Max B. Schäfer*, Bha A. Al-Abboodi and Peter P. Pott

Haptic User Interface of a Cable-Driven Input Device to Control the End Effector of a Surgical Telemanipulation System

Abstract: In robotic telemanipulation for minimally-invasive surgery, lack of haptic sensation and non-congruent movement of input device and manipulator are major drawbacks. Input devices based on cable-driven parallel mechanisms have the potential to be a stiff alternative to input devices based on rigid parallel or serial kinematics by offering low inertia and a scalable workspace. In this paper, the haptic user interface of a cable-driven input device and its technical specifications are presented and assessed. The haptic user interface allows to intuitively control the gripping movement of the manipulator's end effector by providing a two-finger precision grasp. By design, the interface allows to command input angles between 0° and 45°. Furthermore, interaction forces from the manipulator's end effector can be displayed to the user's two-finger grasp in a range from 0 N to 6 N with a frequency bandwidth of 17 Hz.

Keywords: robot assisted surgery, telemanipulation, haptic input device, haptic user interface

https://doi.org/10.1515/cdbme-2021-2054

1 Introduction

Robotic telemanipulation systems tackle major drawbacks of conventional minimally invasive surgery (MIS), such as the un-ergonomic working posture of the surgeon and the non-congruent movement of input device and manipulator [1, 2]. During conventional MIS, even though only in reduced extent, an indirect haptic sensation via the long and slender instruments still allows surgeons to roughly distinguish stiffness and texture of different surfaces [3]. The use of robotic telemanipulation systems for MIS leads to the loss of any haptic sensation if not equipped with a haptic feedback system. There are various approaches in research and in commercially available systems to enhance robotic telemanipulation systems with haptic feedback [4, 5], mostly based on rigid parallel or serial kinematics [6]. As a result, they must cope with limited stiffness and/or relatively high inertia, leading to limited haptic transparency. Consecutively, there is still the need to increase haptic transparency by aiming to display the mechanical impedance from the manipulator side as accurate as possible to the input side of a telemanipulation setup.

Furthermore, the known haptic input devices allow for a completely free movement in space, while the manipulator is strongly limited due to the invariant trocar point. This leads to a non-congruent mapping of input device to manipulator movements. According to the principle of compatibility of movements, a work task can be performed more efficiently in terms of increased accuracy and reduced time, if a congruence between input and manipulator kinematics is present [7]. As a result, a mimetic input device has the potential to further increase performance by providing the user a realistic impression of the kinematic setup around the situs. This

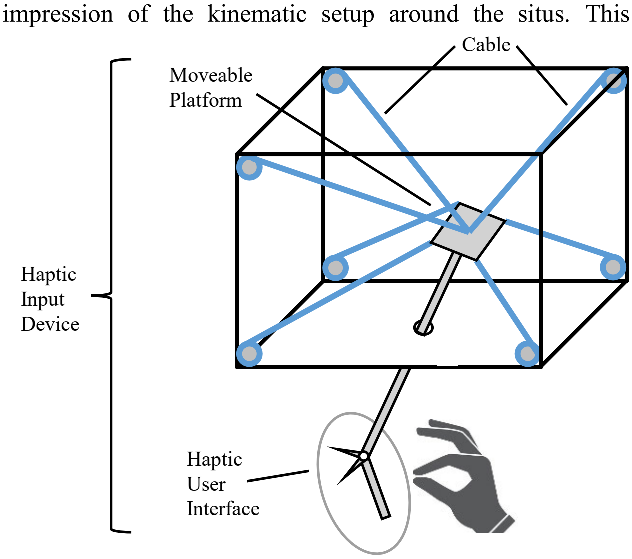

Figure 1: Schematic drawing of the Haptic Input Device with the presented Haptic User Interface providing congruent movements to the tip of a surgical tool during MIS

*Corresponding author: Max B. Schäfer: Institute of Medical Device Technology, University of Stuttgart, Pfaffenwaldring 9, Stuttgart, Germany, max.schaefer@imt.uni-stuttgart.de
Bha A. Al-Abboodi, Peter P. Pott: Institute of Medical Device Technology, University of Stuttgart, Germany

demands for a mimetic input method for robotic telemanipulation systems in MIS.

Input devices based on cable-driven parallel mechanisms allow an arrangement with congruent movements of user interface and manipulator. In addition, a cable-based approach has the potential to be a stiff alternative with low inertia and scalable workspace [8–10]. This should enable a higher level of haptic transparency and can therefore benefit an effective user interaction.

The proposed haptic input device is based on parallel kinematics where cables are used instead of rigid links (Figure 1). Since cables only transmit pulling forces, a minimum of n+1 cables are required to achieve n degrees of freedom of the moveable platform. High stiffness of the system can be ensured by using light cables with high tensile stiffness. Due to the high configurability of this setup, different working ranges can be realized. Further, any desired user interface can be mounted to the moveable platform. This allows to arrange the user interface congruent to the kinematics of the manipulator. Aiming at MIS, consideration of the invariant trocar point will enable to provide congruent movements between input and manipulator side. Figure 1 shows a possible setup of a cable-based input device with the user interface providing congruent movements to the tip of a surgical tool during MIS. The user interface allows the guidance of the movable platform, to command grasping movements to the manipulator's end effector, as well as to display grasping forces from the manipulator's end effector back to the user. In this paper, the haptic user interface as a central part of the cable-based input device (see marked area in Figure 1) and its technical specifications are presented and assessed regarding displayable forces and the system frequency response.

