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REVIEW

A Review of Robotic and OCT-Aided Systems for Vitreoretinal Surgery

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ABSTRACT

The introduction of the intraocular vitrectomy instrument by Machemer et al. has led to remarkable advancements in vitreoretinal surgery enabling the limitations of human physiologic capabilities to be reached. To overcome the barriers of perception, tremor, and dexterity, robotic technologies have been investigated with current advancements nearing the feasibility for clinical use. There are four categories of robotic systems that have emerged through the research: (1) handheld instruments with intrinsic robotic assistance, (2) hand-on-hand robotic systems, (3) teleoperated robotic systems, and (4) magnetic guidance robots. This review covers the improvements and the remaining needs for safe, cost-effective clinical deployment of robotic systems in vitreoretinal surgery.

Keywords: Image-guided surgery; Medical robotics; Micromanipulator; Ophthalmic surgery; Ophthalmology; Optical coherence tomography; Telemanipulation; Vitreoretinal surgery

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Key Summary Points

To overcome the barriers of perception, tremor, and dexterity in vitreoretinal surgery, robotic technologies have been investigated with current advancements nearing the feasibility for clinical use.

There are four categories of robotic systems that have emerged through the research: (1) handheld instruments with intrinsic robotic assistance, (2) hand-on-hand robotic systems, (3) teleoperated robotic systems, and (4) magnetic guidance robots.

The future of vitreoretinal surgery may include some of the robotic systems or implementations of technology introduced in the development of the robots.

Limitations of surgical robots include barriers presented by sensor-actuation lag that can be limited by using high sampling frequencies. Also, heavy computational demands from visual feedback technologies currently make real-time integration challenging.

Clinical surgical robotics will likely use technologies such as optical coherence tomography and tool tip force measurements to add accuracy.

DIGITAL FEATURES

This article is published with digital features, including a summary slide, to facilitate understanding of the article. To view digital features for this article go to https://doi.org/10.6084/m9.figshare.14125301.

INTRODUCTION

Needs and Challenges in Ophthalmic Surgery

Despite vast advances in vitreoretinal surgery since Machemer et al. [1], it presents challenges to surgeons in terms of precision, perception, and manipulation dexterity. A typical setup during these procedures involves multiport access into the vitreous cavity with thin tools (e.g., picks, graspers, light source). Visualization of the retina through a surgical microscope is achieved through the pupil with adding a focusing lens on or above the cornea. Surgeons have to stabilize the eye while operating one to two instruments within the vitreoretinal space. Surgical tools generally lack distal dexterity owing to their small size (generally less than 900 μm in diameter) and they have to be maneuvered under deficient perception conditions. For example, the visualization of the anatomy is limited through a dilated iris, especially if dilation is poor. Tool shadows are hard to perceive because of complex lighting conditions with chandelier illumination or a small moving endoilluminator light held in the surgeon's second hand and the retinal anatomy presents semitransparent features (e.g., retinal membrane) that can be difficult to see. Added to these challenges is the difficulty of measuring tool tip interaction forces because of the interference from tool–trocar friction forces as concluded by Jagtap et al. [2]. Further, Jensen et al. [3] showed that the delicate anatomy of the retina can apply reaction forces less than 7.5 mN for 77% of the duration of a vitreoretinal procedure which was perceived by the surgeon only 20% of the time. This review describes current retinal surgical limitations, the parallel developments of optical coherence tomography (OCT) and surgical robotics, and the intersection of the two technologies which have the potential to revolutionize patient care.

Success of many vitreoretinal procedures depends on safe manipulation of the delicate anatomy of the retina. For example, epiretinal membrane peeling requires careful peeling of a layer that can be on average 61 ± 28 μm thick

[4] while avoiding trauma to the underlying retinal anatomy. Treatment of retinal detachments requires maneuvers using picks and miniature graspers/cutters while avoiding exacerbating the retinal detachment and avoiding inadvertent touching of the lens or causing retinal hemorrhage. Previous experimental characterizations of physiologic tremors illustrate the challenge of accomplishing such precise tasks. For example, the average root mean square (rms) amplitude of tremor with a four-subject user study ranged between 14 and 142 μm [5] when holding a tool still and between 59 and 341 μm when actuating a microsurgical grasper. In another example Singh and Riviere [6] tracked the tool motion during epiretinal membrane peeling and reported the rms amplitude of tremor at 38 μm for a single-subject study. These reported magnitudes of tool tremor are large enough to make microretinal procedures exceedingly challenging. To overcome tremor, four approaches using robotics were considered in the literature. In the first method, a handheld miniature robotic platform was used for tremor cancellation of tracked instruments. Examples of this approach include Riviere et al.'s Micron [7], Song et al.'s SMART OCT-based device [8], and Cheon et al.'s OCT-guided depth-locking handheld microinjector [9]. In the second method, a hand-on-hand approach is used where the surgical instrument is held by a robot and the surgeon's hand. Forces by the surgeon's hand are used to command the robot (tool) motion while also providing tremor filtration, Taylor et al.'s Steady-Hand eye robot [10] for example. A third approach using telemanipulation with a surgeon controlling a robotically guided surgical tool via a control station detached from the robot was initially explored by Charles [11], Wei et al. [12], Yu et al. [13], and Meenink et al. [14]. Finally, the fourth approach using extraocular magnetic fields achieves manipulation of two types of intraocular robots. Kummer et al. [15] demonstrated intraocular microcapsule robots and Charreyron et al. [16, 17] demonstrated steerable magnetic-tipped catheters for drug injection delivery and retinal vein cannulation.

