Haptic Interface for Robot-assisted Ophthalmic Surgery*

A. Barthel[1], D. Trematerra[1], M. A. Nasseri[2], D. Zapp[2], C. P. Lohmann[2], A. Knoll[1] and M. Maier[2]

***Abstract*— Vitreo-retinal surgery is challenging, as delicate structures have to be manipulated. Eliminating tremor caused by human motions when doing micromanipulation can therefore improve the outcome of such an intervention. An eye surgery robot has been built to overcome this problem. The contribution of this paper is the design of a telemanipulation setup for the robotic system. A telemanipulation setup using a haptic device featuring force feedback as a user interface for controlling a hybrid parallel-serial micromanipulator is designed and developed. The position error control scheme is chosen and different control modes are provided. The output forces of the haptic device are analyzed. The system allows the surgeon to perform precise and comfortable micromanipulation. Nevertheless a way to provide more meaningful force feedback still has to be found.**

I. Introduction

Ophthalmic surgery could benefit from the use of medical robots to a great extent. Due to major improvements in precision and sensory feedback, medical robots could enable new classes of surgeries as well as improve current therapies in ophthalmology. A user interface in micro-manipulation has specific requirements: the first important aspect is eliminating tremor in human motions when performing small scale manipulations. Furthermore, input motions of the user have to be scaled down for the robot. Motion scaling is needed in order to exploit the ability of the robot to carry out small and precise motions beyond human precision. Finally, the input scheme has to be designed while considering the workflow of the target procedure. The user interface should be able to be integrated into the surgical workflow and needs to be adapted as closely as possible to these tasks. In ophthalmic micro-surgery, most of the force sensations lie below the human detection thresholds. It is therefore mainly a visual intervention relying on surgical microscopes. The idea of giving additional force feedback to the surgeon using robot-assisted surgery could have potential. Indirect cues from modalities like Optical Coherence Tomography (OCT) scans of the retina may be used to enrich the perception of the surgeon. The handling of the micro-manipulator that is used in this work could also benefit from force feedback. Because other than by observing the robot, the operator cannot estimate if his commands have been successfully carried out. A change in position, in turn, can be very hard to see as the tooltip precision of the robot is around $5\mu m$ [6]. The objective of this project is to enable the surgeon to have precise, ergonomic and intuitive control of the robot using a haptic device.

Research in the field of surgical micro-manipulation focuses not only on master-slave tele-operating systems but also on hand-held assistive tools. Two such systems will be introduced shortly. The first one is the Steady-Hand Eye robot which works with a cooperatively-controlling technology; this robot was developed at John Hopkins University to assist in retinal microsurgery [10]. The robot comprises three parts, one for translational movements, one for rolling, and one for tilting. At the end-effector of the robot, there is a tool adapter with a force sensor. The forces that the surgeon exerts when moving the tool are measured and the robot is able to accompany this movement tremor free and with greater precision. The second system is Micron, which is being developed at Carnegie Mellon University [2]. Micron uses an active stabilization technique. It is a hand-held microsurgical instrument which is designed to actively detect and cancel human physiological tremor during vitreo-retinal microsurgery. The Micron is equipped with an accelerometer and uses this information along with vision based methods to filter tremor and unwanted motion. The accurate, filtered motion is then generated using piezo actuator technology.

II. Setup

The robot used as a slave is a novel assistant for ophthalmic surgery. The parameters of the robot as well as the kinematics and dynamics have been thoroughly analyzed be-

Fig. 1: Setup consisting of the robotic assistant for ophthalmic surgery and the Phantom Premium haptic device. Their coordinate frames are marked.

