Received: 1 February 2023 | Revised: 29 March 2023 | Accepted: 24 April 2023

DOI: 10.1002/rcs.2524

REVIEW ARTICLE

The International Journal of Medical Robotics and Computer Assisted Surgery

WILEY

Review on challenges for robotic eye surgery; surgical systems, technologies, cost-effectiveness, and controllers

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Funding information
Narodowa Agencja Wymiany Akademickiej, Grant/Award Number: PPN/PPO/2018/1/00063/U/00001; Politechnika Warszawska, Grant/Award Number: 504440200003

Abstract

In recent decades, a number of surgical systems have been developed and are applied for a growing variety of surgeries. This review will consider the significant challenges of robotic surgery for the eye. These challenges take into account the different eye diseases, available technologies, and costs in different surgical systems for the eye. The conditions of a suitable controller will be discussed with consideration of relevant control engineering concepts. Comparison is made between the different characteristics of surgical robots for the eye. In this review, some comparisons will be made in eye surgical robots, control algorithms, sensors in surgical robots, communication protocols, and actuators.

KEYWORDS
cost-effectiveness, Da Vinci system, robotic eye surgery, surgical robots

1 | INTRODUCTION

A capable machine that can automatically carry out complex actions is called a robot. In recent decades, the use of robots for medical and surgical purposes has increased significantly. Robotic surgery is not strictly conducted by the machine but is more precisely robot-assisted surgery.[1] Some advantages of robotic surgery are increased precision, elimination of tremors, reduction of human error, task automation and capacity for remote surgery.[2]

While technology progresses rapidly, a question that needs to underpin all new advances in robotic surgery is whether any given system is feasible. The feasibility of robotic surgery has been justified to some extent.[1,3] Whether this is also applicable to robotic eye surgery needs to be elucidated. Channa et al. have shown the feasibility of robotic eye surgery for the delicate anterior segment and vitreoretinal surgical procedures.[4] Tsirbas et al. concluded that the use of surgical systems for ocular surgery warrants further investigation and proposes applying robotic systems in controlled human trials.[5]

The American companyIntuitive Surgical made the Da Vinci surgical system and was approved by the Food and Drug Administration (FDA) in 2000.[6] Three versions of the Da Vinci system have been developed, notably: S,[7] Si,[8] and Xi.[9] The Da Vinci S system has three manipulator arms (which the surgeon controls), the Si system has two master grips and one manipulator arm, and the Xi system has two master grips and four manipulator arms[10] The system is currently expensive and is the biggest drawback of using this robot. The purchase price for each unit of Da Vinci ranges from 1 to 2.5 million dollars,[11] and around two hundred thousand surgeries have been undertaken using this system in 2010.[12]

Several types of surgeries have been performed using surgical robots in recent years; the impact of robotic-assisted prostatectomy has been described,[13–16] and radical prostatectomy techniques such as open, laparoscopic and robotic-assisted have been compared.[17] These comparisons are based on length of hospital stay, blood loss, learning curve and costs. Other surgeries that have been performed using robots include hysterectomy,[18,19] nephrectomy,[20,21] radical cystectomy,[22] urologic,[23] pancreaticoduodenectomy,[24] transhiatal oesophagectomy[25] and adrenalectomy.[26]

In addition to the Da Vinci system, a number of other robots have been designed and built for surgical purposes: in 1978 PUMA robot,[27] in 1980 PROBOT,[28] in 1992 ROBODOC,[29] in 1996 AESOP,[30] and in 1998 ZEUS.[31] With the development of the first version of the Da

Vinci robot in 2000, a major breakthrough occurred in robotic surgery. The Trauma Pod system has recently introduced a further advance in fully automatic surgery.[32]

The advantages and disadvantages of robots created for eye surgery have been investigated[2] and further reviewed.[33–36] Smet et al. in[35] reviewed three designs of intelligent surgical tools for eye surgery such as steady hand, co-manipulation devices and tele-manipulators using either a fixed or virtual remote centre of motion. Robotic vitreoretinal surgery using different robotic-assisted surgical systems, such as Da Vinci, Johns Hopkins Steady-Hand Eye Robot (SHER), Intraocular Robotic Interventional Surgical System (IRISS), and intelligent instruments provide the surgeon with real-time physiological information during each surgical manoeuvre, have been reviewed.[4]

In[36], some of the benefits of robotic eye surgery were examined. It was concluded that despite barriers such as cost and availability, future benefits of robotic eye surgery outweigh such barriers.