Vitreoretinal surgery is also complicated by perception barriers owing to operating through a microscope and due to limited tactile feedback. Typically, humans rely on a tactile response as a form of confirmation of contacting an intended target when performing a task such as surgery. However, the delicate intraocular anatomy does not produce reaction forces great enough to overcome the friction between a surgical tool and trocar to reach a level perceptible to humans. With this lack of tactile feedback, surgeons are forced to rely heavily on visual cues to discern tool proximity and contact of the surgical tools with the anatomy [3]. However, intraocular visualization via a surgical microscope has limits of useful depth perception and the visible field of view is restricted by the dilated iris. In addition to manipulating instruments inside the eye, surgeons may also tilt the eye under the microscope. In some cases, the target anatomy is difficult to visualize using white-light imaging. For example, epiretinal membranes are mostly transparent which standard light microscopes are incapable of visualizing without the addition of a steroid suspension or indocyanine green (ICG) to stain the membranes. Surgeons may also use endoscopes for auxiliary peripheral visualization; however, these scopes have limited resolutions compared to current microscopes. To address the challenge of depth perception, previous investigations have augmented instruments with OCT probes. For example, Balicki et al. [18] used an A-scan OCT probe to maintain the distance of a robotic-controlled tool tip from retinal anatomy. Yu et al. [19, 20] used forceps integrated with a B-mode OCT probe for depth perception feedback. In Yu et al. [19] it was shown that OCT feedback improved depth perception and success of approaching a surface and peeling a surface membrane.

In addition to precision and perception challenges, there are challenges due to rigid instrumentation offering limited maneuverability. Vitreoretinal surgical tools are generally slender instruments with rigid shafts. These instruments are constrained to the traditional four-DOF (degrees of freedom) motions available to minimally invasive instruments (tilt in two directions and rotation about and translation along the longitudinal axis of the tool). As a result, the tool tip dexterity of these instruments is quite limited. One can reach a particular site, but with limited control of tool tip orientation. Surgeons have to carry out surgical maneuvers of lifting membranes with picks and graspers despite their limited distal tip dexterity and contend with the need for bimanual manipulation in order to stabilize the eye while operating tools inside it. Ikuta et al. [21] proposed the use of manual active bending forceps, but the current clinical repertoire of surgical forceps still remains predominantly without active distal bending. The four scenarios of ocular and intraocular manipulation have been considered [22] with an emphasis on quantifying the possible benefits of instrumentation with intraocular dexterity. It was shown that adding a single DOF of bending sideways can increase orientational dexterity, compared to rigid instruments, by 31.6% and 57.7% for translational and rotational manipulation, respectively. Several tools and robotic instruments have been considered to overcome the problem of intraocular dexterity. In Simaan et al. [23] the concept of intraocular dexterity tools using continuum bending cannulas was introduced and later implemented by Wei et al. [12, 24] and Yu et al. [13]. He et al. [25] introduced a prototype of a 0.9 mm handheld continuum robot offering intraocular dexterity that was later integrated with a robotic platform by Song et al. [26].

The aforementioned challenges of tremor, limited visual and tactile perception, and tool tip dexterity can be alleviated in several ways. For example, active tools can limit the effects of human tremor to increase surgical precision by filtering sensor input to produce tremorless actuator control. Visual perception can be augmented using OCT to obtain cross-sectional imaging of tissue yielding a richer set of information of target anatomy. Using sensors that can detect forces imperceptible to humans enhances a surgeon's effective tactile perception. For higher dexterity, continuum segment tools offer higher ranges of motion with manipulation directly by a surgeon or attached to robotic systems for greater levels of manipulability and accuracy. In the following we discuss some of the tools that have been developed to address the three main areas outlined above limiting vitreoretinal surgery and discuss prospective areas of development to further lessen these constraints.

METHODS TO IMPROVE VISUALIZATION: OPTICAL COHERENCE TOMOGRAPHY (OCT)

OCT is a standard diagnostic and surgical planning ophthalmic tool that can develop cross-sectional images of tissue using light reflectance. Dayani et al. used a handheld device during planned surgical procedure interruptions [27]. Binder et al. first used a microscope-mounted unit following surgical manipulations [28]. The Duke [29–38], Cleveland Clinic/Case Western Reserve [36, 39–47], Vanderbilt [48], and international groups [28, 49–52] developed improvements for the microscope-mounted intraoperative OCT systems with commercial US Food and Drug Administration (FDA)-approved systems available for the operating room [53].

