Endo[PA]R: An Open Evaluation System for Minimally Invasive Robotic Surgery

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***Abstract*— EndoPAR (Endoscopic Partial-Autonomous Robot) is an open experimental platform for robot assisted minimally invasive heart surgery with haptic feedback. The manipulator set-up is composed of two low-payload robots equipped with sensorized surgical instruments and a third robot carrying a stereo camera system. Trocar kinematics, enabling surgical manipulation through small incisions, has been implemented for all robotic arms. In order to ensure operation close to reality, a thorax and heart phantom for surgical training was used in the experiments. Stereo vision is provided via a head-mounted display and force-reflective input devices are employed for user interaction. The system was evaluated by surgeons and it was capable of performing automated knot-tying.**

I. 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 (“key-hole”) 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. [1]). 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. [2] and [3]).

Despite the mentioned advantages of robot assisted minimally invasive surgery, all research groups involved in, agree about the fact, that the lack of force sensory and force feedback are the biggest drawbacks of currently available systems (cf. [11]). Consequently 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 (as different from conventional manually executed) suturing and knot-tying. These tasks, performed by human operators, were recorded, and after some processing steps they were autonomously replayed.

II. PREVIOUS WORK

Since the interesting field of robotic surgery has attracted many researchers, there is 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 ([7]). The Korean Advanced Institute of Science and Technology has developed a micro-telerobot system that also provides force feedback ([5]). In Germany two systems for robotic surgery were built at the Research Facility in Karlsruhe ([6]) and at the DLR in Oberpfaffenhofen ([4]). 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. [9] 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. [10] have analyzed a variety of surgical tasks (among other things knot tying) and decomposed them into subtasks. They did not include force measurement.

III. MATERIALS AND METHODS

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, a third robot is carrying an endoscopic camera system. The motor part of our system consists mainly of two major parts: A low payload robot that carries an adapter for flanging the instruments. This contrivance can accept different exchangeable surgical instruments, which are deployed with the surgical workstation daVinci (TM). 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. 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 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.

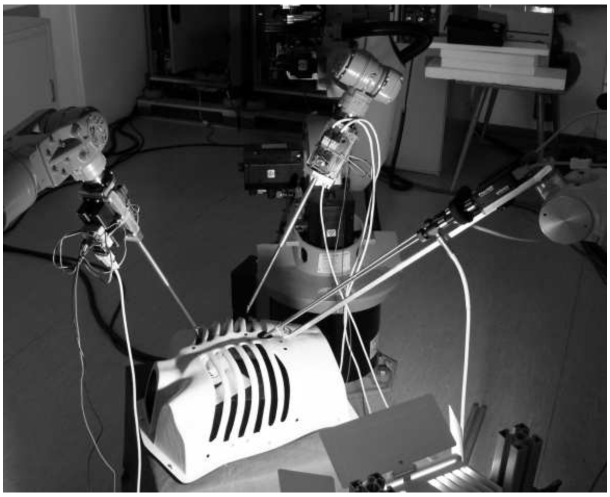

Fig. 1. System Overview

Since the rotation of the robot's flange and the rotation of the instrument share one axis, the combination of robot and instrument results in a manipulator with eight degrees of freedom. That means our system is a redundant manipulator. This can be exploited to evaluate different kinematical behaviors. To address the aspect of intuitive operability of the user interface, we apply the concept of so-called *trocar kinematics*: the manipulator has to pass through a fixed hole ("port") in the patient's chest. This restricts the degrees of freedom of the instrument. Feed (translation) and rotation axes must always intersect with the fixed port.

We have equipped all surgical instruments for our setup with strain gauge sensors. They are applied by means of adhesive sealing and heat shrink tubing. Strain gauge technique is well-approved in other areas (like crash testing) and provides solutions for multifarious requirements (like high temperature, moisture and corrosive environments). Raw signals acquired from the gauges are preprocessed with high-precision amplifiers. They are finally transferred to the control computer by means of a *DeviceNet* bus. For user input and force reflection we employ two *PHANToM* devices. Those are available in different versions with different capabilities. Our version provides a full 6 dof input, while force feedback is restricted to three translational directions. The user controls a stylus pen that is equipped with a switch that can be used to open and close the micro-grippers. An endoscopic stereo camera system delivers 3D impression of the scene to a binocular head-mounted display.

