Steady-Hand Manipulator for Retinal Surgery

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Abstract. This paper describes the ongoing development of a robotic assistant for microsurgery and other precise manipulation tasks. It reports a new and optimized version of a steady-hand manipulator for retinal surgery. The surgeon and the robot share control of a tool attached to the robot through a force sensor. The robot's controller senses forces exerted by the operator on the tool and uses this information in various control modes to provide smooth, tremor-free precise positional control and force scaling. The result is a system with a higher efficacy, flexibility and ergonomics while meeting the accuracy and safety requirements of microsurgery.

1 Introduction

Many areas of clinical practice involve the manipulation of extremely small, delicate structures. Such structures occur in several organ systems, but are prevalent in the eye, ear, nervous system, and elements of the circulatory system. Within the eye, the manipulation of vitreoretinal structures is particularly difficult given their relative delicacy, inability to regenerate if injured, the surgical inaccessibility, and suboptimal instrumentation to visualize these structures.

1.1 Retinal Microsurgery. Limitations of current practice

During vitreoretinal surgery, the surgeon must visualize the pathology on a micron scale and manually correct the pathology using direct contact, free hand techniques. The procedure occurs within the confines of a very small space that is surrounded on all sides by vital structures.

At present, the conventional vitreoretinal system uses an operating microscope to visualize surgical instruments that are placed in three sclerotomy incisions 20-25 gauge in diameter. A prototypical surgical maneuver is the dissection and separation of fibrous scar tissue from the retinal surface (membrane peeling). This delicate maneuver is physically not possible for many ophthalmology specialists due to visualization limitations, excessive tremor, or insufficient fine motor control. Physiological tremor, which contributes to long operative times and which is exacerbated by fatigue, is a severe limiting factor in microsurgery [1]. Manual dexterity, precision and perception are particularly important during tasks where the ability to position instruments with great accuracy often correlates directly with the results of the procedure [1, 2]. In a recent study, the root mean square (RMS) amplitude of the tremor of an ophthalmic surgeon under surgical conditions was measured to be 108 μm [3]. While it may be possible to briefly position an instrument at a specified target with great accuracy, maintaining the position for extended periods of time becomes increasingly difficult due to physical, visual and mental fatigue [4].

From the surgical tool manipulation point of view, we have identified three major problems: 1) micron scale manual dexterity and precision are required for retinal surgery, 2) stability of instruments with respect to the retina for extended periods of time becomes increasingly difficult due to physical, visual, and mental fatigue and 3) tremor and motion accuracy affect the duration, quality, and consistency of the procedure which in turn affect the quality of the surgical outcome. To overcome these problems, we are developing a robotic assistance system for retinal procedures such as vein cannulation and retinal sheathotomy. The proposed system will operate both with and without image guidance from the operating microscope.

There is extensive literature reporting robotic systems for surgery (e.g., [5]), including commercially deployed systems (e.g., [6]). A number of researchers have proposed master-slave microsurgical systems (e.g., [7]), including some systems for the eye ([8]). With the exception of exploratory work by Hunter *et al.* [9] most of this work has focused on direct improvement of a surgeon's ability to manipulate tissue remotely or at a very fine scale, rather than exploiting the ability of the computer to assist the surgeon more broadly.

In contrast, the JHU Steady-Hand Robot (SHR) [10, 11] was designed to cooperatively share control of a surgical tool with the surgeon while meeting the performance, accuracy, and safety requirements of microsurgery. The absolute operational positioning precision is approximately 5 microns. However, this first prototype had serious limitations that prevented it from becoming a clinically useful system. In particular, the parts of the mechanism nearest the patient were bulky and ergonomically inconvenient for the surgeon. This paper describes our second prototype, which is designed to overcome these limitations.

2 Mechanical System Design

The design of our second prototype began with an analysis of the necessary degrees of freedom (DOF), options for obtaining a remote center of motion (RCM), and establishment of specifications for mechanical parameters such as range of motion, precision, and maximum velocity. These are discussed in the following sections.

2.1 Degrees of Freedom (DOF) Analysis

We critically analyzed the necessary DOF in tool positioning for eye surgery. There are three phases in surgical tool motion: approach phase (A), insertion phase (I), and retinal surgery phase (R). In the approach phase, the surgeon requires at least 3 DOF (X, Y, and Z) to bring the tool to the entry point on the eye surface (sclerotomy incision). Although these 3 DOF could be realized by many combinations of rotary and translational axes, we chose a Cartesian design (XYZ stage). In the insertion phase, the surgeon requires 3 DOF (one translation plus two rotations). For the retinal surgery phase, four DOF are required: three rotations and one translation (Fig.1).

