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Sensorized and Actuated Instruments for Minimally Invasive Robotic Surgery

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Abstract. Minimally invasive surgery (MIS) challenges the surgeon's skills due to his separation from the operation area which can be reached with long instruments only. To overcome the drawbacks of conventional MIS robotic surgery systems with integrated haptic feedback play an important role. This paper describes the development of actuated and sensorized instruments for minimally invasive robotic surgery which are a necessary prerequisite for haptic feedback.

1 Introduction

Minimally invasive surgery (MIS) is an operation technique established in the 1980s. In contrast to open surgery only three small incisions are necessary (typically smaller than 10 mm). This reduces pain and trauma, leads to shorter hospital stays and shorter rehabilitation time and provides also cosmetic advantages. However, MIS also challenges the surgeon's skills due to his seperation from the operation area. Especially two things are disadvantageous [1,2,3,4]: haptic feedback is reduced and full dexterity of the distal instrument tip is lost. In order to give back haptic feedback and full dexterity to the surgeon it is necessary to integrate sensorized and actuated instruments into a robotic surgery system. Until now mainly two commercial robotic systems for MIS are available and also in clinical use: the Zeus system from Computer Motion Inc. [5] and the daVinci system from Intuitive Surgical Inc. [6]. None of them provides haptic feedback although it is expected that this will help to reduce unintentional damage of tissue and operation time.

A key issue for a successful integration of haptic feedback is the development of appropriate instruments. They must contain a miniaturized force/torque sensor (FTS) to measure manipulation forces and torques and they must provide two additional actuated degrees of freedom to twist the instrument tip in combination with actuation for the functional end (e.g. a gripper). Furthermore, if the distal end is too expensive to be built as a disposal part it has to be sterilisable. The paper describes the development of sensorized and actuated instruments according to these requirements which is a prerequisite for the integration of haptic feedback into a minimally invasive robotic surgery system.

2 Articulated Joint

The design of the articulated joint as universal joint with intersecting axes (see Fig. 1 left) allows for twisting the gripper about its longitudinal axis without pivoting the instrument shaft about the point of insertion. The range of motion in the joint is restricted to about 40° in both directions. The setup of the drive cables in the joint (Fig. 1 left) forces the cables to run tangent to the drive pulleys at all times. The middle of each cable loop is tied to the distal component of the joint, while the proximal ends are connected crosswise at the actuator. Therefore the length of both cable loops remains constant at every joint position. With this layout only two fixed rotary drives are needed to fully actuate the joint, yielding nearly linear transmission characteristics. Some sliding motion between cable and joint body occurs during certain movements, however friction between joint body and cable is small due to the low friction coefficient of steel and Vectran^{TM}.

Proposed manipulation forces are 20 N at the instrument tip and the gripping force is 20 N, respectively. The gripper is actuated by one cable counteracted by a spring. The cable force necessary to close the gripper and securely hold a needle is calculated to be 70 N. Maximum driving forces for the joint actuation are about 100 N. To guarantee zero backlash, the cables are prestressed with the maximal expected driving force, accounting for a worst case cable force of 200 N.

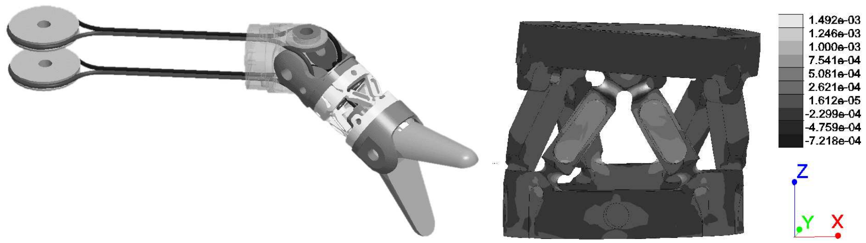

Fig. 1. Articulated joint with drive cables (left) and average xz-strain on force/torque sensor for load $F_x = 20\ N$ (right)

3 Distal Sensor

Realistic force information can only be measured inside the patient's body close to the operation site, minimizing the errors due to friction between the instrument and the point of incision. The sensor should be separated of the drive mechanism to prevent the influence of backlash and friction on the sensor's performance.