Non-OCT surgical intraocular endoscopes are FDA-approved [54–60], but there is not yet an approved facile ophthalmic OCT probe to enable peripheral retina visualization as well as bypass corneal and lenticular opacities that may hinder direct central visualization [61]. Iftimia et al. [62] developed an A-scan 250 μm OCT probe for one-dimensional measurement of tissue.

Balicki et al. [18] reported an intraocular common path A-scan OCT probe. A 20-gauge coplanar probe was developed which successfully guided the depth of mid-infrared laser incisions of the retina [63]. The OCT-imaging component alone was housed within a 25-gauge tube which was readily amenable to imaging through the more recent 23-gauge and 25-gauge trocars preferred for contemporary retinal surgeries [64]. Addition of a needle [65] or forceps [19] increased the size only to 23 gauge. This OCT probe has been added to robotic platforms described in the following section.

Ray et al. presented a custom mount that attached the Bioptigen handheld probe to an ophthalmic surgical microscope [66]. OCT images from 24 patients undergoing macular hole or epiretinal membrane surgery were analyzed with subsequent quantitative measurement of geometry and retinal thickness providing insight into the anatomical changes in the retina resulting from macular surgery and verifying surgery completion. The feasibility and safety of microscope-mounted OCT in prospectively and retrospectively enrolled eyes during several ophthalmic surgeries was reported, and it enhanced surgeons' understanding of the underlying anatomy in more than 40% of the cases during lamellar keratoplasty and retinal membrane peeling [67–69].

Microscope-integrated systems have been developed which combine the OCT and surgical microscope optical paths to enable imaging simultaneously with surgical maneuvers [30, 31, 41, 42, 70, 71]. The Duke research prototype [30] was clinically evaluated in a study involving eight patients undergoing surgery for macular holes, epiretinal membranes, and vitreomacular traction [32]. The results confirmed the ability to observe surgically induced changes in retinal contour and macular hole configuration. The ability to acquire OCT images simultaneously through the microscope overcame a major limitation of a separate external large imaging probe by eliminating the need for frequent pauses during surgery. Commercial systems are now available with the first being the Zeiss RESCAN 700. Increases in imaging speed combined with improved computation using graphics processing units (GPUs) have enabled real-time 3D [72] and 4D [73, 74] intraoperative OCT. This provides improved feedback on instrument position. Real-time adjustments of the OCT focus to maintain parfocality with the surgical microscope at different axial positions and zoom levels is possible [41]. Improved visualization includes heads-up display (HUD) technology that adds OCT visualization into the microscope ocular view [45] to project OCT cross-sections [42] onto the surgical field. Carrasco-Zevallos et al. demonstrated volumetric 4D OCT data for real-time surgical feedback [73, 75]. Others are examining displaying images on virtual reality (VR) platforms and gradually OCT has been added to several robotic systems as reported in the following section.

ROBOTIC SYSTEMS FOR VITREORETINAL PROCEDURES

To address the host of complications with vitreoretinal surgery the literature presents several types of robotic systems with an array of features offering surgical advantages. These robotic systems fall into four categories distinguished by their interaction with the surgeon: (1) handheld, (2) telemanipulated, (3) hand-on-hand, and (4) magnetically controlled systems.

Handheld Systems for Vitreoretinal Procedures

Handheld robotic surgical tools have been explored to address the challenges of physiologic tremor and force perception with minimal disruption to the surgical workflow. One example of a handheld robotic surgical device is Micron [7, 76]. Micron is a vitreoretinal surgical tool designed to sense a surgeon's tremor and distinguish those movements from intentional motion. It leverages the effects of constructive and destructive interaction of wave signals to filter the user's tremor from the tool tip. The device senses the user's movements and identifies tremor as any input signal within the 8–12 Hz frequency band as determined elsewhere [5]. To stabilize the surgical tool, piezoelectric actuators direct Micron's tool tip in a direction opposite and equal in magnitude to the tremor. Becker et al. [76] (Fig. 1i) improved on the target acquisition of Micron by adding image guidance. Two cameras were attached directly to a surgical microscope as a stereo pair for registering the tool tip's location and to measure the tool's lateral displacement relative to target vessels. The displacement data is used as an additional feedback signal in combination with the user's movements to achieve 63% success in experimental vessel cannulation as shown in Fig. 1ii.

