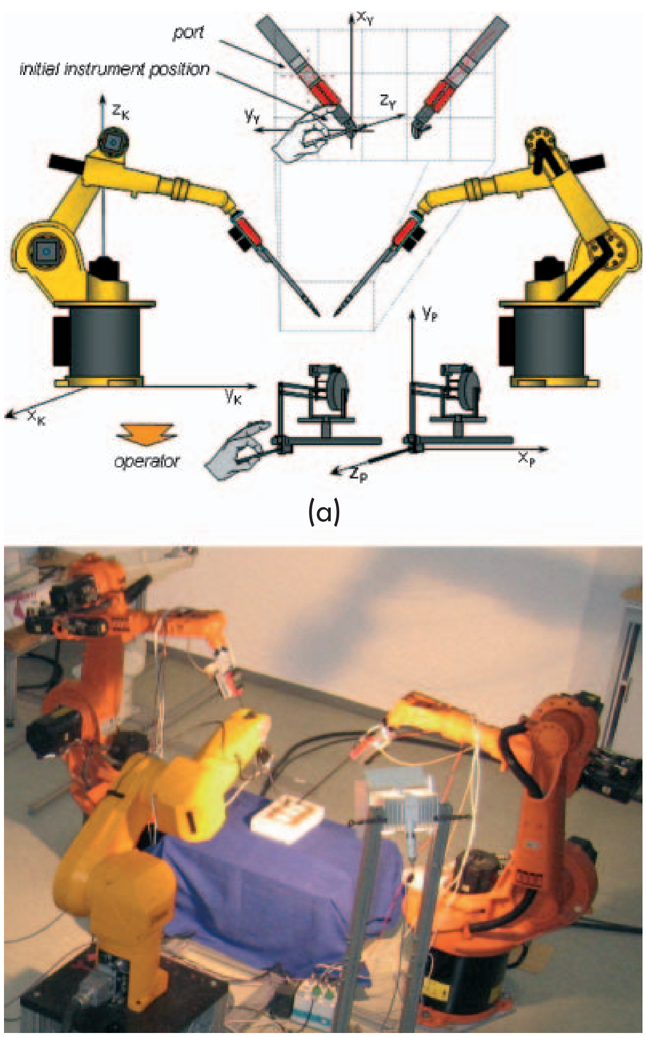

Figure 1 System Overview. (a) Model. (b) Robotic lab.

The surgical instruments provide three degrees of freedom. A micro-gripper at the distal end of the shaft can be rotated and the adaptation of pitch and yaw angles is possible, since the angle of each of the two jaws of the gripper can be controlled separately. 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. In order to control the instrument, servos are applied on each driving wheel by means of an Oldham coupling allowing smooth movements of the instruments. The servo controllers are connected via serial lines to a multiport card. The KUKA robot disposes of six degrees of freedom. Since the rotation of the robot's arm and the rotation of the instrument share one axis, the system finally is retooled with eight degrees of freedom. This redundancy allows the end effectors to reach every position and orientation within the working space under the restriction of trocar kinematics. The translational movements of the instruments are essentially restricted by shifts and rotations through the endoscopic incisions. In order to provide the surgeon with a comfortable environment, it is necessary 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. 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, there is only one possibility for aligning the instrument. The angle of the corresponding joints of the instrument can be found by geometric considerations.

Force feedback in surgical instruments

Since the shaft of the surgical instrument is made of carbon fibre, force sensors have to be very sensitive and reliable. Therefore strain gauge sensors are applied, which are employed for industrial force registration. The sensor gauges are applied at the distal end of the instrument's shaft near the gripper as shown in Figure 2. One full bridge of sensors is used for each direction. The signals from the sensors

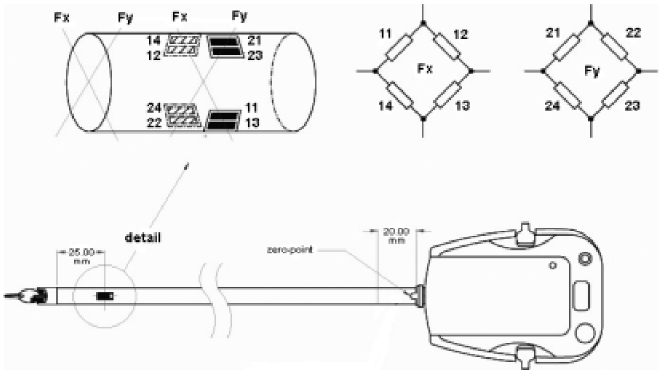

Figure 2 Application of strain gauge sensors. One full bridge for each direction in X and Y.

are amplified and transmitted via CAN-bus to a PC system. Since the direct reading of a sensor is associated with noise, a smoothing filter is applied in order to stabilize the results.