*This work was supported by TUM Graduate School of Information Science in Health

[1]A. Barthel, D. Trematerra and A. Knoll are with the Department of Robotics and Embedded Systems, Institut für Informatik, Technische Universität München barthel, knoll@in.tum.de

[2]M. Ali Nasseri, M. Maier, D. Zapp and C. P. Lohmann are with the Augenklinik rechts der Isar, Technische Universität München ali.nasseri, mathias.maier, daniel.zapp, c.lohmann@mri.tum.de

978-1-4244-9270-1/15/$31.00 ©2015 IEEE

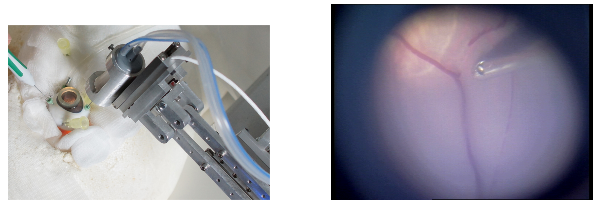
fore [5]. Key features of the design of the robot are the small size of 185 x 44 x $226mm$ and the low weight of only $300g$. These properties make the system portable and comparatively easy to bring into the operating room. To achieve such a small construction, five piezo prismatic actuators are used to manipulate the end-effector. The actuators are equipped with optical micro sensors to provide very high precision with an accuracy of $10\mu m$. Those piezo prismatic actuators are arranged in two Parallel Coupled Joint Mechanisms (PCJM) and one prismatic joint [6]. When both sliders of such a PCJM move with the same speed, the result is a translation. An offset between the two sliders results in a rotation. The advantages of such PCJMs over a serial configuration are greater overall stiffness, a higher force output, and that they can act as a prismatic and rotational joint at the same time. With an optional revolute joint on the tool, the device has six degrees of freedom (DOF). The Phantom Premium 1.5 6DOF by Sensible Technologies has been used as a haptic interface. It comprises a base that can be placed on a desktop, an arm with two interlinked joints and a stylus attached at the end that can be rotated. The device provides force feedback for all six degrees of freedom. The Phantom Premium devices have gained popularity in research [9]. The kinematics and dynamics of the device have been thoroughly analyzed [1]. The complete setup is shown in Figure 1. The coordinate frames shown comply with the introduction of the robot [6] and the documentation of the Phantom Premium.

III. Methodology

A. *Workflow of a Robot-Assisted Vitreo-retinal Surgery*

The workflow of vitreo-retinal surgery was analyzed in a clinical experiment at the department of ophthalmology at the *Klinikum rechts der Isar*, the university hospital of the *Technische Universität München*. This was done before the design of the new user interface. The high precision of the robot could make the procedure of directly injecting thrombolytics into retinal vessels possible. This specific procedure, which is called retinal endovascular fibrinolysis (REF), could be one of the interventions at which this project will be targeted in the future. The environment is a surgeons' training room that provides the same conditions as for real surgery on human eyes. The surgical site consists of an operating table, an operating microscope, and the eye surgery robot. The tests were done as ex-vivo experiments on fresh pig-eyes. The setup is shown in Figure 2. The aim is to adapt the new user interface as closely as possible to the tasks that have to be performed during the surgery. This is why tracking and analysis of the motions of a surgeon during ophthalmic surgery has been performed before [8]. The findings of that study were used to reenact the movements of the surgeon with the robot.

- Two trocars are placed on the sclera, one trocar for the tool and one for illumination.
- The surgeon navigates the tip of the needle near to the trocar. This is done by translating the linear positioners of the robot.



(a) Setup of a robot-assisted vitreo-retinal surgery

(b) view through the operating microscope

Fig. 2: Two ports with trocars for the needle as well as illumination are visible. An infusion line helps maintaining intra-ocular pressure. The lens on top of the eye magnifies the view through the operating microscope.

- The Remote Center of Motion (RCM) is set to ensure that the trocar does not move in a way that causes damage to the sclera. With a fixed RCM no translational input will be processed as only rotations around the trocar and moving the needle in or out along this axis are allowed. This concept also inhibits the eye from rotating due to manipulation of the tool. This is important for the surgeon looking through the operating microscope at the retina on the back of the eye.
- As the next step, the orientation of the insertion has to be adapted. Just by changing the position of the last slider, the tool then gets inserted into the eye.
- While looking through the operating microscope the surgeon can guide the tool to its target by rotating around the RCM and moving the tool further inside the eye.

The previous analysis outlined the rough navigational steps of a tool used in vitreo-retinal surgery. An examination of the reachability within the eye using the virtual fixture of the robot is part of another survey [7].