Force sensing was introduced by Gonenc et al. [77] using fiber Bragg grating (FBG) strain sensors to enable force sensing at the tool tip following the design from Iordachita et al.'s [78] vitreoretinal tool with a 0.25 mN resolution (5.6×10^{-5} lb). The sensors are located at the

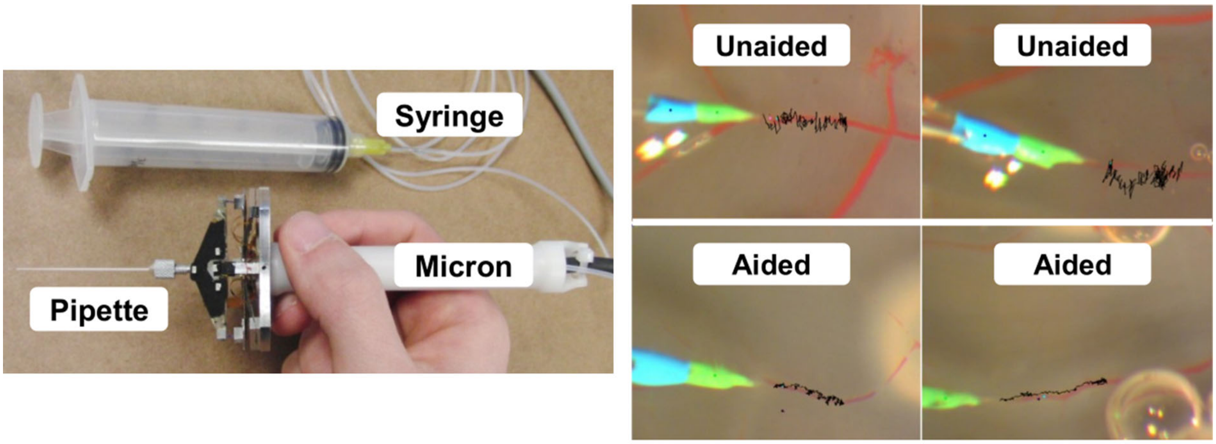

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Fig. 1 **i** An active surgical tool, Micron, that senses a user's tremor during manual microsurgeries and cancels the effects of tremor on tool tip trajectory using piezoelectric actuators for procedures such as retinal vein cannulation. **ii** The improvement of tool tip trajectory during manual manipulation with the inclusion of visual feedback to Micron (Figures reproduced with permission from Becker et al. [76])

tool's tip to isolate retinal forces from the sclerotomy interaction forces, thereby inhibiting the user from imposing damaging forces on the retina. Yang et al. [79] optimized the Micron's design to allow six DOFs with a 4-mm-diameter hemispherical workspace by using a parallel actuator architecture offering more robust tremor control. Yang et al. [80] used the six-DOF Micron to demonstrate the advantage of using tremor stabilization in acquiring clear B-mode and C-mode OCT image acquisition and presented a precursor of a clinical tool capable of tremor filtration paired with the visual feedback capabilities of OCT.

The Integrated Robotic Intraocular Snake or IRIS, developed by He et al. [25], is a robotic surgical tool prototype offering surgeons intraocular dexterity that is meant to be a handheld device or a mountable attachment to a robotic platform. IRIS was designed to match the sizing of 20-gauge ophthalmic surgical tools with a 0.9 mm outer diameter. The continuum segment of the IRIS is 10 mm long and has two rotational DOFs each with ± 45° of bending. The linear actuators of the IRIS exhibited large backlash and low actuation resolution which limited the realizable precision of the final design.

Telemanipulation Robotic Systems for Vitreoretinal Procedures

Wei et al. [12, 22] presented a multiplatform robotic system in Fig. 2 that can manipulate the eyeball and offer intraocular dexterity via a bending continuum robot capable of deploying microstents or grippers. The system allows for a software-controlled remote center of motion (RCM). The robotic arms of this system have been demonstrated to enable deployment of microstents in chorioallantoic chick membranes [24] and were integrated with OCT for control feedback [20] (Fig. 3).

Yu et al. [19] developed surgical forceps shown in Fig. 4 integrated with a B-mode forward-imaging OCT probe enabling real-time intraocular imaging to improve accuracy for membrane peeling procedures. The forceps were made with a 25-gauge stainless steel (SS) tube within a 23-gauge SS tube. The outer tube slides along the 25-gauge tube forcing the opening and closing of the forceps. The group showed that integration of the custom OCT forceps with the robot manipulator improved accuracy and reduced the number of attempts needed to accomplish a membrane peeling procedure. Their results also emphasized the importance of