Force feedback device

Position and orientation of the manipulators are controlled by two PHANTOM® devices, Sensable Inc., see Figure 3. It provides enough space to perform surgical procedures. The user controls a stylus pen equipped with a switch that can be used to open and close the micro-grippers.

One outstanding feature of the PHANTOM® devices is their capability of displaying forces to the user. Forces are fed back by small servomotors 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 position. This version of the PHANTOM® device is able to display forces in all translational directions, while no torque is fed back. In order to display realistic forces during operation, we equipped the surgical instruments with force sensors.

Optical system

To enable proper telemanipulation it is indispensable to work on a 3D-display providing a distinct vision of the region of interest. An additional robot is equipped with a 3D endoscopic camera (Figure 4). Like the instruments, the 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.

Winding

In the first task of surgical operation the telemanipulator system was introduced in winding the thread during surgical knot-tying. Forces are acquired only in the XY-plane perpendicular to the instrument shaft, as the current set-up does not yet allow the measurement of forces along the shaft. Winding thread to form loops is a subtask in instrumental knot-tying. If executed by a surgeon, only very low forces arise, since a human operator copes with this task using only visual feedback. However in robot assisted surgery scenarios, high fidelity force sensation feedback is indispensable, as the visual modality is very difficult to analyse. Accordingly, robotic winding can be accomplished only in a force-controlled manner. On one hand forces are preferably kept constant; on the other hand suture breakage must be avoided. Figure 5 shows the force progression during a winding process. The frequency of force peaks in a certain direction grows, as the suture material gets shorter.

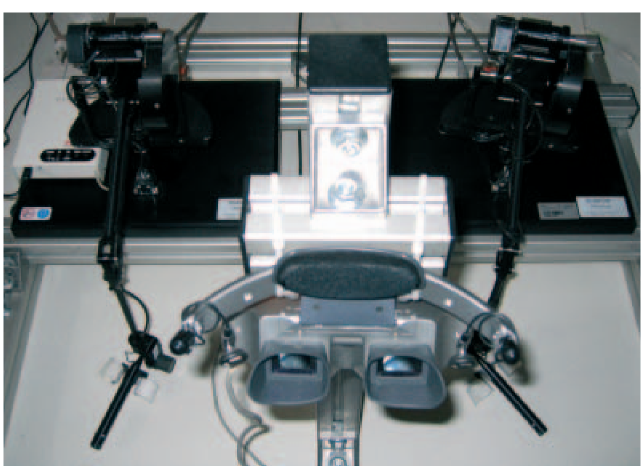

Figure 3 PHANTOM® Devices for haptic feedback with head mounted display.

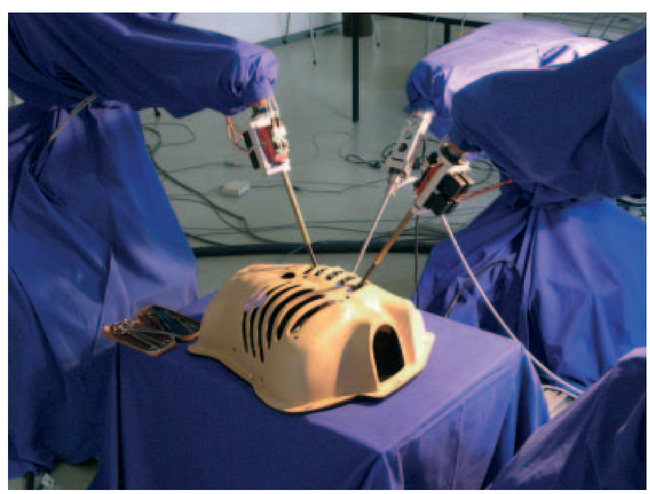

Figure 4 Set-up with two surgical instruments and one camera port.

