# Experimental validation of instrument insertion precision in robot-assisted eye-surgery

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***Abstract* — In vitreoretinal surgery micro-surgeons operate on fragile and small structures ranging from 0.15 to 400 micron on the back side of the eye. Despite observing the anatomy through a stereo-microscope, the overall depth perception is limited. A major challenge consists in reaching high motion precision in the insertion direction and under limited depth perception. In fact, a targeted precision of a few microns is nearly impossible to achieve by hand. Prior art includes robotic assistants that are based on co-manipulated, handheld or tele-operated robots, where respectively motions or forces are filtered out or scaled. Even if this leads to an increase in precision of the said gesture, the precision that can be reached is bounded by the hardware (surgical robot) that is being used. As far as the authors are aware of, no detailed study has been presented before describing the precision that can actually be reached in the insertion direction. This abstract analyses the reachable precision in the insertion direction of a co-manipulated surgical robot. To demonstrate the insertion quality, experiments were conducted displaying fine computer-controlled insertion motion, allowing cannulation of veins from ex-vivo pig eyes.**

***Keywords — eye; surgery; RVO; comanipulation; robot; retina.***

## I. INTRODUCTION

### A. *Vitreoretinal surgery*

Performing retinal surgeries is a very complex task due to the size and fragility of the targeted retinal anatomy. For instance, widespread diseases such as Retinal Vein Occlusion (RVO) require procedures too difficult and risky to perform, forcing to rely on less effective treatments. Worldwide, 16.4 million of people suffer from RVO making this disease the 2nd most common retinal vascular disorder after diabetic retinal disease [1]. RVO consists in clot formation inside the retinal veins, whose diameter varies from 50 µm to 400 µm [3]. The patient loses slowly his/her sight and can even become blind. Today, only expensive treatments are available that merely tackle the symptoms, but, do not affect the cause [2].

A promising curative treatment is retinal vein cannulation (Fig. 1), where clot-dissolving drug is being injected into the occluded veins. In order to dissolve the clots, the drug needs to flow up to 45 minutes inside the veins. To perform such a treatment, a small incision point is first performed on the sclera to approach the retinal veins with, in our case, a bent needle. A surgical microscope gives visual feedback to the surgeon while he/she moves the needle down towards the target. Despite limited depth perception the surgeon needs to puncture and cannulate the diseased vessel without piercing the vein. Such double-puncture would allow the drug to flow below the retina causing substantial damage. The surgeon needs to pay attention to avoid damaging the retina as well, as this will lead to blind spots in vision. For a successful cannulation the surgeon thus needs to display extreme positioning precision, especially in depth direction [4].

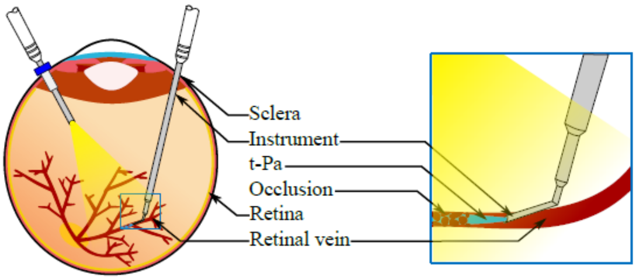

Fig. 1. Retinal vein cannulation.

### B. *Robot assisted surgery*

The use of a robotic manipulator allows the surgeon to improve instrument positioning precision in order to overcome the abovementioned problems. The instrument/needle is attached to the manipulator at its end-effector. In a co-manipulation setup the surgeon directly grasps and interacts with the robotic manipulator. The manipulator then assists in approaching the retina, which helps the surgeon in several ways. Firstly, physical and/or virtual damping in the manipulator can filter out the tremor and can slow down the intended movements; overall facilitating a slow and precise approach of the vein. Secondly, the system can maintain a stable position once the needle is inserted into the punctured vein allowing a steady and reliable injection of the drug.