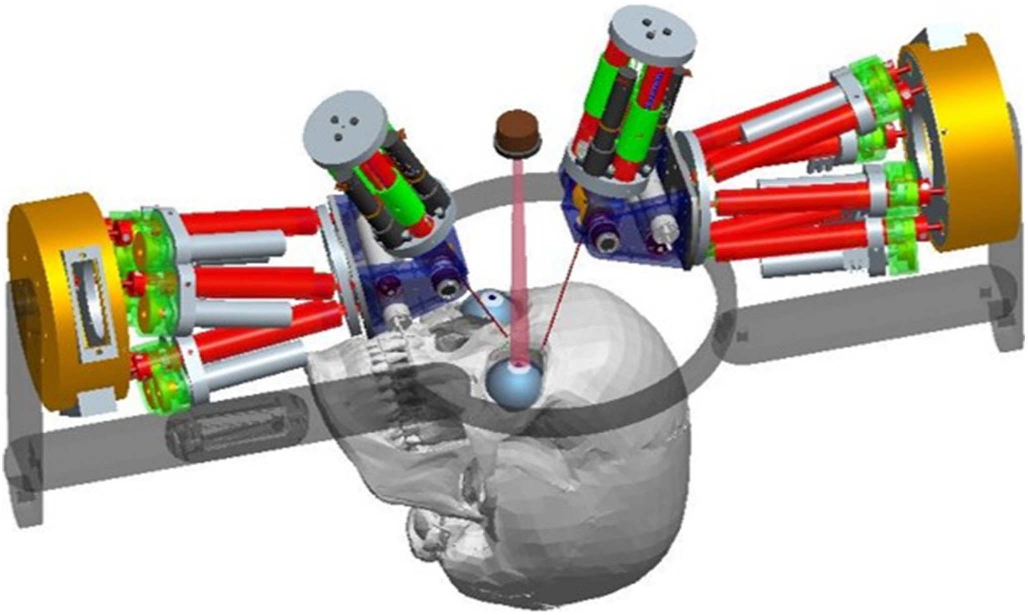

Fig. 2 A two-arm parallel robot used for vitreoretinal operations that allow eye maneuvering and intraocular dexterity (Figure courtesy of Nabil Simaan)

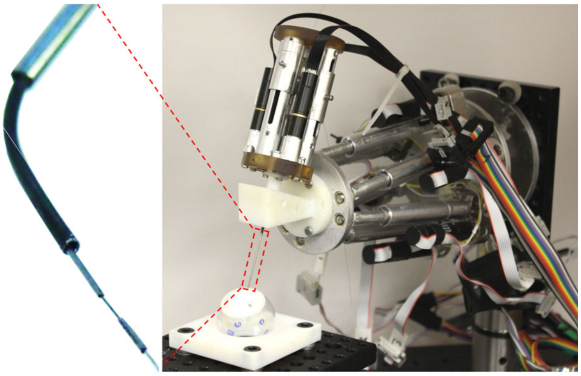

Fig. 3 A nine-DOF robot with parallel actuation platform carrying a stenting robot capable of maneuvering with precision better than 5 µm (Photo courtesy of Nabil Simaan)

proximity of the OCT image monitor to the surgeon to minimize head and eye movements of the user.

Nasseri et al. developed a six-DOF miniature robot [81] (Fig. 5). This robot creates linear and rotational motion using two parallel prismatic joints. There are two advantages of such a parallel mechanism. First the overall stiffness is greater than what would be possible with serially linked actuators. The second advantage is the increased DOFs enabled with two separate actuators. This six-DOF robot creates a highly dexterous system eliminating a surgeon's tremor input and minimizing the effect of user fatigue; however, challenges associated with intraocular maneuverability are not addressed.

The Preceyes Surgical Robotic System was developed for microintraocular procedures like retinal vein cannulation and internal limiting membrane peeling. The Preceyes system has a motion controller that the surgeon uses to command surgical tool tip position. The surgical tool is attached to a parallelogram manipulator that enables operation around an RCM. By setting a virtual point, at the sclerotomy, around which a tool will rotate provides advantages for the user. First, minimized interaction forces between the surgical tool and sclerotomy mitigate any scleral trauma; second, the orientation of the orbit remains unaffected, which maintains line of site to the surgeon. The group has also integrated the system with external OCT imaging to establish tool tip boundaries aiding the user in tool manipulation and preventing inadvertent retinal contact or puncture [82].

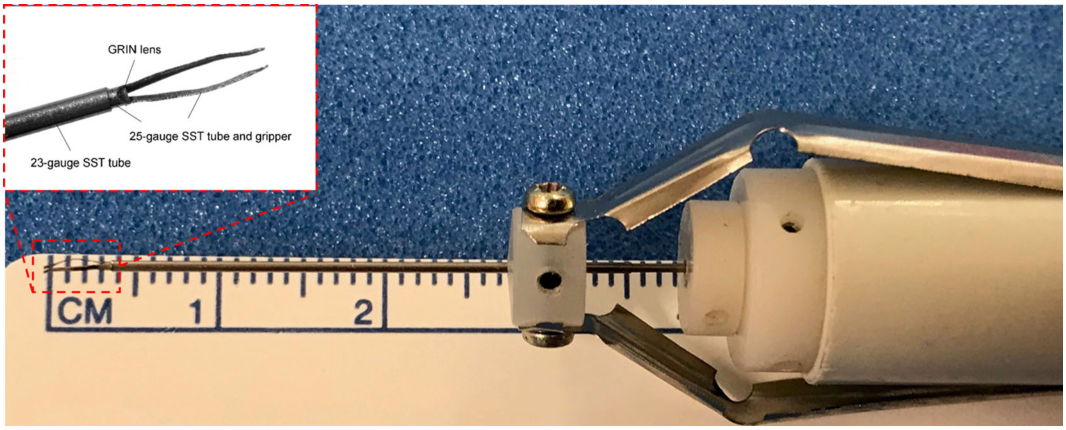

Fig. 4 OCT-forceps with OCT fiber embedded in the 25-gauge stainless steel tube (SST). External actuation causes the 23-gauge SST to slide axially on the 25-gauge SST causing opening–closing of the forceps (Photo courtesy of Karen Joos)