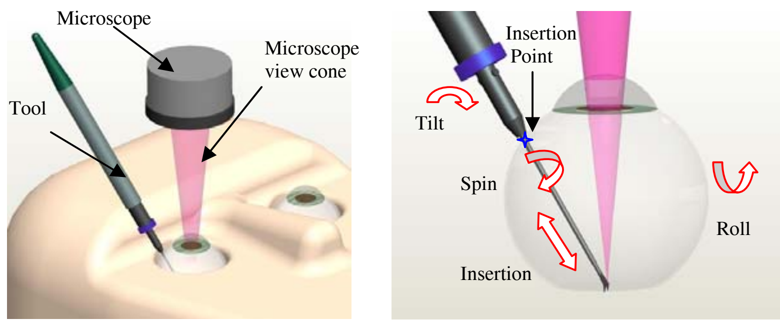

Fig. 1. Setup in retinal surgery phase: general view *(Left)* and magnified local view *(Right).*

The three rotations are local DOF and are necessary for tool orientation. In our evaluation of the manual retinal surgery procedures, we learned that the tool tip positioning accuracy is not very sensitive to the tool spin. We therefore decided to drive only the tool tilt and roll motions, leaving the spin motion for manual manipulation. The insertion could be a local DOF or generated by combining the general DOF (first three DOF). We chose the latter solution. The advantage is that we eliminate a DOF, which allows a more compact design, while the disadvantage is that we require coordinated motion of three axes to produce the insertion motion. This makes it more challenging to obtain high accuracy and, as discussed in the next section, is not consistent with the philosophy of a remote center of motion (RCM) kinematic design. Thus, the new robot has only 5 DOF: 3 translations (general DOF) and two rotations (local DOF). By eliminating two local DOF (tool insertion and spin), we have the possibility to create a thin tool holder and reduce the interaction between the robot and microscope work space.

As for the range of motion, taking into the account the eye size, its location on the face, and the insertion point position on the eye, we estimated that for the tool motion close to and inside of the eye, we need a work space around 50x50x50 mm, and for the tool orientation, around ±30º about each axis of rotation. Taking into account the necessary space in the approach phase, we set the final range of translation motions at ±50 mm. Because of variability in the configuration of the human face, it could be necessary to increase the rotating angles and/or to set different relative positions of the robot with respect to the patient.

2.2 Real RCM Point versus Virtual RCM Point

The retinal surgery phase requires tool motions to be constrained by an insertion point (i.e., the sclerotomy). As shown in Fig. 1, the allowable motions are the three rotations about the insertion point and the translation of the tool through the insertion point. This implies a remote center of motion (RCM), where the three rotation axes intersect at the insertion point. An RCM robot achieves this by mechanical design [13]. Furthermore, many RCM designs include a final actuator to provide the tool insertion (this can also be considered as a way to translate the RCM point along the tool axis). A real (mechanical) RCM design provides several advantages for surgical applications, such as increased safety due to the minimal number of actuators that must be powered to achieve each task motion. It is also possible to achieve an RCM point by using software to coordinate the robot joints (i.e., a virtual RCM), but this can reduce the accuracy and safety of the task motions.

This discussion of a real (mechanically constrained) versus virtual RCM point is relevant to the design of the tilt mechanism. This mechanism must be precise, assure the necessary range of motion, be compact, and have a remote center of motion that coincides with the insertion point. We analyzed many solutions for the robot wrist by analogy with welding robots. Finally, we considered three mechanisms: a parallel six-bar mechanism with a geometrically imposed RCM [12, 13], a parallel six-bar mechanism with offset (also with RCM) [14], and a slider-crank mechanism (not an RCM). Though a real RCM has certain advantages such as those cited above, for this system we value a compact design with high stiffness and accuracy. Therefore we chose to implement the slider-crank mechanism, with a virtual RCM..

2.3 Mechanical System Specifications

In establishing the specifications for the robot mechanical system, we considered its interaction with patient anatomical structures, surgeon workspace, and imaging system. Other important factors were the patient safety in correlation with surgery accuracy. The preliminary system specifications are given in Table 1.

Table 1. Robot performance specifications for approach phase (A), insertion phase (I), and retinal surgery phase (R) motions.