B. *Design of a Controller for a Telemanipulation System*

In contrast to the systems introduced in the *Introduction* the novel eye surgery robot is not designed to act as a handheld assistant. Instead, controlling the robot requires the development of a tele-manipulation system. A tele-manipulation system, also called tele-operating system, consists of a master and a slave device [4]. The human operator gives commands to the master interface and gets feedback about the progress of the task. The slave carries out the commands and interacts with the environment. In other words, the device state of the master interface is mirrored by the slave device. The choice of a control design for the tele-manipulation system is crucial. Depending on the abilities of the robot, the input device, and the desired haptic feedback, a fitting architecture has to be chosen. The system being discussed here has direct control, as no tasks will be carried out autonomously or semi-autonomously. This is in contrast to shared control and supervisory control [9]. As the aim is to provide feedback to the operator, information has to be transferred in two directions. This control strategy is called bilateral tele-manipulation [4].

1) Position Error Control Scheme: For the implemented system the position error control scheme [4] was chosen. Another method that can be considered is the position-force architecture [9] or also called force reflection [4]. The position of the master is sent to the slave while the user experiences forces that are sent back by the robot. This requires some kind of force sensor on the end-effector of the slave robot. The eye surgery robot in our case cannot be equipped with such force sensors, because the tip of the needle is required to be very small. The piezo actuators are not equipped with force sensors, either. The behavior of the positioners is highly non-linear and only the current position can be read out by the proprietary control boards. When using the position error control scheme only positions are being transmitted between master and slave. The forces applied to the input device and the slave robot are calculated with the equations 1 and 2.

$$F_m = k_m(x_m - x_s) \tag{1}$$

$$F_s = k_s(x_m - x_s) \tag{2}$$

x_m denotes the position of the Haptic Interface Point (HIP) of the master device. On the Phantom Premium this is the tip of the stylus. Whereas x_s describes the current position of the Tool Center Point (TCP) of the robot. The TCP of the robot is the tip of the instrument. As the targeted procedure is injection in retinal vessels in REF, this is a needle at this time. Offsets characterizing the needle are used to determine the distance of the TCP from the position of the last link. The assumption is that the needle does not bend and thus no registration is done. k_m and k_s are the position error gains of master and slave. Both forces applied to the robot manipulators and the haptic interface are proportional to the difference of desired and current position. The availability of the exact current position from both the haptic interface and the slave robot and the lack of force sensors make this the only feasible control design for the current hardware setup. With position error control the operator feels friction and inertia of the robot manipulators. This is not desired as it complicates perception of the environment and might prevent precise positioning. The surgeon might not be able to distinguish friction and inertia of the robot from the contact with tissue on the retina. If force reflection could be employed, this would not be the case [9]. For being able to sense environmental forces it is required that the robot is back-drivable. This implies that the motors can easily be moved by external forces. With the current robot hardware this is not the case. Indeed the force of $5N$ needed to push the linear positioners is advertised as a safety feature [6]. However, the small allowed interaction forces with the retina, which are typically below human perception thresholds, will not generate sufficient position error between master and slave so that this can be felt through this position error control scheme. An advantage of the position error control scheme is the fact that the operator gets clear feedback when trying to reach beyond the workspace of the slave device [3].

2) Force Feedback and Spring-Damper System: Equation 1 models a virtual spring following Hooke's law. The gains k_m and k_s act as virtual spring constants. To achieve better stability, damping is added to the haptic interface to make the force proportional to the velocity [9]. The forces for the spring-damper system with velocity gain b_m are calculated in equation 3.

$$F_m = k_m(x_m - x_s) - b_m(\dot{x_m} - \dot{x_s}) \tag{3}$$

$$F_s = k_s(x_m - x_s) \tag{4}$$

3) Transformation: The workspace coordinate frames of both devices are specified in the Cartesian coordinate system. Viewed from the front, by default the Phantom's positive x axis points to the right of the Phantom, parallel to the front plane; the y axis points up; and the positive Z axis points toward the user (see Figure 1). In contrast, the coordinate system of the eye robot, again seen from the front, has the x axis pointing up; the y axis pointing to the right; and the z axis pointing away from the user. Thus, a rotation of the coordinate systems of the devices is needed to ensure that the slave moves in the desired direction.