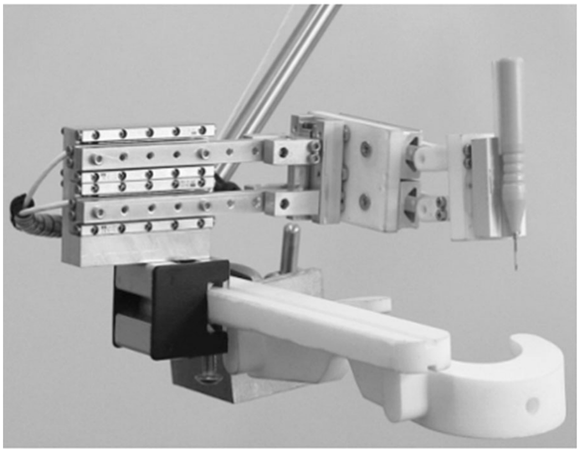

Fig. 5 A hybrid parallel-serial surgical cooperative robot capable of microscale motion using piezo actuators (Figure reproduced with permission from Nasseri et al. [81])

Gijbels et al. [83] developed a telemanipulated robotic system to aid in retinal vein cannulation and epiretinal membrane peeling and achieved successful in vivo human retinal vein cannulation [84]. By enabling axial translation as in Gijbels et al. [83], the size of tooling around the eye was minimized and the robot workspace for maneuvering around the microscope viewing cone was maximized. Wilson et al. [85] also developed a unique telemanipulated intraocular robotic interventional surgical system (IRISS) with two manipulators that mount and travel on semicircular tracks. The tracks can be independently positioned with two separate actuators to allow six DOFs of surgical tool manipulation. Each tool is kinematically constrained to a fixed RCM defined by the device geometry. The IRISS was tested on cadaver porcine eyes to demonstrate retinal vein cannulation and for cataract extraction. The group also tested the feasibility of using OCT for calibrating the RCM point and concluded that RCM alignment using visible red dot lasers may introduce deviations too large for full autonomy.

Del Giudice et al. [86, 87] developed continuum robots for multiscale motion (CREM) demonstrating a novel concept for teleoperated robot actuation for surgeries requiring microscale motion like microvascular reconstruction and image-based (OCT) diagnosis. The CREM robot is capable of maneuvering tools within both macro- and micro-workspaces with a positional resolution of 1 μm. It was shown that 3D OCT images may be obtained by using the robot's micromotion capability while carrying a B-mode OCT probe, which was an adaptation from Shen et al. [88]. In addition to validating 3D OCT on a cadaveric porcine retina, closed-loop control and OCT-guided visual servoing at the micromotion scale was also demonstrated for targeting a needle into a microchannel. While this system was not miniaturized to operate within the eye, the same design concept may be used for high-precision and low-cost robotic devices for manipulating needles within the eye with OCT feedback.

Hand-on-Hand Robotic Systems for Vitreoretinal Procedures

By minimizing positioning error of a tool tip caused by human tremor, some active surgical tools enable microsurgeries that are impossible with traditional surgical tools. Maneuvering handheld robotic tools for microsurgeries still requires a tremendous level of skill, however, as the level of tremor filtration is limited by the stroke magnitude of the device's actuators. Like telemanipulated robots, hand-on-hand robots offer a greater advantage of tremor filtration by leveraging the mechanical stiffness of robotic systems to drive surgical tools in tandem with the surgeon.

Hand-on-hand robotic systems allow the surgeon to drive a tool mounted on a robotic platform using force input commands. This approach has several advantages in terms of reduced cost and ease of clinical deployment. In addition, the robot can be used for tremor filtering, for position recall, and for reducing surgeon fatigue since the robot can hold the tool at a fixed position even if the surgeon lets go of it.

The Steady-Hand Robot [10] and Steady-Hand Robot 2 [89], shown in Fig. 6, were developed to augment a surgeon's capabilities with retinal and other microsurgeries in mind. The Steady-Hand is a cooperative robotic system, where the surgeon and a robotic actuator simultaneously control a surgical tool. The surgeon manipulates surgical tools in the same fashion as traditional tools with the robot controller reading force signals from the surgeon's hand movements to drive the robot. The robot is capable of producing smooth, natural motion profiles that a surgeon would typically use during retinal procedures while eliminating the extraneous tool movements that result from tremor.