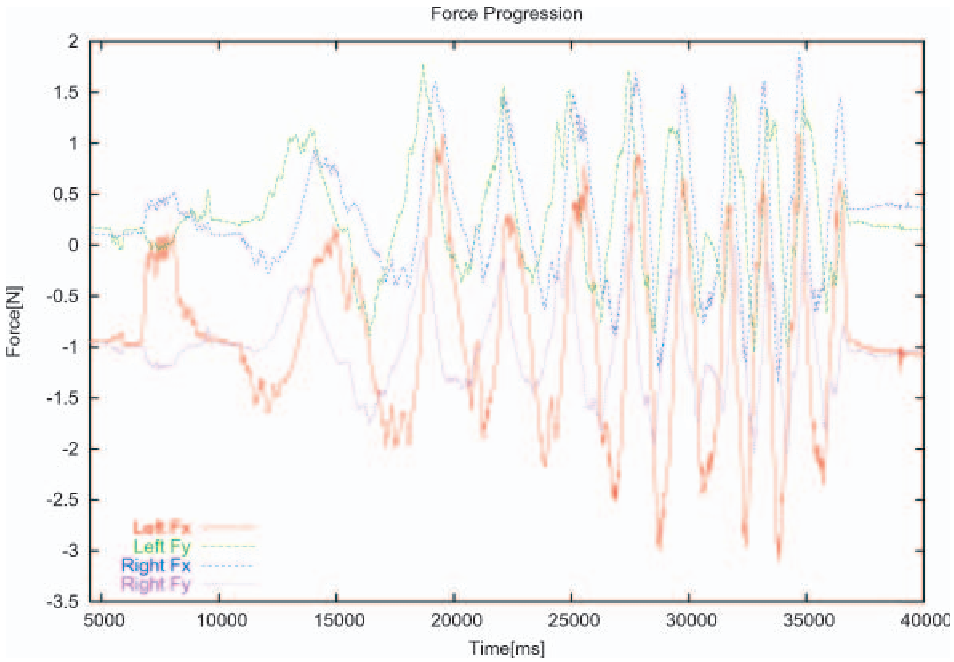

Figure 5 Winding a thread to make loops.

Preventing suture material damage

The tensile strength of absorbable and non-absorbable sutures is critical, both during and after surgical procedures. Having tested the breaking strengths of all used materials, suture material damage can be prevented by limiting the applicable forces to adequate maximal values. Figure 6 shows the progression of forces while trying to break the original surgical suture material, in this case PROLENE® (7/0, diameter 0.05 mm, Polypropylene, non-absorbable).

Collision detection

Avoiding the collision of the instruments in robot assisted minimally invasive surgery is a challenging task. Therefore a symbolic representation of the whole robotic system, including both the

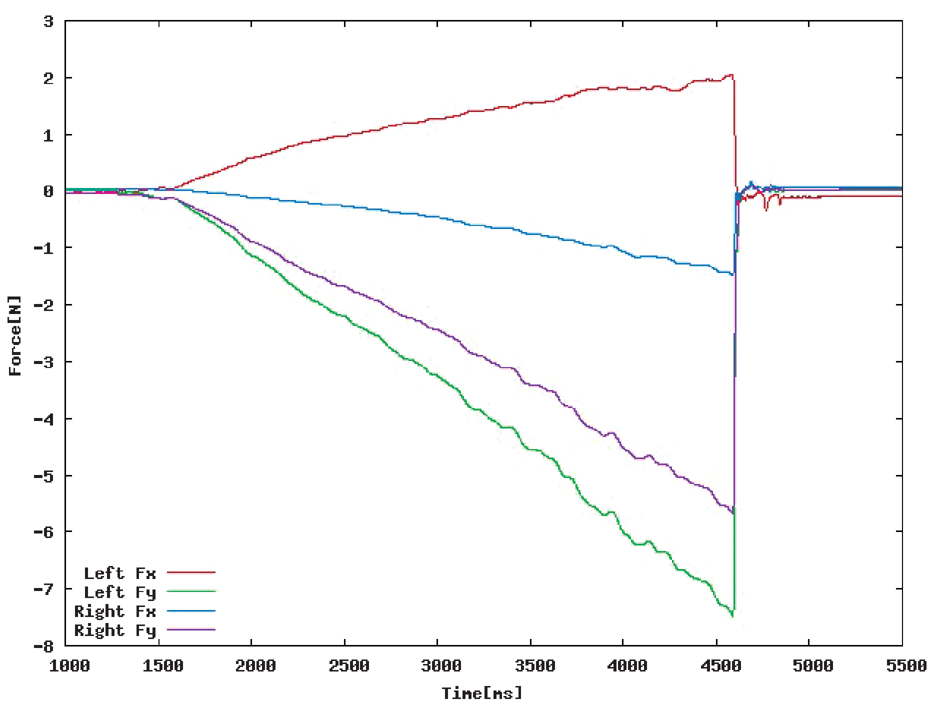

Figure 6 Breaking surgical thread (PROLENE® 7/0).

instruments and the arms, is necessary. Furthermore the exact control of position and the detection of collision by a software subsystem are indispensable. However most of the available systems do not provide the infrastructure mentioned above. A human operator is able to avoid instrument collisions, but in an autonomous mode other solutions are necessary. A force controlled set-up will not prevent collisions, but an early detection can avoid damage to the instruments. Figure 7 shows the forces recorded during an instrument collision. The velocity of the instruments was within ranges typical for that scenario. The highest peak (Y–force component of the left instrument) arises within approximately 35 ms. With a robot arm interpolation of 12 ms there are nearly three interpolation periods to react, providing a satisfactory collision interception.

Knowing the position and orientation of the instruments feedback forces are transformed to the coordinate system of the PHANTOM® devices. For the introduction of an autonomous surgical knot, trajectories and forces that occurred during a knot performed by a surgeon were recorded and reproduced by the system by methods of skill-transfer.

