Robotic Ocular Surgery

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ABSTRACT
Robotic surgery is becoming increasing popular, yet the range of applications is still very limited. One of these underutilized areas is ocular procedures. This paper presents an outline of the state-of-the-art in this field noting how robots can greatly improve the treatment of many eye conditions as well as how ophthalmic use of robotics continues to offer challenging problems.

Keywords
Robotic ocular surgery; ophthalmic robotics; robotic eye surgery.

1. INTRODUCTION
Advances in surgical robotics has increased rapidly over the past thirty years. Though one of the newest types of medical technology, robots have been applied to many specialties and their acceptability and use have increased dramatically in a short period of time.

While all types of medical robotics are undergoing active research and advances, this paper focuses on a specific type of surgical robot. It provides a very brief introduction to robotic surgery and then continues on to focus on robots designed for ophthalmic procedures. Various aspects of this technology will be explored including manipulator design, sensors, control and teleoperation. Specific design challenges, both addressed and unresolved, are also discussed.

2. ROBOTIC SURGERY
Robotic surgery has been a reality since a PUMA was used in 1985 for a brain biopsy [1]. Benefits of using robots to perform surgeries include smaller incisions, better accuracy, tremor reduction, adjustments to scale, and higher mobility [2]. All of these things benefit the patient by providing a more directed surgery and faster recovery time.

The use of robots in general surgery have increased dramatically since FDA approval in 2000. Robots were used in over 20,000 surgeries every year by 2010 of the da Vinci system in [3] and is now estimated to be used in more than 200,000 surgeries a year. There are hundreds robotic surgery systems in various stages of development [3] [4]. By far, the most popular surgical robot currently on the market is the da Vinci by Intuitive Surgical. The da Vinci surgical robot is commonly used for hysterectomies, prostatectomies, urologic procedures, heart valve repairs and several other general laparoscopic surgical procedures. Other popular surgical robots fully in use target orthopedic surgeries. These include MAKO Robotics’ RIO for knee and hip replacement surgery [5] and Mazor Surgical’s SpineAssist and Renaissance [6] for aiding spinal surgeries.

3. OCULAR ROBOTICS
Currently, there are no robots on the market designed specifically for intraocular procedures; though some are some are very close to this possibility. However, extraocular procedures and some tasks using current commercial systems are being performed.

Eye surgery is currently performed by the ophthalmologist manipulating instruments by hand while looking into a binocular microscope. The microsurgery’s success depends upon the dexterity of the physician during what can sometimes be long and arduous procedures. Hand tremors alone can be over ten-times greater than the desired positional accuracy. Due to the risk of unintended damage from a hand tremor, patient movement or the fatigue and strain on the surgeon’s eyes and hands; robots are a good solution to improve existing instruments and increase the number of physicians able to perform these surgeries [7].

3.1 Special Design Considerations
Ocular robotic surgery has a few key aspects that make it different from other types of robotic surgery. One of these is the issue of scale. Small errors in position that may be acceptable in general internal surgeries are not tolerable in eye surgery. The components of the eye are very small and delicate compared to most other organs such as the heart, bones or reproductive organs. In addition, some structures such as the retina are unable to fully heal if damaged and are also hard to access both visually and via instruments [8]. The solution to this problem has been to consider designing smaller instruments and manipulators specifically intended for micro-eye surgeries, rather than those for more general surgeries [9].

The second key aspect is that any instruments that enter the internal parts of the eye must not produce any significant forces at the insertion point. Small tensions that may be acceptable on skin can severely and permanently damage the sclera and other vital components. Not only can this cause unnecessary scarring, but it can lead to vision loss or blindness. Avoiding lateral forces at the point of entry is a problem that is being tackled by a variety of means. These include manipulator design and control systems. One manipulator design feature to minimize insertion tension is to implement a remote center of motion (RCM) where the instrument has a motionless pivot point where the instrument sits at the sclera or other point of entry. The manipulator moves below this pivot point as the control mechanisms are worked above. An early design included a 4-DoF manual manipulator, though it slowed the physician’s ability to perform tasks [10]. Another team utilized this system concept with a robotic manipulator and was able to show that precision and dexterity could be greatly increased [8].
3.2 Current Proposed Systems

Ophthalmic uses of robotics are currently under development including the Eye-RHAS (Eye Robot for Haptically Assisted Surgery) and PRECEYES [11], IRISS (Intraocular Robotic Interventional and Surgical System) [12], and Steady Hand Robots [8] [7]. By most accounts, certain procedures such as LASIK are also considered robotic because mirrors or fiber optics are actuated to quickly direct the laser beam at the desired target on the eye, even while the eye is moving. The surgeon does little intervention once the procedure is started [4].

