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Estimating Gripping Forces During Robot-Assisted Surgery Based on Motor Current

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Abstract: Accurate measurement of interaction forces during robot-assisted surgery requires compact force sensing modalities in the surgical tools, thus might add considerable cost to the setup. Measuring the motor current to estimate gripping forces, is an advantageous approach since no expensive force sensor is needed. In this paper, a mechanical interface is presented, which allows actuating conventional articulated instruments for robot-assisted surgery. The interface features the estimation of static gripping forces at the instrument's tip based on the motor current. The evaluation shows reproducible results, and the current-based approach seems to be a cost-efficient way to estimate gripping forces.

Keywords: robot-assisted surgery, articulated instruments, gripping forces, haptic feedback, telemanipulation

1 Introduction

During minimally invasive surgery (MIS), the limited degrees of freedom (DOF) of the instrument reduces the dexterity for the surgeon. Instruments for manual use with additional DOF, such as wrist-like articulation of the tip, address this issue [1], however, finding an intuitive user interface remains challenging. In contrast, using such instruments in robot-assisted surgery (RAS) is state-of-the-art due to the greater design freedom of the user interface. To preserve a haptic impression for the surgeon, not only the translational forces between instrument and tissue, but also gripping forces are of relevance [2] and must be obtained and displayed to the user.

Accurate measurement of interaction and gripping forces during RAS requires compact force sensing modalities implemented in the surgical tools, thus might add considerable cost to the setup [3]. The use of existing surgical instruments for RAS would be beneficial regarding economical and infrastructural aspects, such as facilitating the adoption into clinical workflows, to enable widespread usage, and to enable a versatile application of various instruments in different surgical scenarios. There are different methods to enhance instruments with a gripping force measurement, such as obtaining forces or torques in the drive train of the instrument or the motor current [4 - 6]. In contrast to the development of instruments with integrated force sensing capabilities, such as by KIM et al. [7] or THOLEY et al. [8], the enhancement of existing instruments with a sensing approach at the proximal part of the instrument seems to be a resource-efficient alternative. Especially the estimation of gripping forces based on the motor current is advantageous, since no expensive force sensors are needed, and presumably, a rough estimation of the acting gripping force is sufficient for the user to achieve a more delicate interaction with the tissue.

In this paper, a mechanical interface is presented, which allows to robotically guide and actuate instruments with wrist articulation based on rigid kinematics instead of the frequently used cable-based actuation. The mechanical interface inherits current sensing, enabling the estimation of gripping forces. In the following, the interface is briefly described, and the gripping force estimation is presented and assessed.

2 System Design

2.1 Telemanipulation System

For research purposes, a telemanipulation system is used that consists of standard or commercially available components and can be easily reconfigured. As the manipulator of the telemanipulation system, a seven-DOF articulated robotic arm (Panda, Franka Emika GmbH, Munich, DE) is used (Fig. 1). To guide and actuate surgical instruments, a mechanical interface is mounted to the tool center point (TCP) of the manipulator by a passive universal joint. As a result,

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when forces are applied to the tissue by the instrument's tip, lateral forces onto the abdominal wall in the trocar point are accepted. With the position of the manipulator's TCP and an inertial measurement unit to determine the orientation of the mechanical interface, the pose of the instrument's tip can be obtained. The manipulator and the mechanical interface can be controlled with a haptic input device that allows the user to command poses and gripping movements to the instrument.

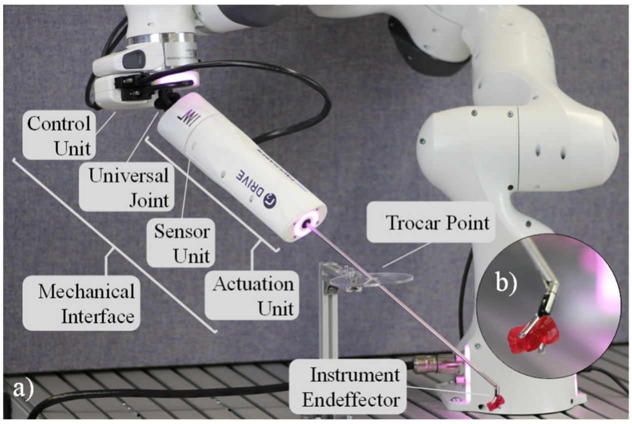

Figure 1: Manipulator with the mechanical interface (a) and close-up view of the instruments endeffector (b).