This review will consider the following:

- The background of robotic eye surgery robots and future prospects and challenges.
- Survey of eye diseases that can be treated with robotic surgery.
- Survey of available technologies for robotic eye surgery.
- Review of features of robotic eye surgery, including time and costs.
- Presentation and review of suitable controller conditions.

2 | BACKGROUND AND CURRENT STATE OF ROBOTIC EYE SURGERY

2.1 | Comparison of eye surgical robots

A comparative analysis based on accuracy, Degree of Freedom (DoF), price, average speed, multitasking, reduced tremor, learning curve, vision methods, automation, and the Remote Centre of Motion (RCM) is shown in Table 1. Accuracy is vital for robotic eye surgery because the eye is a small organ, and the proportion of the eye that is dedicated to high image quality is even smaller. Robots for eye surgery must have a sufficient level of accuracy, which depends on the type of eye surgery and will be discussed in the next section.

A suitable surgical robot should have the ability to move in different directions to allow for flexibility within the surgical procedure. One of the most important challenges in adopting surgical robots for eye surgery is the cost of the robot(s) and whether this offers better value than non-robotic surgery. The speed of movement of the robot and the ability to multitask are also critical features as high-speed robots can reduce the time required for surgery, and multitasking can permit a robot to be used for a number of different surgeries. Surgical robots should reduce or eliminate any tremors that arise in the hand of the surgeon in order to improve the accuracy of surgery. The required learning curve should be reasonable to allow the surgeon to feel comfortable with the robot and yet not prolonged to become unnecessarily costly. A learning curve is defined as the time difference between the times taken to complete the tasks during the first and the final trials. The learning curve should have a reasonable duration to allow the surgeon to feel comfortable with the robot and yet not too prolonged so as not to become unnecessarily costly. It is vital for the surgeon to be able to see the position of the robot and the directions in which it moves, so the optics of the robotic system must be at a very high level; the 3D high-definition system is currently the best available.

An RCM is defined as a remote fixed point around which a mechanism or part of it is able to rotate, and there is no physical revolute joint over there.[37,38] Likewise, the position and type of the RCM are very important since this is the part of the eye surgical system which performs the surgery. Especially in robotic eye surgery, the RCM in eye surgical systems plays a significant role because of the sensitivity of the human eye. Using a suitable RCM mechanism can increase the safety and reliability of the surgical systems.[39] The RCM mechanisms are used for preventing excessive forces during eye surgery.[39] There are some risks of unintentional trauma if a suitable RCM has not been used for eye surgery. Finally, the level of automation is an important consideration and will depend on how the surgery is to be applied. These levels include non-automatic, semi-automatic, and fully automatic. For remote surgery, fully automatic robots may be the best option, but this may not necessarily be the best option for other forms of surgery.

2.2 | RAMS

In 1996, the Robot-Assisted Microsurgery (RAMS) was designed, and a simulated eye microsurgery procedure was successfully demonstrated using the RAMS telerobot system.[34] The RAMS utilised the master-slave concept, which involves tracking the moves made by the surgeon's console (master part). The robot arms (slave part) consist of associated motors, encoders, gears, cables, pulleys and linkage parts. The tip of the robot moves under computer control, aligning precisely with the hand movements of the surgeon.[34] One of the studies investigating the feasibility of tele-robotic microsurgery using RAMS reported that the RAMS slave robot was unsuited to holding a needle and suturing. Figure 1 shows the RAMS telerobot system.

One of the disadvantages of this robot is that it has no mechanical Remote Centre of Motion (RCM) which is necessary for Minimally Invasive Surgery (MIS), such as vitreoretinal surgery.[40] The RAMS is too slow as its average speed is 0.4 mm/s[41] and has a long learning curve.[42]

In[41], a newly developed microsurgical robot research platform (MRRP) for RAMS was described. The MRRP platform consists of a slave robot with bimanual manipulators, a vision part that can be utilised to train microsurgical skills, and two master controllers. The positioning accuracy of MRRP is sub-micron scale.[41]

TABLE 1 Comparison of different eye surgical robots.