Robots have been tested for ophthalmic uses since at least 1992 [13]. A 6-DoF parallel robotic arm [14], simply referred to as “The Eye Robot,” shown in Figure 1 was not only used in live animal experiments, but was also used for testing the feasibility of adding haptic feedback [13]. A similar design was proposed by another early system shown in Figure 2. This ultramicrosurgery system was created to experimentally prove that robotic technology opened up the possibility of a wider range of procedures that could be performed within the eye, particularly vitreoretinal drug delivery [15].

Figure 1: “The Eye Robot”

The Steady Hand Robots were created at Johns Hopkins University for vitreoretinal surgery. They aid in the control of an inserted instrument as shown in Figure 3. Force sensors are used to detect hand motion in order to move the robot arm with the surgeon, while eliminating tremors and stabilizing the motion. The first prototype, Eye Robot 1, had a positioning precision of 5-microns, but did have many other limitations. The researchers worked to obtain the specific goal of performing retinal vein cannulation, which would allow for direct targeting of drug delivery to this structure [8]. Eye Robot 2 [7] was built to improve upon some of the limitations of its predecessor. Previously rejected design alternatives such as a six-bar mechanism in the manipulator RCM were reconsidered and implemented to give a greater range of motion rather than a more compact design.

Figure 2: Experimental ocular ultramicrosurgery robot

Figure 3: Steady Hand Eye Robot 1

Other designs have been introduced that include various parallel robotic arms. These are popular due to the high stiffness and accuracy. One of these devices uses two 6-DoF parallel robotic mechanisms to control the position of a halo as shown in Figure 4 to gain very high precision [16] [17]. Another device (Figure 5) uses a master/slave system and has been specifically designed for vitreoretinal surgeries and has proven to significantly reduce the effect of tremors. It has been carefully designed for the demanding specifications and sterilization abilities to ensure commercial viability [18].

One novel design uses tiny MEMS-controlled pneumatic actuators to mimic the motion of a human hand. Tiny bladders are inflated and deflated according to controlled pneumatic pressure in order to make the 4-mm long fingers curl or straighten as shown in Figure 6. The system is able to lift and manipulate retina tissue and so shows promise to perform as micro forceps in ocular procedures [3]. Another novel concept is the OctoMag. It utilizes eight electromagnets set at predefined angles to direct an untethered ferrous micro-robot similar to that shown in Figure 7 to perform desired tasks [19].
Figure 4: Design for a surgical system using a halo positioned by two robotic arms

Figure 5: A parallel robotic arm for vitreoretinal surgery

Figure 6: Microhand forceps closing under increasing pneumatic pressure
IRISS was designed with the intention to perform all types of intraocular surgeries [12]. The robot serves as a slave and is controlled by a similarly constructed master console. The design focuses on maintaining the RCM via both hardware and software controls. Each stage of the robot maintains a RCM via a curved track for motion as can be seen in Figure 8.

In addition, proposals to use da Vinci system (Figure 10) have been presented. The high cost of the da Vinci system is a notable problem in gaining widespread use of this system for ophthalmic uses. However, discounting this with the assumption that many medical centers now have these robots available anyway, it is interesting for many to try to use these already-mainstream robots for ever more specialized tasks. An early test showed that while it was feasible to use the da Vinci for eye surgery, it was much slower than using traditional instruments [9]. It was suggested that developing smaller manipulators for the da Vinci would be beneficial. This sentiment was reiterated two years later in [20].

PRECEYES is a company that started as a spin-off from university research in the Netherlands that included work on the Eye-RHAS control console [11]. The company hopes that they will be the first in the world to have a robotic system on the market for eye surgery. The system, shown in Figure 9, consists of two arms that help guide the surgical instruments. They reduce tremors and also provide haptic feedback.
when the da Vinci system was used to test whether a more intricate procedure (a penetrating keratoplasty operation) could be performed within a human head. The procedure was considered successful, but it was noted that the da Vinci was not optimized for performing eye surgeries. Vitreoretinal operations are never attempted with the standard da Vinci since the 10-mm diameter manipulator arms are much too large to safely enter the sclera and be used [21]. In order to address these issues, a research team has developed a parallel robotic manipulator called the Hexapod Surgical System (HSS) to be placed onto the da Vinci arms as shown in Figure 11. This system combines two proven technologies so that a complete eye surgery can theoretically be performed with both intraocular and extraocular tasks [22]. Further work is needed to fully realize the use of a da Vinci robot for ocular surgeries, however. Areas of concern include manipulator size, stability of the da Vinci arms, and scaling to mimic natural arm positions.

Figure 10: da Vinci surgical robotic system

Figure 11: Hexapod Surgical System for micro-macro manipulations
3.3 Component Considerations

It is also worth pointing a few key subtechnologies that have not been thoroughly customized and perfected for use in ocular surgeries. Some of the work that has been done is touched upon.