RESULTS

Regardless of the above mentioned issues several knot tying tasks were performed successfully with this system and recorded both force progression and the corresponding trajectories (described by position and orientation of the instruments). The first experiment was the replay of a previously recorded knot-tying task. Since the system features a high repeat accuracy, this procedure was performed very reliably. The only prerequisite is positioning the needle at a known site. Since the surgeon places the needle and the geometry of the system is known, the corresponding position can always be located. Due to exact kinematics, execution at up to double normal speed has raised no difficulties. As the objective is not restricted to acceleration, the optimised trajectories are generated with respect to smoothness and path planning. Therefore spline approximation is applied to the raw data, see Figure 8. These results are described in a symbolic representation of the trajectory in a

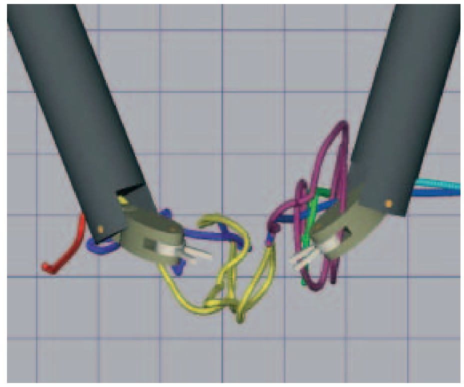

Figure 8 Spline approximated trajectory (knot-tying).

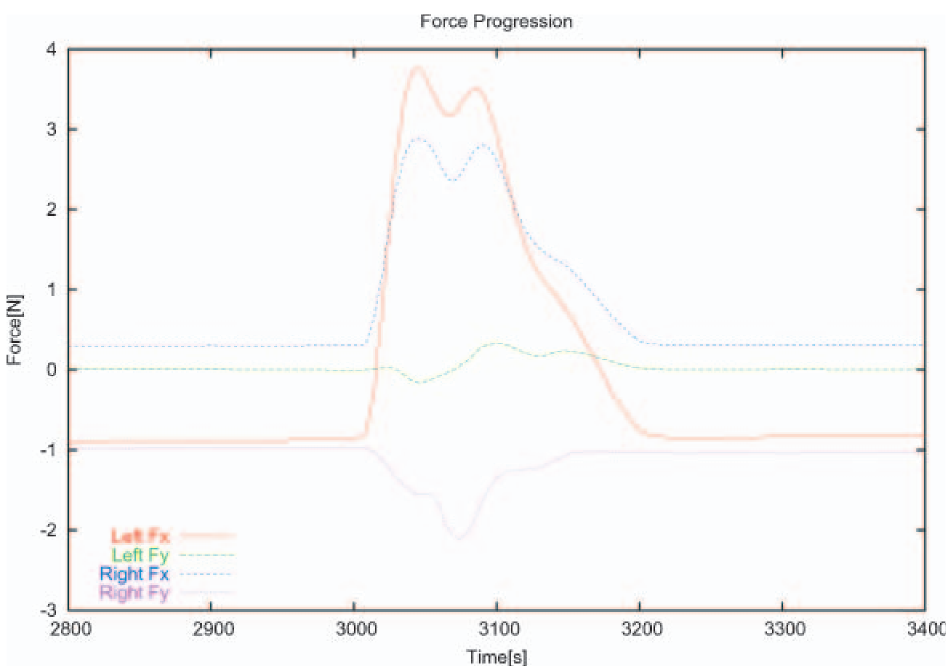

Figure 7 Colliding instruments.

parametric space-curve. Before applying the generated curve to the real system, collision avoidance has to be guaranteed, since over modified paths can contingently result in instrument collision.

If the system is used by a human teleoperator, the surgeon feels the impression of direct haptic immersion, while the system records forces during any time of a given task. Applying the recorded data, the system is able to perform autonomous knot tying with delicate surgical material without breaking the thread or the needles.

CONCLUSIONS

We present a novel approach of a robotic system for minimally invasive surgery. The main purposes of the system are to present an experimental platform for evaluation of force feedback and machine learning. The performance of certain surgical tasks like knot-tying will benefit 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 tolerable amplitudes. Collision of instruments can be detected and intercepted by real-time force evaluation. Forces are measured at the surgical instruments and fed back into the surgeon's hands using multidimensional haptic styluses. Ongoing research is planned for future evaluation to improve the set-up of the instruments and to incorporate the results of the force evaluation into the control software. A simulation environment is designed for modelling haptic interaction with a tissue model. This can be applied for offline evaluation of critical tasks.

In our experimental set-up, we were able to demonstrate for the first time, that autonomous surgical knot tying is possible using stereoscopic view and force feedback. Further investigations will evaluate the usefulness of haptic information on procedures performed by a human teleoperator.

ACKNOWLEDGEMENTS

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