RCM	Automation (automatic)	Vision	Learning curve	Reduced tremor	Multitask	Average speed	Price (Per unit)	DoF	Accuracy	Features	
No mechanical RCM	Non	3D	Long	Yes	Yes	0.4 mm/s	*	6	10–30 µm	RAMS[34,40–42]	Robot name
*	Non	Microscope	Long	Yes	Yes	*	*	5	70 µm	ORP[43,44]	
Unmodifiable	Semi	HD 3D	Short	Yes	Yes	170–370 mm/s	$1–2.5 million	7	1.47 mm****	Da Vinci Si[77–81]	
Unmodifiable	Semi	HD 3D	Short	Yes	Yes	170–370 mm/s	$1–2.5 million	7	1.47 mm****	Da Vinci Xi[77–81]	
Adaptable	Semi	**	Long	Yes	Yes	*	*	6	10 µm	HSS[2,50]	
Mechanically fixed	Semi	HD 3D	Long	Yes	Yes	25 mm/s	*	7	10 µm	IRISS[4,52]	
***	***	***	Short	Yes	Yes	8–12 Hz	*	6	0.3 mN	Micron[53,54]	
Parallelogram mechanism-based	Semi	3D	Short	Yes	Yes	415 mm/s	*****	6	2–10 µm	RHAS[55,57]	
Flexible in location	Non	surgeon's eye	Short	Yes	No	1–10 mm/s	*	5	2–5 µm	SHER[58–63]	
Reachable by frames	Non	PS3 eye camera	Short	Yes	No	*	*	2	0.1–1 mm	ARAS-DIAMOND[40,64–67]	

Note: *This information is not available. **The HSS is a capable tool added to surgical robots. ***Vision, RCM and automatic are not defined for Micron because this is an instrument. ****For more information see[81]. *****The price of RHAS is reported as being lower than the Da Vinci system.[57]

2.3 | ORP

The first clinical attempt to inject a drug into the eye using a robot was made in 1998 with the Ocular Robotic Prototype (ORP) robot.[43] ORP is a spherical robot with micron precision. Figure 2 shows the ORP robot with a drug delivery injector head and glass pipette. The feasibility and accuracy of ORP for the retinal vessel sheathotomy, posterior vitreous detachment, and retinal vessel microcannulation were investigated and found to be successful for 10 of 12 attempts at vitreoretinal surgery.[44] The ORP has sufficient accuracy of 70 μm,[44] but its learning curve is long,[43] and its vision tool consists of a single microscope.[43]

2.4 | Da Vinci

Figure 3 shows a sample picture of the Da Vinci surgical system, which has been used for corneal suturing,[45] cataract[46] and pterygium surgery.[47] Penetrating keratoplasty was successfully performed on twelve corneas, and the system was reported to provide the necessary dexterity needed to perform the range of different surgical steps.[45] This study was the first eye surgery that used the Da Vinci Xi robot.[45] Subsequently, the Da Vinci Xi surgical system was used for twenty-five successful cataract operations[46] to remove a pterygium.[47] The Da Vinci system price is one of the challenges of this robot to use for eye surgery, but a greater disadvantage is the mechanical structure and its lack of suitability for eye surgery. The purchasing price per unit ranges from 1 to 2.5 million dollars.[48] The RCM is too proximal from the surgeon compared to conventional manual surgery, where the surgeon directly handles the instruments. This is an important issue for eye surgery; the Da Vinci system has an RCM specifically designed for laparoscopic surgery, which does not meet the requirements of eye surgery. In addition, it has a mechanical RCM that cannot be modified.[46]

Da Vinci robots have been used to develop the fully automatic surgical system called the Trauma Pod,[32] which is a complete surgical system that includes systems of management and display, control and supervision, monitoring, robotic hand washing nurse, device replacement, device delivery, and drug supply.[32,49]

FIGURE 1 RAMS telerobot system.[34]

FIGURE 2 Ocular Robotic Prototype (ORP) with a drug delivery injector head and glass pipette.[43]

2.5 | HSS

The Stewart platform is a six DoF parallel mechanism which is placed on a platform with respect to a base. The Stewart platform consists of translation in the *x*, *y* and *z* directions and provides orientation in roll, pitch, and yaw angles. The Hexapod Surgical System (HSS) is a type of Stewart platform that is shown in Figure 4.[50] HSS can be mounted to