3.3.1 Sensors

Tissue damage due to excessive forces from instruments is a great concern in intraocular surgery as previously noted. When performing eye surgeries, most of the force thresholds are too small for surgeons to manually detect due to being below the human sense of touch [23]. Currently, surgeons rely on visual inspection to detect and avoid excessive lateral force at the point of entry. This means that they must have a clear view of the insertion point and manipulator end at all times and the issue of looking for signs of excessive force must always be in their minds. However, by implementing force sensors, these micro-forces can be sensed and the information can be used to aid physicians during delicate procedures. This is also a crucial step in order to make certain maneuvers autonomous in the future, such as automatic suturing or drug delivery.

One group of researchers have worked to measure tool-tissue forces distally [24]. By using force sensors in the shaft and transmitting information via fibers optics to the tool handle outside of the eye (shown in Figure 12), accurate vitreoretinal force information is obtained with a minimal increase in the inserted portion of the instrument. They have noted that placing force sensors in other positions has severely decreased the accuracy and amplitude of the readings or makes the manipulator too large to be used for most intraocular use.

![Fiber optic force sensors](Figure 12: Fiber optic force sensors)

3.3.2 Control

One issue with control of robotic manipulators in eye surgery is the guidance of surgical instruments. As noted, the Steady Hand Robots hold the instruments and move according to forces applied by the surgeon's hand via admittance control, reducing tremors in the process [8]. It also offers the great advantage of holding the instrument position should the surgeon let go, allowing for the surgeon to rest and avoid fatigue during certain procedures such as the injection of medication into a vein.

As mentioned before, one of the problems with inner eye surgery is the need to avoid stresses on the tissue at the insertion point. Software, alone or in addition to hardware, can be used to solve this issue. Eye Robot 1 used software to compensate for simplification of a six-bar mechanism to a compact slider-crank mechanism in order to keep the RCM stationary. In contrast, Eye Robot 2 uses the more complex mechanism to maintain the RCM and uses control software only to improve the stability of the RCM. Information from force sensors aid the surgeon by encouraging movements that cause the least amount of force on the tissue. This algorithm is called “micro-force guided cooperative control” and it showed promise when tested on raw chicken eggs [7]. Additional improvements in sensors can increase the information available for both the control system and the human surgeon.

3.3.3 Teleoperation

There is a growing trend to increasingly use telemedicine. In ophthalmic applications, most current teleophthalmology practices are limited to consultation. While both synchronous teleoperation and store-and-forward models can be followed, only the latter is currently practiced outside of experimental procedures [25]. This involves manually taking general eye exam images as well as images of any features of interest and sending the information to a remote location for interpretation and diagnosis.

Synchronous teleoperation has been tested for ocular procedures since at least 1997. This teleoperation model includes the real-time control of surgical robot from a distant location. Benefits are that a specialist in one location can control a robot and perform surgery on a patient in another location. This may be necessary if the patient is in critical need and does not have time to travel or wait for a specialist to arrive. Teleoperation may also be used to remotely provide first-response care in areas not easily accessible due to geography, politics or disasters. This can include providing soldiers and civilians with care inside active war zones. It could also be a tool to provide care when distances are too great to travel for any specialized care, such as during a space exploration mission. Telerobotic surgery also allows for procedures to be performed by one or more physicians located at a distance from the patient. This can not only allow for more opinions and options for the patient to consider, but can also provide a means for training surgeons for rare and new procedures. Information can be recorded to be used in virtual reality training exercises as well to create a virtual training library.

Time delays are the biggest obstacle when controlling a robot real-time from a great distance. A contemporary system offers the simple solution of simply adjusting the scale of motion to reduce tremors and thereby smooth the reactions [18]. It was noted that scaling too much was found to slow the ability to complete the procedure quickly. It will therefore be necessary to determine an optimal point to balance the speed of the manipulator with the time delay.

4. CONCLUSION

This paper provided an outline of the current state of ophthalmic surgical robots. Experiments using robots to operate on various parts of the eye have been conducted for the past couple of decades. The feasibility of the use of robots has not only been demonstrated,
but has also proven to offer abilities and procedures that are currently not possible by manual operations.

It can be expected that some specialized ocular robotic systems will soon show up on the market. Still, there are many improvements possible that will allow these systems to be used to their full potential. These currently include advances in sensors, haptic control and teleoperation issues. Given the great rise in robotic surgeries for many other procedures and the tremendous improvements currently not possible by manual operations but has also proven to offer abilities and procedures that are currently not possible by manual operations.

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5. ACKNOWLEDGMENTS
One of the authors (MM) would like to thank the DOD/Army Research Office for providing support under grant no. ARO Grant No. W911NF-11-1-0131 to perform this research. Their support is very much appreciated.

6. REFERENCES