During the last decade, a large number of robotic devices for retinal surgery have been developed [5–8, 12]. However, as far as the authors are aware of, none of these works investigated the actual achievable positioning precision at the level of the end-effector. Due to factors such as play, friction and limited compliance, there might be a significant deviation between the precision at the level of the actuation and at the level of the instrument tip.

This paper focuses on the motion precision in the depth direction of a Remote Center of Motion (RCM) robot previously reported by the authors [9]. Here, the precision at the level of the end-effector is measured giving important information on the quality that retinal veins could be approached and punctured.

## II. BACKGROUND INFO

The authors reported previously on the development of a robotic comanipulation system [9] and a telemanipulation system [10] for retinal surgery. The authors showed that both comanipulation and telemanipulation systems increase the positioning precision during a positioning task in an eye simulator [11].

The said robot (Fig. 2) possesses a mechanical RCM, resulting in 4 degrees of freedom (DOFs): 3 rotations $\boldsymbol{\theta}$, $\boldsymbol{\psi}$ and $\boldsymbol{\phi}$ around the RCM and 1 translation $\boldsymbol{R}$ along the RCM (note the rotation $\boldsymbol{\psi}$ is a passive joint). When aligning the RCM with the incision point on the sclera, the eye will not move even if the robot is actuated. Furthermore, the actuators for the remote DOFs are put at the basis of the robot, minimizing inertia effects. Thanks to a combination of parallelograms the flexibility that appears in serial configurations is overcome, leading to a stiff and precise system.

Compared to alternative systems the robot has 1 extra remotely actuated DOF. The insertion itself is controlled by coordinated control of a motors placed at the base. By not using a translation stage at the level of the instrument, a compact size end-effector can be provided. This allows easy integration into the operating room near the patient and the microscope. Here the workspace is very much confined. The robot is to work nearby the patient; the surgeon needs to be able to grasp the end-effector while not colliding with the operating microscope. The approach angle to the patient's eye is fairly limited. Thus a compact end-effector is highly desirable. Of course it is important that such compact end-effector does not jeopardize the reachable precision in the insertion direction.

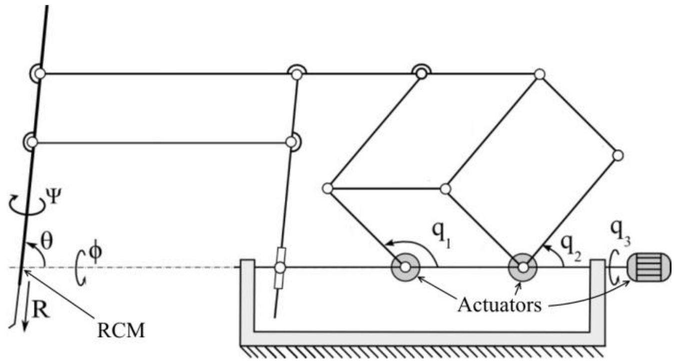

Fig. 2. RCM based robot with 4 DOFs.

## III. DIFFERENT APPROACHES FOR PRECISE INSERTION

To insert a needle inside a vessel, different solutions can be envisioned. When operating a co-manipulation device, the most straightforward approach consists in simply letting the user operate the instrument, closing the loop by visual observation through the microscope. Limitations in capability to dampen out physiological tremor, failure to correctly observe the instant of puncture but also the limited human response time affect the achievable insertion precision. Dedicated proximity, force or contact sensors could be installed to overcome these problems. By correctly feeding back this information the quality of insertion can be improved. Such closed loop solution unfortunately implies a higher complexity of the employed instruments. Its functioning also depends on the robustness of the sensors. Alternatively, the insertion can be computer-controlled near the region of interest. This would constitute a simpler approach as no additional sensors are needed. Comanipulation could be used for efficient and correct aligning of the instrument above the targeted vessel, i.e. in the visible area. Computer-controlled insertion could then be applied to proceed even into the less visible area. In practice the control could be limited to making small precise incremental steps to puncture the vessel (without piercing it).