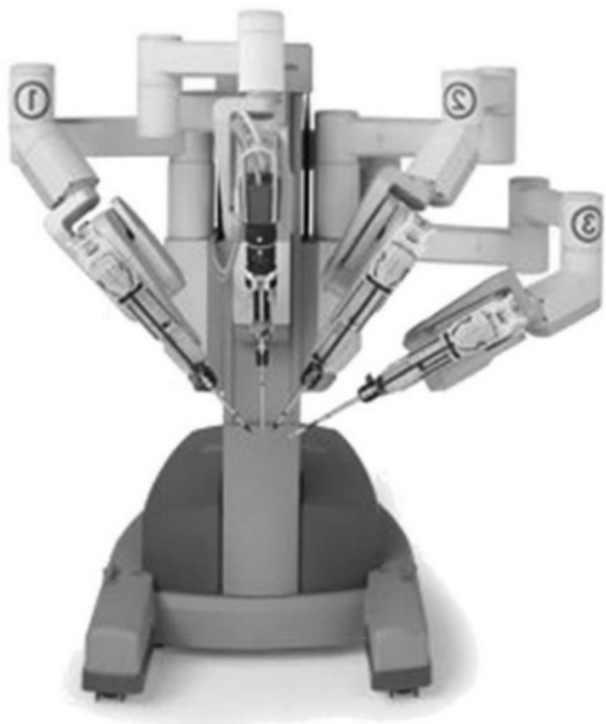

FIGURE 3 Da Vinci surgical system.[8]

different robots, and the Da Vinci system is a good choice for attaching to HSS. HSS is the first robot that has been used to complete an ocular procedure. This robotic system has the potential to provide a robotic surgical solution for both intraocular and extra-ocular sites.[50] The HSS provides an RCM dedicated to robotic eye surgery with reasonable accuracy.[50]

2.6 | IRISS

The IRISS or Intraocular Robotic Interventional Surgical System is a semi-automatic robot with two joysticks to control two independent arms holding the surgical instruments. Each arm has seven DoF that provides significant movement for surgical manoeuvres.[4] The schematic of IRISS with the seven DoF around the RCM is shown in Figure 5.[51] This system successfully performed intraocular procedures on sixteen porcine eyes.[52] The IRISS has a spherical mechanism that can kinematically guarantee a mechanically fixed RCM which provides an important advantage for this robot.[51] The long learning curve of IRISS is one of its disadvantages.[52]

2.7 | Micron

Micron is a freehand active tremor-cancelation instrument. Some advantages of Micron are the capability of motion sensing, a more natural feel, actuation of compensatory tip deflections, and filtering of erroneous motion. Micron can detect the translation and rotation motions in six DoF[53] and can be combined with other robots. Gonenc et al.[54] developed a system for membrane peeling that combined the Micron with force-sensing motorized micro-forceps. This combination is a module that provided force-sensing capabilities in two DoF and with a resolution 0.3 mN. Figure 6 shows this combined module.

2.8 | RHAS

The robot for Haptically Assisted Surgery (RHAS) is one of the newest robots that has been designed for eye surgery. This robot is also known as EyeRHAS. This robot was developed by Meenink et al. in 2013 and was found to have an accuracy of 2–10 μm.[55] This precision is calibrated at the instrument's tip when positioned at the retina. The improvement is 10 to 20 times that of manual surgery.[55] It reduces the tremor by a factor of 10 or greater in high-precision vitreoretinal surgery.[56] Figure 7 shows the RHAS robot, which was developed using a parallelogram mechanism-based system for its RCM.[57] This type of RCM mechanism has the advantage of appropriate dexterity. However, this needs to be balanced against

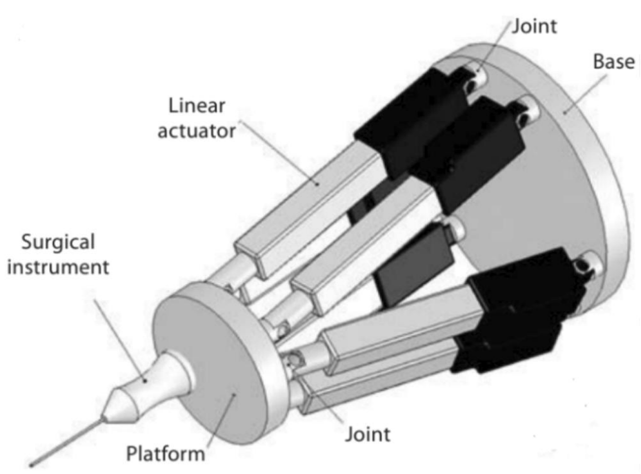

FIGURE 4 Hexapod Surgical System (HSS) based on Stewart platform.[50]