The first realization of the Steady-Hand from Taylor et al. [10] improved success of needle insertion into a hole 150 μm in diameter by 36% [90] when compared to manual needle insertion. Balicki et al. [18] used a custom 25-gauge surgical pick with integrated OCT for epiretinal membrane peeling. With the OCT surgical pick providing visual feedback, the Steady-Hand was able to maintain a specified distance of the surgical tool tip from retinal

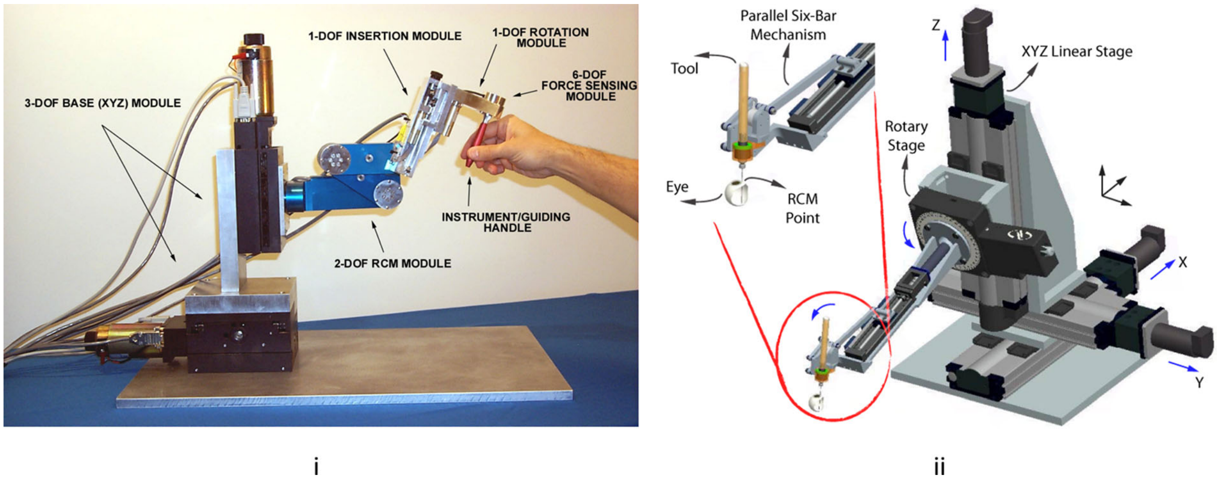

Fig. 6 **i** An early iteration of a cooperative surgical robot, the Steady-Hand Robot with robotic platform and surgical tool attached to a six-DOF force sensor for robot control (Photo courtesy of Russell H. Taylor and Iulian I. Iordachita). **ii** An iteration of the Steady-Hand Robot, the Steady-Hand Robot 2, or Eye Robot 2 (ER2). (Figure reproduced with permission from Üneri et al. [10])

tissue to within 10 μm of a desired 150 μm. The OCT imaging enabled identification of structures beyond surface layers as targets that can be used to guide tool puncturing tasks while limiting puncture depths. Üneri et al. [89] evolved the Steady-Hand by including a force sensor attached to the surgical tool. The additional sensor provides applied tool forces as feedback data to the robot controller to limit maximum forces applied to intraocular tissue. The force feedback data aids in guiding surgeons to avoid unintended destructive contact and, like the OCT feedback, is used to maintain tool positioning with respect to intraocular anatomy. The combined inputs from the OCT imaging and force sensor optimize tool trajectory, for instance, while maintaining tool angle during a peeling motion that minimizes resistance to limit membrane tearing.

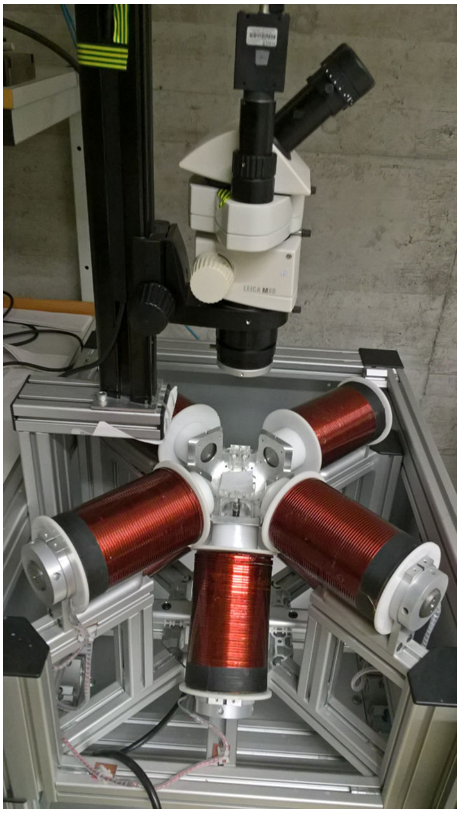

Fig. 7 The extraocular magnetic field generating system, OctoMag, capable of guiding magnetic drug-eluting microcapsules and magnetic tip microcannula in five DOFs, i.e., three degrees of positional control and two orientational degrees (Figure courtesy of Bradley Nelson and MagnebotiX AG, Zurich, Switzerland)