IV. 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.

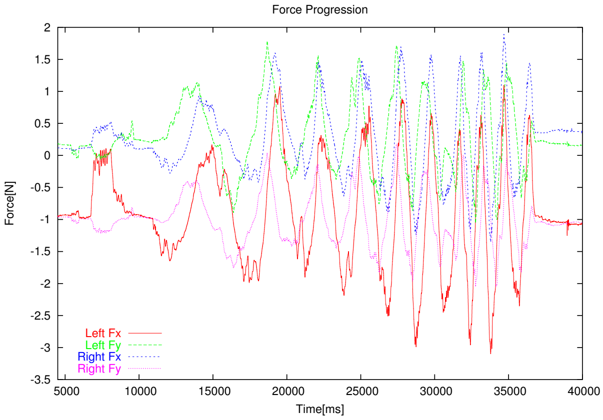

Fig. 2. Winding a thread to make loops

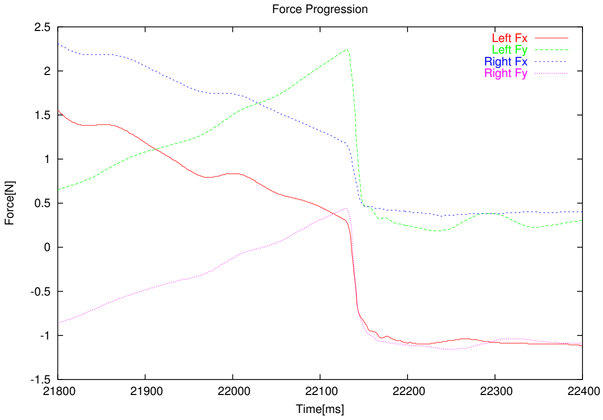

Fig. 3. Breaking a thread during winding

A. 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 is a subtask in instrumental knot tying (cf. [10]), 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. 2 shows the force progression during a winding process. The frequency of force peeks in a certain direction grows, as the suture material gets shorter. Nevertheless the forces are quite constant during the whole manipulation. Figure 3 shows a magnified view of an accidental break of the thread during a further winding process. Due to the high time resolution (1 ms) the instant recognition of such suture breaks is possible, preventing the robotic system from unexpected behavior.

B. Preventing Suture Material Damage

The tensile strength of absorbable and non-absorbable sutures is critical, both during and after surgical procedures. Breaking forces can be measured using either a ”straight pull” test or a ”knot pull” test. Given the forces of all used sutures, it is possible to prevent suture material damage by limiting the applicable forces to adequate maximum values. Fig. 4 shows the progression of forces while trying to break original surgical suture material, in this case Ethicon PROLENE (7/0, Polypropylen, not absorbable). Fig. 5 shows breaking the thread (PROLENE 7/0) while tying a knot. As expected, the thread was broken at the knot position by significantly less force impact.

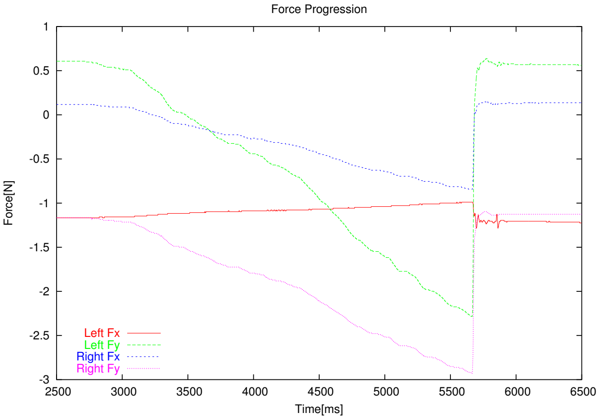

Fig. 4. Breaking Ethicon $7/0$ by normal pulling

C. 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 in approximately $35ms$. With a robot arm interpolation of $12ms$ there are nearly 3 interpolation periods to react when such a situation appears, providing a satisfactory collision interception.