2.2 Mechanical Interface

The mechanical interface is designed for the r2 instruments by Tuebingen Scientific Medical (Tuebingen Scientific Medical GmbH, Tübingen, DE). The instruments allow articulating their endeffector around a wrist joint, rotating the endeffector around its axis, rotating the instrument around its shaft axis, and a gripping movement. To access the actuation part of the instrument, the handle for the manual operation was removed.

The mechanical interface consists of a control unit, a universal joint, and the actuation unit with an integrated sensor unit (Fig. 1). The control unit comprises the electronic components necessary for the control of the actuation unit, such as an Arduino Nano (Arduino S.r.l., Monza, IT), the motor controllers (DRV8801, Texas Instruments Inc., US), the current sensor (INA219, Texas Instruments Inc., US) and communication interfaces for the integration into the telemanipulation system's control architecture. The sensor unit contains the HEX 21 6-axis force and torque sensor (Wittenstein SE, Igersheim, DE), to determine translational interaction forces at the instrument's tip. The actuation unit contains the electromechanical components for the actuation of the DOF of the instrument, such as four DC gear motors with incremental encoders (Dr. Fritz Faulhaber GmbH & Co. KG, Schönaich, DE). The gripping movement is actuated by a type 1512 DC gear motor with 112:1 gear ratio and a rack and pinion gear. The gripping movement is limited to the maximum opening angle of the respective endeffector, which is 60° for the atraumatic grasper and dissector and 45° for the needle holder. Further, the wrist joint enables a 90° articulation angle in one direction, the endeffector rotation is infinite, and the shaft rotation is limited due to cable guidance to 360°. Additionally, to obtain the pose of the instrument's endeffector, an inertial measurement unit (IMU) with a BNO055 chip (Bosch Sensortec GmbH, Reutlingen, DE) is integrated. The actuation unit of the mechanical interface has an overall length of 246 mm and a diameter of 70 mm.

2.3 Control of the Mechanical Interface

In the control unit, the control algorithms for the actuators are executed and the current sensor is read out to estimate a gripping force based on the motor current. All motors are supplied with a nominal voltage of 12 V and pulse width modulation. The current sensor is placed between power supply and motor driver board and is read out by the Arduino via I^2C. Averaging over four measurement values, to reduce sensor noise, results in an overall sampling rate of 300 Hz.

Gripping movement, as well as endeffector and shaft rotation, are controlled by a proportional controller. Due to the high friction, for the wrist articulation proportional-integral-derivative control is applied. Since incremental encoders are used and thus, no absolute position feedback is available, every axis must perform a homing movement. Therefore, gripping and wrist articulation move in one direction until the motor stalls, which is detected by an increase in the motor current. Both, endeffector and shaft rotation feature reflective optical switches (ITR 20001/T, Everlight Electronics Co. Ltd., TW) to enable the homing procedure.

3 Methods

To evaluate the forces, which can be applied to an object with the instrument's endeffector, and to validate the relation between motor current and gripping force, a test rig was set up (see Fig. 2). Motor current and gripping force are expected to follow a linear relationship, mainly influenced by the gear reduction ratio and the instrument mechanics. The test rig offers the possibility to measure forces between two small gripper branches without the need of placing a small force sensor between those branches. Therefore, a lever kinematic allows equiping the test rig with conventional S-shaped force sensors. Due to the lever kinematic, all measured values must be divided by a factor of two. A type KD40s force sensor (ME-Meßsysteme GmbH, Hennigsdorf, DE) with a measurement range of ± 50 N and a sampling rate of 200 Hz was used. The gripping width can be adapted to the instruments endeffector type by adjusting the distance between the gripping brackets.