Robot Specification		Units	Value
Roll/tilt motion		degrees	±30
XYZ motion		mm	±50
Roll/tilt precision		radians	~0.00005
XYZ precision		µm	~2
Net precision at retina		µm	~5
Cartesian tip speed	- phase A	mm/s	10
	- phase I	mm/s	5
	- phase R	mm/s	<1
Deviation of the tool shaft	- phase A	mm	<1
from the center of	- phase I	mm	<0.2
Sclerotomy point	- phase R	mm	<0.2

2.4 Mechanical System Components

The robot mechanical system consists of three major parts (Fig. 2): the XYZ system, the roll mechanism, and the tilt mechanism. The XYZ system assures the global motions of the surgical tool. The roll mechanism, consisting of a rotating table, was tilted at -15º from the horizontal direction to assure better access of the surgical tool to the eye depression of the patient face. This roll mechanism configuration is appropriate for the actual tilt mechanism type and for a robot located on the same side of the face as the targeted eye. If the robot location is on the other side of the face, it is necessary to avoid collision with the patient nose, which could be accomplished by increasing the tilt angle or by tilting the robot using a passive arm. For the current prototype, the roll mechanism assures a rotation of 360º for the tool. We chose this motion range so that we could simulate many surgical procedures.

The tilt mechanism (slider-crank) is attached to the roll mechanism through a long tubular arm. In this way, nearly the entire robot is away from the surgery area. Also, this configuration assures a better possibility to separate the non-sterilized robot from the sterilized surgical area. The translating joint of the tilt mechanism is realized by a rotary motor and a micrometer screw without backlash. To eliminate the translating joint backlash, the slider was realized from two parts that make contact on an oblique surface. The two parts are pushed against each other by a nut through a wave spring.

A 6-DOF force sensor is rigidly attached to the crank (the last element of the tilt mechanism). A tool holder is located between the force sensor and the surgical tool. This is a very important part of the robot: it must be sterilizable, it must be attached to the force sensor through an emergency release mechanism, it must assure the spinning rotation of the tool, and it must assure a precise and easy attachment for the tool. For the current prototype, we implemented only the last two functions. Because of the variability in size and shape of the surgical tools used in retinal surgery, it could be necessary to develop some custom made adapters for each tool type. At that time it will be possible to make a decision regarding the emergency release mechanism.

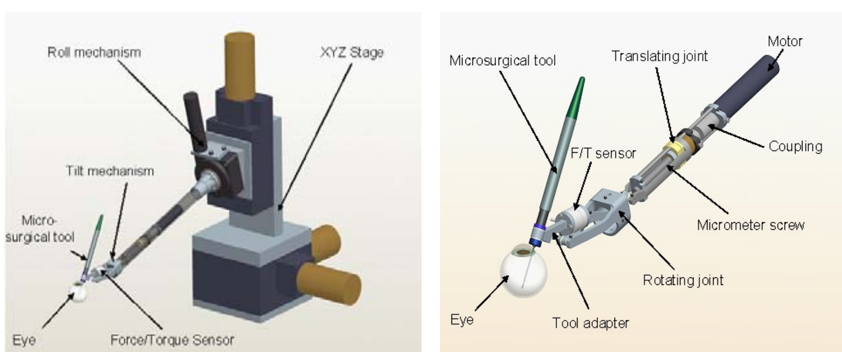

Fig. 2. Robot mechanical system (*rendering of CAD model*): general view (*left*) and tilt mechanism (*right*).

3 Mechanical System Implementation

The manipulator itself consists of four modular subassemblies: 1) An off-the-shelf XYZ translation assembly; 2) A roll mechanism; 3) A tilt mechanism; 4) Specialized instruments held in the tool holder.

The XYZ translation assembly is formed by mounting a single axis Z-stage orthogonal to a dual axis X-Y table (NEAT: LM-400 and NEAT: XYR-6060, respectively, from New England Affiliated Technologies of Lawrence, MA). Each axis consists of a crossed-roller way mounted table actuated by an encoded DC servo motor driven leadscrew. The travel along each axis is 100 mm, and the positioning resolution is <2.5μm (1 μm encoder resolution).

For the roll mechanism, we employed a rotary table model B5990TS from Velmex, Inc. Bloomfield, NY, motorized with a DC motor RE 25, 10 Watt connected through a planetary gearhead GP 26 B (14:1 reduction), and encoded with a Digital MR Encoder (512 counts per turn) from Maxon Motor AG. The range of motion is ±180º with a repeatability of 1 arc-second.