4) Scaling: Motion scaling is applied to input from the haptic device to allow for highly precise operations and to get a more reasonable workspace mapping [9]. While there is no scaling of orientation, the position input of the master is scaled down. At the same time there is a scaling of the positions transmitted from the robot. To achieve meaningful force feedback these motions are scaled up. With a scaling factor μ the positions are calculated as follows:

$$x_{md} = \frac{x_s}{\mu} \tag{5}$$

$$x_{sd} = \mu x_m \tag{6}$$

C. Control Modes

The used haptic device has no decoupling of translations and rotations as no translational movement can be performed without implicitly changing the rotation. This fact leads to the consideration of splitting these two types of input motions. Separating translational and rotational movement also complies with the workflow of vitreo-retinal surgery as described above. At no time there is the need for simultaneously rotating and moving the robot translational as the RCM is set as soon as the tool enters the eye. Thus, a distinction is made between different control modes. Dependent on the currently active control mode the user experiences different restrictions in movement and different input data gets processed.

- The default control mode is the mode enabling translational movement as it is the first step in the workflow of vitreo-retinal surgery. The operators movements are constrained to two dimensions. The vertical component of the force vector F_m therefore is set to keep the stylus on the fixed plane. A spring with maximal stiffness is modeled. For inserting and retreating the needle a separate 3D mouse is used.
- When switching to the mode that enables rotation of the robot the haptic device tries to keep the HIP at

its current position by again modeling a spring with maximal stiffness. The user can then rotate the stylus.
- As soon as entering indexing mode, the forces F_m in all directions are set to zero and x_{des} stays constant. In every iteration the difference between the current position of the tip of the stylus x_m and the position when beginning indexing get computed. When leaving indexing mode this difference gets added to an indexing offset.

IV. Results

The scaling factors were defined experimentally. They are set to $\mu = 0.01$ and $\mu_{rot} = 0.03$ for rotational movements. As a threshold for filtering noise from the haptic input device $0.2mm$ was chosen. By setting the spring constant to $k_m = 0.05$ and the damping factor to $b_m = 0.005$ the system proved to be sufficiently stable. The force output experienced by the user is limited to $6N$ in each direction. This is still under the maximum force of $8.5N$ stated in the device specifications of the manufacturer. The new software component runs in its own thread with a sampling time of $20Hz$, the same rate as the control loop of the robot. The forces to be rendered by the motors of the Phantom Premium are updated on a frequency of $1000Hz$. The discrepancy between slave and master robot loop rates stems from the necessity of giving smooth haptic feedback on the one hand, while on the other hand the piezo actuator controller is not able to handle more frequent input or query the slider position more frequently. The forces to be rendered by the motors of the Phantom Premium haptic device were measured in order to evaluate the telemanipulation system. Several test runs were made that simulated a typical navigation task (see Figure 3) and the measurements of the forces commanded to the haptic device were gathered. The jittering of the raw data contrasts with the smooth and precise movement of the robot. It also shows that the system responds with only minimal force up to $1N$ when manipulating the tool tip of the eye surgery robot on a small scale. At this stage of development, force feedback is not yet suitable for eye surgery application. The position error control scheme as implemented lets the user perceive unwanted friction and inertia of the robot as well as requiring relatively high environmental forces for the surgeon to notice. Future work could make meaningful force feedback possible using force sensors or a further improved robot design.

V. Conclusion

A user interface for a hybrid parallel-serial telemanipulation system has been designed. The haptic device could be successfully integrated into the robotic setup. The operator now has direct control via a position error control scheme and is provided with force feedback. According to the analyzed workflow of vitreo-retinal surgery different control modes are provided. Several extensions have been implemented to make the control of the robot more comfortable. The output forces that the operator perceives have been visualized and evaluated. Future work will include