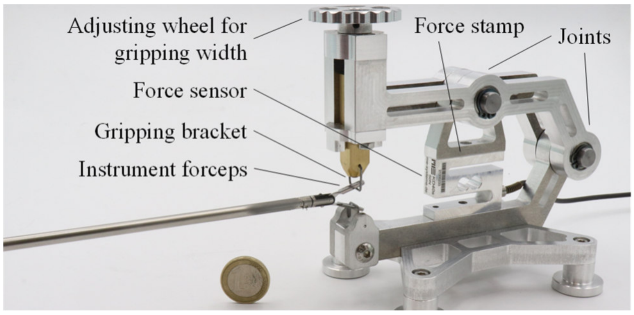

Figure 2: Test rig for the measurement of gripping forces.

The maximum gripping forces of the endeffector type dissector, atraumatic grasper, and needle holder were evaluated by grasping the gripping brackets with a duty cycle of 100 % leading to the highest possible motor torque. The maximum gripping forces were measured at three measurement points on dissector and atraumatic grasper and on one measurement position on the needle holder (Fig. 3). For all endeffector types, a wrist articulation of 0°, corresponding to a straight instrument, and an opening angle of 50° were chosen for the isometric measurement. For every measurement point, twelve measurements were carried out to obtain a mean maximum gripping force. On every measurement point, the force was held for 0.5 s to reduce dynamic effects and to enable averaging to reduce noise of both, current and force sensor.

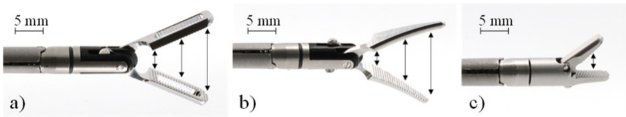

Figure 3: Atraumatic grasper (a) and dissector (b) with proximal, medial, and distal measurement positions, and needle holder (c) with only the medial measurement position.

To characterize the relation between motor current and gripping force, the duty cycle was increased in steps of 4 % from 28 % to 100 % and the resulting motor currents and gripping forces were measured. Between every step, the gripper was completely opened to reduce the influence of static friction. This resembles a scenario where the endeffector is completely opened and a user starts grasping tissue. Analogous to the maximum gripping force measurement, different measuring points were used (Fig. 3) and for every measurement point, twelve measurements were carried out.

A second measurement covers the scenario, in which a user has already grasped an object and then wants to apply a higher gripping force. Therefore, a base duty cycle of 28 % was applied to the actuator and was then increased by a differential step of 0.8 %. Afterwards, the gripper was completely opened, again actuated with the base duty cycle, and then increased by a multiple of the step width. This procedure was repeated until a local maximum of the derivative of the force signal was detected. The step in the duty cycle and thus in the motor current, which causes a change in the force signal, can be understood as the smallest differential force, which can be obtained during operation. This resolution is not limited by the current sensor but rather caused by friction of the actuation path with a high break-away force. The measurement was carried out ten times with the atraumatic gripper in the medial position. Since the test rig does not allow endeffector movements, and thus hinders the actuation from overcoming initial break-away loads caused by static friction, a 5 mm layer of polyurethane foam was placed between sensor and force stamp. This ensures a more realistic behavior but still allows the assumption of a constant opening angle.

With the suggested method of estimating gripping forces based on the motor current, it is not possible to determine absolute gripping forces, since the position of a grasped object between the gripping branches as well as the opening angle of the gripping branches changes the transmission ratio of the instrument's gripping mechanism. It is instead possible to determine what percentage of the available actuation force is provided from the actuator.

4 Results

The mean maximal gripping forces of the three different endeffector types are listed in Table 1 with respect to the measurement position.