## IV. ROBOT POSITIONING ALONG THE INSERTION DIRECTION

As previously mentioned, the robot has its actuators located at the base. Although limited flexibility exists, due to capstan, play at the joints (although properly pre-tensioned) and Coulomb friction present in the system, a discrepancy might exist between the displacement of the end-effector and the displacement measured by the encoders. As a result the insertion depth might be misinterpreted by relying solely on forward kinematics and the encoder readings.

A setup with a laser distance sensor has been built to directly measure the quality of the insertion. This information is then compared to the position that is estimated based on motor encoder measurements. Figure 3 gives a sketch of the experiment. The employed laser distance sensor is OADM 12I6460/S35A with a resolution of 2 µm. It measures the relative distance between the sensor and the end-effector. In order to get the best resolution and linearity, the end-effector was positioned at 16 mm from the sensor with a motion range of +/- 1 mm around it. The range was further determined so that the executed insertion trajectory reaches up to the targeted veins - i.e. covering the actual range the needle has to cover.

Based on the range of vein diameters in the retina, the capability to execute steps of 50 µm was evaluated at this point. Given that the RCM is positioned at the incision point on the sclera, the start point for executing positioning steps has been fixed at a distance of 15 mm relative to the RCM, taking into account the usual diameter of an eye and the vessels to reach.

The robot was controlled so that pure insertion motions were executed by the instrument tip, under three different approach angles $\boldsymbol{\theta}$ (Fig. 2, Table 1) to cover the veins in the center of the retina, i.e. 50°, 57° and 65°. These angles are representative for cannulations near the optical disk. Twenty steps were made around the start position. The error along the insertion depth $\boldsymbol{R}$ (Fig. 2) was then calculated as the difference between the estimated step from forward kinematics and encoder measurements at one side and the step measured by the laser distance sensor. Table 1 presents the experimental results showing a maximum mean error of 1.36 µm and standard deviation of 8.32 µm. From these results, we can conclude that the robot accuracy is good, meaning, amongst other, that ***R*** is well estimated by the encoders. However, the precision is more spread. This could mainly be explained by the flexibility and friction coming from the reduction stage, which is based on capstans. It is shown in the following section that such precision is very much acceptable to reliably perform the targeted procedure.

TABLE 1. Difference insertion depth based on forward kinematics and encoder measurements versus laser distance sensor outputs.

| ***θ*** [°] | **65** | **57** | **50** |
|---|---|---|---|
| **Mean error** [µm] | 0.46 | 0.73 | 1.36 |
| **Standard deviation** [µm] | 3.39 | 7.41 | 8.32 |

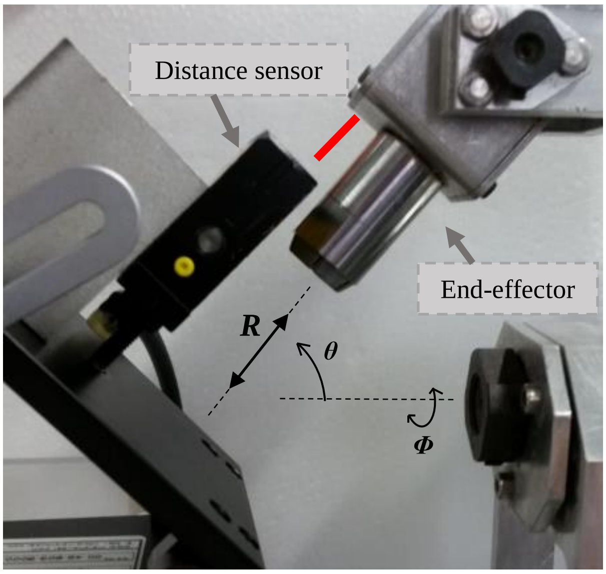

Fig.3. Setup with the distance sensor aligned along the R direction of the end-effector.