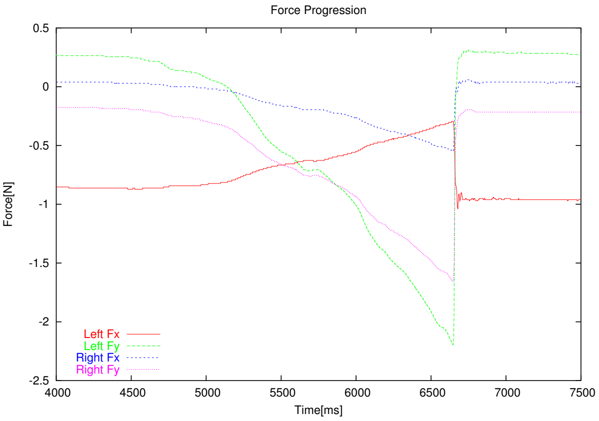

Fig. 5. Breaking Ethicon $7/0$ during knot tying

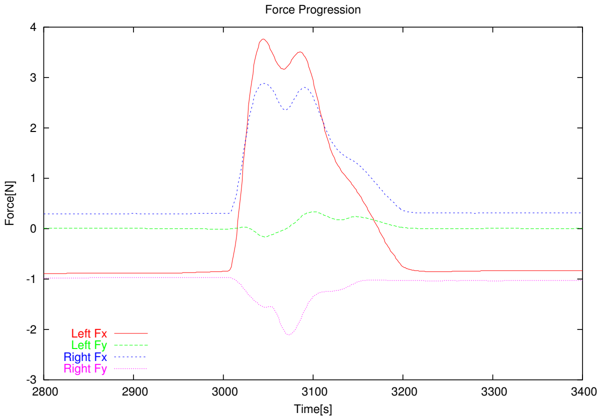

Fig. 6. Colliding instruments

V. PARTIAL AUTONOMY

We have 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). Due to inevitable physiological tremor of the human operator, the acquired trajectories exhibit some noise. Therefore two-stage preprocessing was applied to the raw data. The first stage comprises sliding window averaging, the second stage approximates the smoothed data with natural cubic splines.

Our first experiment was replay of an original sample with no smoothing and approximation applied. 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 fig. 8) . 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.

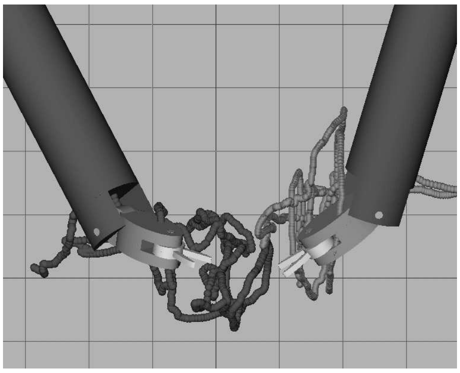

Fig. 7. Raw Trajectory (Knot-Tying)

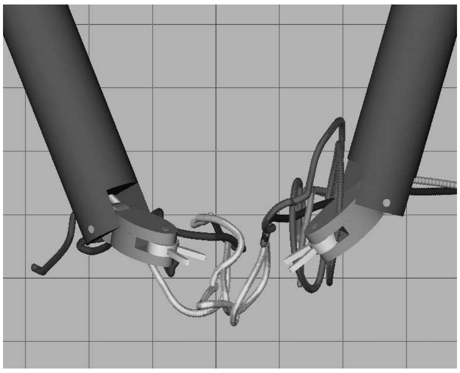

Fig. 8. Spline Approximated Trajectory (Knot-Tying)

VI. CONCLUSION

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 behavior. 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 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 own input instruments to replace the stylus pens. Additionally we are planning to include measurement of torques and their incorporation in the control loop of the system. 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. Integration of force feedback with stereo vision, as offered by the system, can 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.

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