2 Methods

2.1 System Setup and Requirements

A seven degree of freedom (DOF) articulated robotic arm (Panda, Franka Emika GmbH, Munich, Germany) is used as the manipulator of the master-slave telemanipulation setup. A modular adapter allows for actuation of conventional minimally invasive instruments [11].

To achieve a realistic impression of the performed operations in the situs, the user interface should be able to display static and dynamic gripping forces in the same magnitude to the forces, which are applied from the manipulator's end effector to the tissue. For the design of the user interface, gripping forces of up to 6 N are assumed. Since the strength of the cable-based input device is the low mass of the actuated links, the attached user interface also needs to have a low mass to preserve low inertia. Further, to enable a good identification of the user with the system, the design of the user interface should resemble the manipulator's end effector's kinematics.

Ergonomic aspects and human motor skills were considered during the development of the haptic user interface. Limiting constraints for the design are the maximal achievable joint angles of the human hand as well as the maximum diameter a human hand can clasp. Further, different human grasps were evaluated in terms of ergonomic hand and wrist posture and their sensitivity to kinesthetic forces [12].

2.2 Prototyping and Electromechanic Components

Most of the mechanical parts were manufactured using a Prusa i3 MK3S 3D printer (Prusa Research s.r.o., Praque, CZ) and polylactic acid (PLA) filament. To provide durable screw connections, metal thread inserts were melted in the PLA components using a soldering iron. Load-bearing mechanical parts were manufactured from aluminium to guarantee high stiffness.

For actuation, a type 2250 BLDC motor, an AES 4096 L absolute encoder with a resolution of 4096 cpr, a gear-reduction of 66:1, a MC 5005 motion controller and a BC5004 brake chopper (Faulhaber GmbH & Co. KG, Schönaich, DE) are used. The combination of a small motor with slender form factor and a gear offers a good ratio between achievable torque, size, and weight. The actuator was selected slightly stronger than necessary to ensure low temperature during operation, as ventilation is hindered by hand clasping. The control algorithms were implemented in the Faulhaber Motion Manager software (version 6.8) and then deployed to the actuator.

To detect a grasping movement commanded by the user, a force sensing resistor (FSR) with a sensing range from 0.2 N to 20 N (FSR 400 Short, Interlink Electronics Inc., Camarillo, CA, USA) is implemented between the user's fingertip and the interface (*operation sensor*). To provide an interaction force value from the manipulator's forceps for evaluation purposes, a second FSR with the same sensing range is used and mounted between the branches of the manipulator's forceps (*force sensor*).

2.3 System Evaluation

Regarding the magnitude of the interaction forces displayed to the user, the haptic interface was characterized in an experimental setup by using a load cell with a measuring range of 100 N (KD40S, ME-Meßsysteme GmbH, Hennigsdorf, DE) and a measurement amplifier with a measuring frequency of 625 Hz (GSV-2TSD-DI, ME-Meßsysteme GmbH, Hennigsdorf, DE). A virtual interaction force of 6 N was deployed to the interface, being equivalent to an obstacle with high stiffness between the instrument forceps.

To determine up to which frequency interaction forces can be transmitted to the user, a modulated virtual interaction force is displayed at the interface. The frequency of the force signal was swept from 1 Hz to 30 Hz with an amplitude of 2 N. The frequency response is recorded and examined regarding its cut-off frequency.

3 System Design and Results

The haptic user interface consists of a main body forming the handle and of two gripping branches allowing to command gripper movements and gripper postures to the forceps of the manipulator by providing a two-finger precision grasp (Figure 2). The main body contains the actuator with the BLDC motor, the encoder, and the reduction gear. One of the gripping branches is fixated, the other one can be pivoted around the longitudinal axes of the handle. Further, on the movable gripping branch, an FSR is mounted to detect grasping movements commanded by the user. To fulfil the requirement of usability of the interface for users with different hand sizes, the *operation sensor* can be mounted in different positions on the gripping branch.

All cables are led through the bottom end of the user interface, whereas on the top side, an attachment point with a simple screw connection allows the flexible attachment to the cable-based input device. Cables from motor, encoder, and *operation sensor* are guided in a common cord to the control unit of the haptic user interface (Figure 3) which is placed outside of the working range of the haptic input device.