Magnetically Controlled Robot Systems

Finally, other approaches using magnetically controlled microrobots have been explored over the past decade. These systems utilize an extraocular magnetic field to control robotic microcapsules within the eye for procedures like retinal vein cannulation and localized drug delivery using drug-eluting microcapsules. Kummer et al. [15] used a magnetic field system called the OctoMag (Fig. 7) to guide a microcapsule robot in five DOFs, i.e., three degrees of positional control and two orientational degrees. One of the advantages of magnetic systems is achieving high levels of intraocular dexterity and maneuverability without physical attachment to the extraocular space [15]. Minimizing attachments between the extraocular and intraocular space eliminates the eye manipulability constraints imposed by pars plana sclerotomy surgical tools and maximizes the degrees of manipulation available for the line of site of intraocular anatomy. These advantages, however, come at the expense of very complex magnetic field generators that encompass a large portion of the space around the patient's head.

Charreyron et al. [16, 17] used the OctoMag magnetic field system to drive a magnetic tip microcannula for delivery of gene therapy injections to subretinal tissue. The group developed semiautonomous control that automatically aligns the tool magnetic field to keep the tool tip perpendicular to the retinal surface at a target site identified by the surgeon. The user, while following tool manipulation through the microscope, determines when the tool tip is optimally placed for injection. Magnetic microcannulas maintain the advantages of intraocular dexterity that characterize microcapsule robots by relying solely on the magnetic field for actuation. These magnetic manipulators also offer a potential safety advantage over traditional rigid surgical tools because of their limited rigidity and limitations of achievable forces. The group explored the feasibility of autonomous control and also explored OCT imaging for improved tool tip tracking. Their system exhibits 11 degrees of angular error of the magnetic field in a worst-case scenario which translates to 4.2 mm of displacement of a 21-mm-long cannula. For full autonomous control to be clinically realizable, precision of magnetic field alignment will be necessary

DISCUSSION

Vitreoretinal surgical techniques and available procedures are in a transitional state due to the contributions of advanced visualization techniques and the development of robotic surgical devices. The future of vitreoretinal surgery is the possible realization of autonomy for an array of procedures available today, but more importantly, enabling procedures that are not currently available because of human physiological limitations. For instance, gene therapy injections require the utmost precision for target acquisition. Magnetic field generators guide magnetic drug-eluting microrobots enabling intraocular drug injections. Magnetic intraocular robots eliminate the pars plana sclerotomy manipulation constraints but require a large volume of the workspace surrounding the patient's head. An alternative approach for targeting is OCT imaging which delivers high-definition images necessary for intraocular navigation. When OCT imaging is paired with robotic platforms as a feedback modality, the combined system can drive tools to specific retinal locations with improved accuracy and reduced dependence upon human surgical skills.

Some of the robotic systems mentioned are already in a developmental stage where autonomy is possible. The Steady-Hand robot, for instance, demonstrated autonomous manipulation of a needle inserted into a 150–250 μm hole, improving success of insertion by an average of 31.8% compared to handheld insertions. With added OCT imaging, performing vitreoretinal tasks expands further to assist in manipulation of semitransparent membranes and target subsurface tissue. Depending solely on OCT visual feedback, the robot controller can bypass the force input from a user to drive surgical tools to locations identified with the OCT. By utilizing distance measurement capabilities of OCT or force guidance with FBG integrated tool tips, the likelihood of tissue damaging contact is reduced.

With a system like CREM, tasks requiring ultra-precision and autonomous intervention are possible with miniaturization of the technology. Utilizing equilibrium modulation as an actuation technique enables robotics in surgery to carry out microscale tasks with much finer positional adjustments than other robots. Further, enabling these micromanipulation tasks does not sacrifice the capabilities in the macro-workspace enabling a greater number of surgical tasks.

Although surgical robots have shown their capabilities in advancing vitreoretinal surgery, they are not without limitations. Developing OCT-guided robotic tools that do not disrupt the clinical workflow requires hardware capable of high sampling frequencies allowing for improved OCT image quality via filtering and multiframe averaging techniques. Registration of the OCT probe image frame to the robot frame is challenging—especially for systems using an external OCT. Stabilization of the robotic tool relative to the patient head (or use of active eye motion tracking) are key to enhancing safety. Finally, the ability to achieve fast and safe tool retraction in case of involuntary ocular movements or in case of a clinical emergency will be paramount to safe clinical deployment.

CONCLUSIONS

Clinical surgical robotics will likely use technologies like OCT and tool tip force measurements to enhance the surgeon's perception and accuracy. These robotic systems will include powerful control computers, particularly those using OCT, with calibration methods and control algorithms accounting for safe anatomical movements during procedures. The future of vitreoretinal surgery may include some of the robotic systems or implementations of technology introduced in the development of the robots discussed in this review.

This review article is based on previously conducted studies and does not contain any new studies with human participants or animals performed by any of the authors.

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