Table 1: Mean maximal gripping forces and standard deviation.

	Proximal	Medial	Distal
Atraumatic Grasper	8.37 ± 0.28 N	4.62 ± 0.24 N	3.21 ± 0.13 N
Dissector	9.02 ± 0.05 N	4.41 ± 0.03 N	3.12 ± 0.06 N
Needle Holder	-	16.44 ± 0.22 N	-

The relation between the measured motor current and the measured gripping force is shown in Fig. 4.

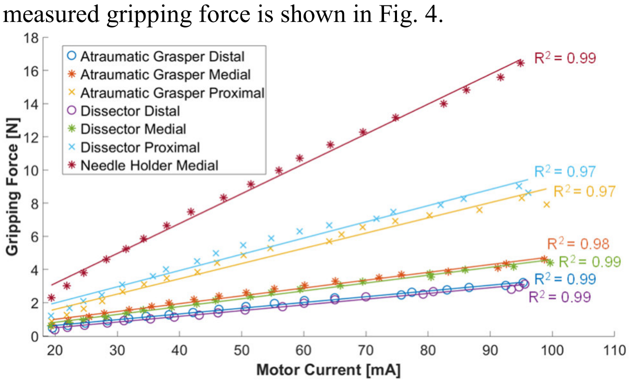

Figure 4: Relation between gripping force and motor current with respect to the different measurement positions.

The smallest differential change in the force signal, which could be measured at the medial measurement position of the atraumatic gripper is a mean step of 0.07 ± 0.05 N, equivalent to 1.5 % of the mean maximal force. To overcome the break-away load, this step is related to a mean change in the motor current of 3.86 ± 0.84 mA. The mean maximal noise amplitude is 0.14 ± 0.06 mA.

5 Discussion

In this paper, a mechanical interface for the actuation of conventional articulated instruments in a telemanipulation system for research purposes is presented and assessed regarding its ability to estimate gripping forces based on motor current. Despite the high static friction and the resulting break-away load, a clear and reproducible linear relation between motor current and force can be seen, which benefits the estimation of interaction forces during operation. The high standard deviation of the differential force measurement is presumably due to the high friction that leads to varying currents necessary to achieve a breakaway of the mechanics.

A strong influence of static friction could be observed, resulting in a high break-away force necessary for initiating a movement of the gripping branches. Especially during the isometric measurements, this hindered the setup from applying forces to the test rig. Since such a stiff object is not very likely to appear in a realistic setting, a flexible element was placed in the measurement setup to allow for a slight displacement and thus avoiding a complete blocking of the instrument's mechanism. In the case of static measurements, the flexible element is assumed to not have any influence on the absolute force measured. To improve the mechanical setup of the interface in the future, the friction can be reduced by using better tribological pairing and lubricant or by reducing the reduction ratio of the actuator and thus achieving a back-drivable system. While the test rig is well suited for static measurements, due to its high mass, dynamic measurements of fast changing gripping forces are only possible in limited extent. Despite the strong influence of the friction, the measurements show reproducible results for all endeffector types and measurement positions, which benefits the goal to provide haptic feedback to the user concerning the gripping force. The presented approach seems to be a cost-efficient and easy-to-implement way to estimate gripping forces and enable to distinguish if an object is grasped too tight or too weak.

To provide feedback with absolute forces, the position of a grasped object within the gripper branches, as well as the opening angle of the gripper branches, must be known, thus, only relative force feedback can be provided with the presented setup. However, due to the user being part of the control loop, and thus perceiving a visual impression of the deformation of a grasped object, the relative force measurement is expected to be sufficient.

The use of available articulated instruments and the estimation of gripping forces by measuring the motor current showed promising results. Additional evaluation needs to be carried out in a realistic setting with tissue-like objects instead of using the isometric measurement setup. Further, the gripping force must be evaluated under different wrist articulation angles since higher friction is expected to occur.

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Author Statement

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