The tilt mechanism (Fig. 3) consists of a custom-made slider-crank mechanism attached to the rotary table through a carbon fiber tube. The slider mechanism, included in the tube, utilizes a high precision lead screw (80 TPI, OD ¼", sensitivity 1μm/inch) from Newport Corporation, Irvine CA, motorized with a DC Maxon motor RE 16, 4.5 Watt connected through a planetary gearhead GP 16 A (19:1 reduction), and encoded with a Digital MR Encoder (512 counts per turn). The crank motion range is ±30º relatively to the vertical tool position. Attached to the crank there is a small commercially available force/torque sensor (Model: NANO-17 SI 12/0.12, ATI Industrial Automation, NC), which has force resolutions of 0.0125N along the X,Y axes, 0.025N in the Z direction, and torque resolutions of 0.0625N-mm about the X,Y and Z axes. Force ranges of ±22.5N in the Z-axis and ±12.5N in the X-Y axes can be measured.

Fig. 3. Robot tilt mechanism.

The tool holder facilitates the attachment of a variety of surgical instruments, such as forceps, needle holder and scissors, that are required during microsurgical procedures. The current prototype assures the tool attachment with a manually actuated rigid coupling with a tapered sleeve mounted inside a tubular shaft. To reduce the friction force during the manual tool spinning, the shaft is supported with two radial ball bearings.

The new prototype of our new steady-hand robot is complete (Fig. 4). The control system has been implemented and the whole system was functionally tested. Also, 3D visualization software was added to the system.

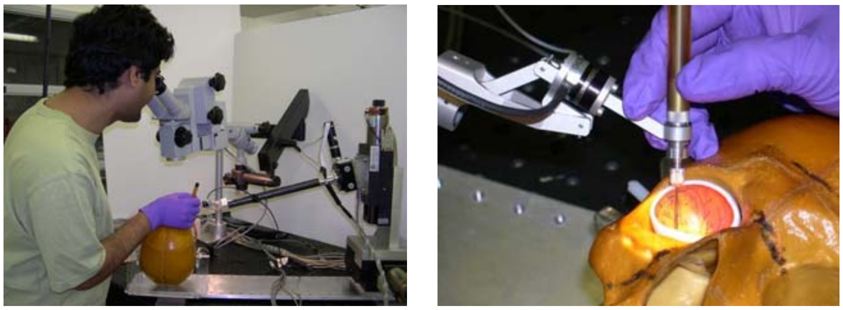

Fig. 4. The new steady-hand manipulator for retinal surgery.

4 Conclusion and Future Work

We have designed and fabricated an advanced and optimized version of a new steady-hand manipulator for retinal surgery. Our approach extends earlier work on cooperative manipulation in microsurgery and focuses on performance augmentation.

Our immediate goal is a rigorous evaluation of the completed system as a microsurgery augmentation aid in terms of efficacy, flexibility, and ergonomics. This will be done using some test environments developed by our colleagues at JHU's Wilmer Eye Institute. The first of these experiments is vein cannulation, another challenging vitreoretinal surgical technique, involving chick embryo chorioallantoic membrane (Fig.5).

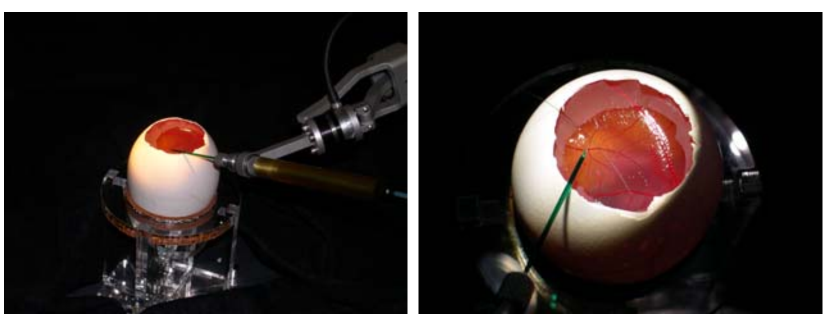

Fig. 5. The set-up for vein cannulation experiment.

In the long term, we expect to improve further the rigidity and the accuracy of the system. Our final goal is to develop a two-handed retinal surgery workstation with high precision and sensitivity, but with the manipulative transparency of the hand-held tools. Although our first focus is retinal microsurgery, we believe that our approach is generalizable to other microsurgery.

Acknowledgments. This work was partially funded by the National Science Foundation (NSF) under Engineering Research Center grant EEC9731748, and by the Johns Hopkins University internal funds.

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