After switching on the control unit, the user interface starts a reference run, the movable gripping branch will perform a complete closure movement and will then rotate back to the maximum opening angle. If referencing was successful, a green status LED indicates, that the user interface is ready for use. After successfully performing the reference run, the motion controller starts reading out grasping angles. Subsequently, the motion controller activates the torque control and the FSRs are read out continuously via analogue inputs. If the *operation sensor* detects an actuation force by the index finger, the BLDC motor rotates and closes the branches as long as the *operation sensor* detects an interaction force or until the moving gripper branch reaches the fixed gripper branch. When the user releases the *operation sensor*, the motor rotates the other way until the maximum opening angle is reached. The opening angle of the user interface is mapped to the opening angle of the manipulators grasping forceps. Interaction forces measured by the *force sensor* at the forceps are displayed to the user. The motor than resists against the closing movement until no interaction force is measured at the *force sensor*, the maximum opening angle is reached again or

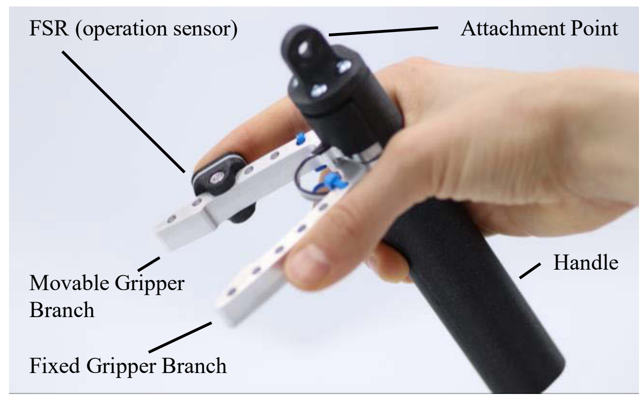

Figure 2: Components of the haptic user interface and the intended precision grasp

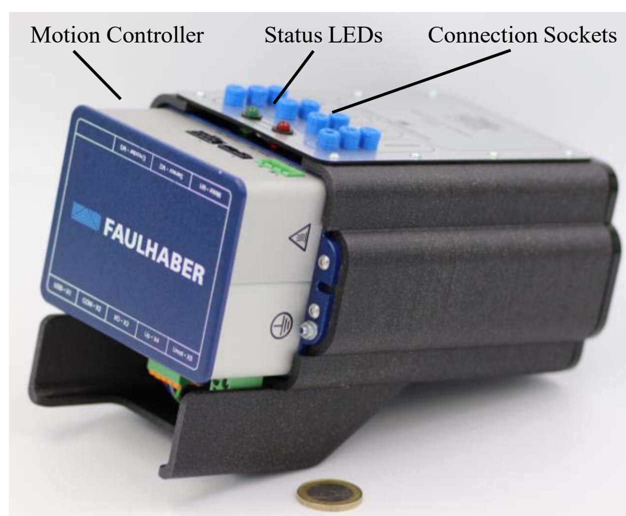

Figure 3: Control Unit of the haptic user interface

the user stops operating the movable gripper branch.

By design, the interface allows to command input angles between 0° and 45° to the manipulator's end effector. The preliminary tests reveal, that interaction forces from the manipulator's end effector can be transmitted in a range from 0 N to 6 N with a frequency bandwidth of 17 Hz. The haptic user interface has a weight of 260 g. The main body has a length of 150 mm and a diameter of 28 mm. The gripper branches have a length of 68 mm.

4 Discussion

In this work, a haptic user interface for the control of the end effector of a surgical tool in telemanipulated MIS is presented. It allows to command input angles to the manipulators forceps and to display interaction forces back to the user.

To cover the initial requirements, the actuator and the gear ratio were chosen conservatively resulting in a high attainable static feedback force, but also in relatively high friction and low back-drivability. As a result, the transmittable frequency of a force signal is relatively low, thus limiting the fidelity of the haptic feedback. Further, as a consequence of the high gear ratio, noticeable grading of the haptic sensation occurs during first tests. However, a rough distinction of objects based on their stiffness is possible.

The chosen design allows a comfortable and safe gripping posture with the main body being clasped by the whole hand while the gripper branches convey an accurate feeling with a two-finger precision grip. Due to the position of the motor and the gear in the main body, the centre of mass of the user interface is located in the middle of the hand, resulting in a low inertia torque and thus in an agile feeling during use. However, the shift of the rotation axis of the user's hand relative to the rotation axis of the gripper branches results in a translational sliding of the fingertips on the surface of the branches. This leads to a varying lever arm of the user's fingertip and thus effects the perceived feedback forces. To reduce this, a congruent virtual centre of rotation could be achieved by for example using a 4-bar-linkage.

The presented user interface is assigned to be attached to the movable platform of an input device based on a cable-driven parallel mechanism. This approach has the potential to provide haptic feedback with high mechanical bandwidth due to low masses and high stiffness. Therefore, a user interface with a low mass is required to preserve the advantages of the targeted setup. The mass of the presented user interface can be further reduced by using a smaller or even no gear ratio since the actuator of the presented interface could easily exceed the required feedback force.

The presented setup proved its suitability as a simple, direct-driven haptic user interface. Future work will address improved haptic feedback quality by using a lower gear ratio to reduce friction and increase back-drivability aiming on a higher frequency bandwidth. Further, size and weight of the device, as well as the congruence of rotation axes of hand and actuation will be addressed.

Author Statement

Research funding: The author state no funding involved. Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent is not applicable. Ethical approval: The conducted research is not related to either human or animals use.

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