Placement of an FTS was considered in three different locations of the instrument tip: in the jaws of the gripper, in the shaft proximal to the joint, or between gripper and joint, as shown in Fig. 1 left. The last possibility was chosen because at this location the sensor is only subjected to the gripper cable force which is acting centrically. Since this force is measured for the control of the gripping force, the FTS output can be compensated for simultaneously.

A Stewart Platform based FTS (see Fig. 1 right) was chosen for its high stiffness, adaptable properties, annular shape, and scalability. Furthermore, only longitudinal force transducers are required. For the small sensor size of less than 10 mm diameter ball joints, as normally used in Stewart Platforms are not applicable due to their high complexity of manufacturing and assembly. These are replaced by flexural joints creating a monolithic sensor structure. Flexural joints support transversal forces and moments, introducing an error compared to ideal ball joints. This error can be reduced only by appropriate link/hinge design [7].

To validate the design, the sensor was fabricated from AlCuMg 1.5 (F55) and instrumented with 350 Ω single element strain gauges. This setup was calibrated using external loads of 2 N and 80 Nmm. Subsequent measurements demonstrated the quality of the calibration as well as linearity of the sensor [7].

4 Propulsion Unit

The propulsion unit is thought to be located at the last axis of a medical robot. The medical robot provides mechanical interface, power and data connections. At the distal end of the unit the above described gripper with FTS and universal joint is located. The purpose of the propulsion unit is to actuate the joint and the gripper and read out the distal sensor.

The sterilisation requirement was solved by separating the unit into two reconnectable components: one steam-sterilisable section in patient contact without any electro-mechanical or thermo-instable components and one spray-sterilisable section not in patient contact containing all thermo-instable components (motors and electronics) [8]. During clinical use separation and reconnection is accomplished by a spring loaded latch mechanism and lateral joining motion (see Fig. 2).

Cables from Vectran^{TM} (a 12-time plaited high module polyester material) with a diameter of 0.6 mm were chosen as force transmission media. Synthetic fibre cables seemed to be favourably to steel cables because of their much lower flexural rigidity. Furthermore, Vectran^{TM} is stable against acids and bases commonly used for sterilisation, withstands a temperature up to 330°C, does not collect moisture or ichors, and has no incline to creep.

Integrated in the propulsion unit are rope position and force sensors. By comparing this information to the distal FTS it is possible to permanently acquire data about the friction in the drive chain, generated in the joint, shaft, and propulsion unit. These sensors also permit plausibility checks and therefore serve as a safety mechanism against cable tear or dislocation from the pulleys. Additionally, accurate knowledge of the cable force allows for a calibration of elastic cable deformation and therefore a more precise positioning of the instrument tip.

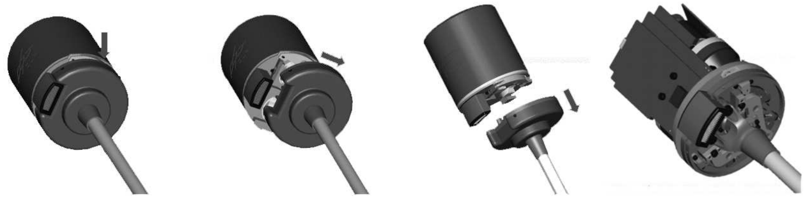

Fig. 2. Propulsion unit: procedure to deconnect the two components (left) and inside view (most right)

5 Summary

A prerequisite for the integration of haptic feedback into a minimally invasive robotic surgery system are sensorized and actuated instruments. Small force/torque sensors placed near the instrument tip in combination with appropriate input devices provide realistic haptic feedback of the remote forces. This gives the surgeon direct access to manipulation forces inside the patient and allows for a more delicate manipulation of tissue, avoiding unintentional damage. Actuated instruments are necessary to provide full dexterity inside the patient. This makes MIS more similar to open surgery and it is to be expected that more operations will be carried out in a less invasive way.

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