Examples of such a computer-controlled insertion and a comanipulated insertion are presented on Fig. 4, under an angle ***θ*** = 57°. The relative position along ***R*** is depicted as a function of the time. Here the aim is to reach a target 50 µm farther than the actual position. The results of the computer-controlled insertions are a function of the stiffness of the associated controller. It is expected that further raising this stiffness will improve the insertion precision. On the contrary, the comanipulated insertion depends on the user's skill and experience. To perform the 50 µm insertion, the covered distance is displayed to the user. The output presented for this second scenario is a favorable case obtained after several attempts.

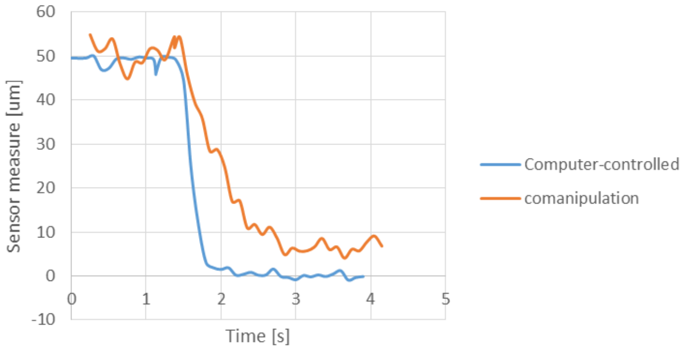

Fig.4. Computer-controlled and comanipulated insertion of 50 µm, at ***θ*** = 57°.

Two interesting observations can be made from the graph (Fig. 4). First, the time to make the 50 µm-step is at least three times smaller with the computer-controlled insertion (0.35 seconds versus 1.2 seconds). This is of particular interest as a higher insertion velocity lowers the risk of pushing the targeted vessel sideways in the process and increases the success of overcoming the elasticity to puncture the vessel. Second, the amplitude of vibrations of the needle tip is observed to be lower in the case of computer-controlled insertions. This lowers the risk of tearing apart the vessel while puncturing it.

## V. EX-VIVO EXPERIMENTS AND DISCUSSION

To validate the computer-controlled insertion, experiments were conducted on central retinal veins of ex-vivo pig eyes. The diameter of the veins was typically about 100 µm. The cornea and vitreous body were removed to get a clear view of the vessels under the microscope. The user positioned the needle tip above the vessel in comanipulation mode. Next, one to three computer-controlled steps of 50 µm were made to reach the center of the vein. After this water was injected through the needle to verify the cannulation success. Seven out of ten performed punctures were successful. In the three failed attempts, a double puncture was made. Here it was believed that either the diameter of the targeted vessels was not properly assessed or the initial position of the needle tip versus vessel (performed in comanipulation with visual feedback only) was inadequately made. In this second case, the first 50µm step only compressed the vessel without puncturing, leading to a double puncture when performing the second step.

These aforementioned problems are believed to be less prominent in in-vivo experiments since then the vessels are under pressure, i.e. less flattened by the needle. Note, not accounted for in these experiments is a possible decrease in performance caused by friction between the needle and the entry point on the sclera. This effect is to be studied in future work. Furthermore, adjusting the step size according to surgeon's experience or from OCT images seems appropriate manners to increase the success rate.

## VI. CONCLUSIONS

In this work, we focused on the performances obtained along the depth direction with the eye-surgery robot developed at KU Leuven. We showed that the mean error of insertion is limited to 1.36 µm and the standard deviation is less than 10 µm. Therefore the robot presents good performances considering the positions used to study it and is then adequate to perform cannulation of retinal vessels. We then demonstrated that computer-controlled insertion of a few microns improves a lot the surgeon's precision in puncturing in a safe and reliable way the retinal vessels.

## ACKNOWLEDGMENTS

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