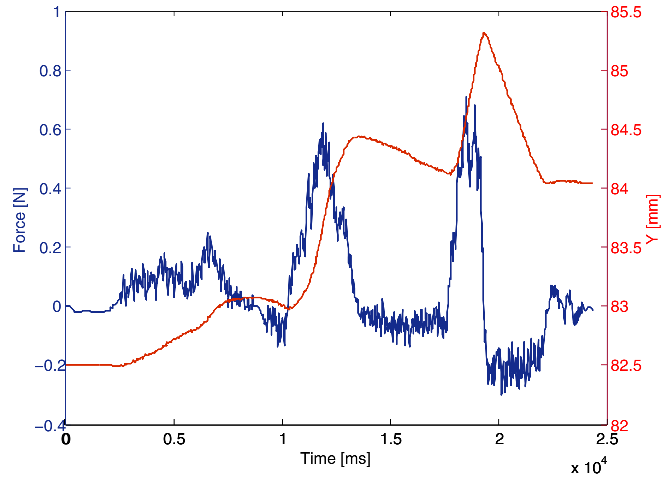


Fig. 3: Forces to be rendered and position of eye surgery robot over a time period of 24.38 seconds.

altering the control scheme and robot hardware to provide more meaningful force feedback. Pre-clinical testing of the system on ex-vivo eyes seems necessary before making further advancements.

References

[1] Cavusoglu, M.C., Feygin, D.: Kinematics and dynamics of phantom (tm) model 1.5 haptic interface. University of California at Berkeley, Electronics Research Laboratory memo M **1** (2001)

[2] MacLachlan, R.A., Becker, B.C., Cuevas Tabares, J., Podnar, G.W., Lobes, L.A., Riviere, C.N.: Micron: an actively stabilized handheld tool for microsurgery. Robotics, IEEE Transactions on **28**(1), 195–212 (2012)

[3] Mamdouh, M., Ramadan, A.A., Abo-Ismail, A.A.: Evaluation of a proposed workspace spanning technique for small haptic device based manipulator teleoperation. In: Intelligent Robotics and applications, pp. 161–170. Springer (2012)

[4] Melchiorri, C.: Robotic telemanipulation systems: an overview on control aspects. In: Proceedings of the 7th IFAC Symposium on Robot Control, pp. 707–716 (2003)

[5] Nasseri, M., Eder, M., Eberts, D., Nair, S., Maier, M., Zapp, D., Lohmann, C., Knoll, A.: Kinematics and dynamics analysis of a hybrid parallel-serial micromanipulator designed for biomedical applications. In: Advanced Intelligent Mechatronics (AIM), 2013 IEEE/ASME International Conference on, pp. 293–299 (2013). DOI 10.1109/AIM.2013.6584107

[6] Nasseri, M., Eder, M., Nair, S., Dean, E., Maier, M., Zapp, D., Lohmann, C., Knoll, A.: The introduction of a new robot for assistance in ophthalmic surgery. In: Engineering in Medicine and Biology Society (EMBC), 2013 35th Annual International Conference of the IEEE, pp. 5682–5685. IEEE (2013)

[7] Nasseri, M., Gschirr, P., Eder, M., Nair, S., Kobuch, K., Maier, M., Zapp, D., Lohmann, C., Knoll, A.: Virtual fixture control of a hybrid parallel-serial robot for assisting ophthalmic surgery: An experimental study. In: Biomedical Robotics and Biomechatronics (2014 5th IEEE RAS & EMBS International Conference on, pp. 732–738. IEEE (2014)

[8] Nasseri, M.A., Dean-Leon, E., Nair, S., Eder, M., Maier, M., Lohmann, C.P., Knoll, A.: Clinical motion tracking and motion analysis during ophthalmic surgery using electromagnetic tracking system. In: Proceedings of the 5th International Conference on BioMedical Engineering and Informatics (BMEI 2012), pp. 1006–1010. IEEE Press (2012)

[9] Siciliano, B., Khatib, O.: Springer Handbook of Robotics. Gale virtual reference library. Springer (2008)

[10] Ueneri, A., Balicki, M., Handa, J., Gehlbach, P., Taylor, R., Iordachita, I.: New steady-hand eye robot with micro-force sensing for vitreoretinal surgery. In: In Proceedings of the 3rd IEEE RAS and EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob), pp. 814–819. IEEE (2010)