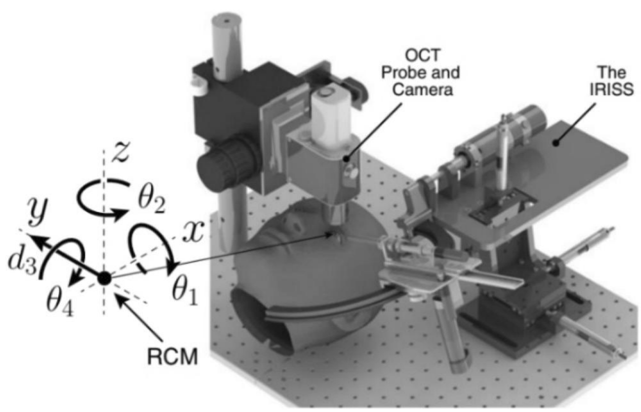

FIGURE 5 Schematic of Intraocular Robotic Interventional Surgical System (IRISS) robot and 7 Degree of Freedom (DoF) around Remote Centre of Motion (RCM).[51]

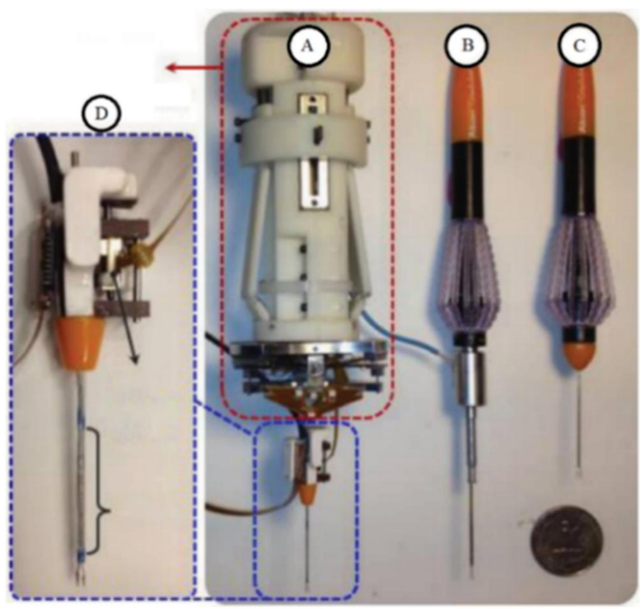

FIGURE 6 (A) Micron, (B) 2 Degree of Freedom (DoF) force-sensing micro-forceps, (C) disposable forceps, and (D) motorized force-sensing micro-forceps magnified.[54]

disadvantages such as intervention between linkages, singularity and lack of absolute rigidity.[40]

2.9 | SHER

Steady-Hand Eye Robot (SHER) is a competent microsurgery platform.[58] The SHER is a collaborative robotic system in which surgeons and robots control the surgical tool.[59] This robot was developed at Johns Hopkins University.[60] The first motivation for designing this robot was for vitreoretinal surgery, which has been further developed.[58–62] An RCM mechanism has been developed for the SHER,[61,62] as shown in Figure 8. This RCM mechanism can be located in a free space approximately 100 mm from the spatial frame of the robot.[63] The speed of SHER is one of its disadvantages, as the speed of this robot is reported to be between 1 and 10 mm/s.[62] Additionally, this robot is not a multitask robot.

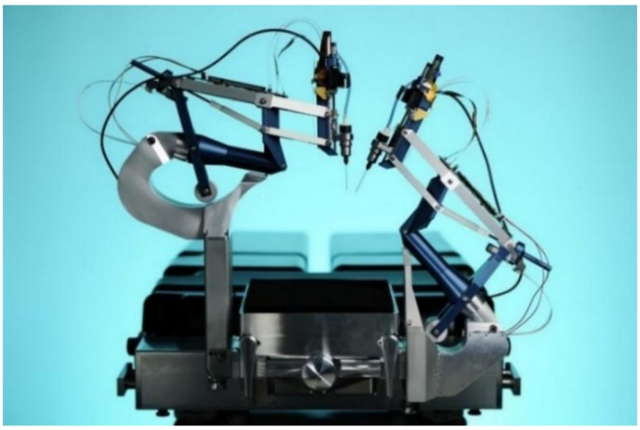

FIGURE 7 The RHAS robot.[55]

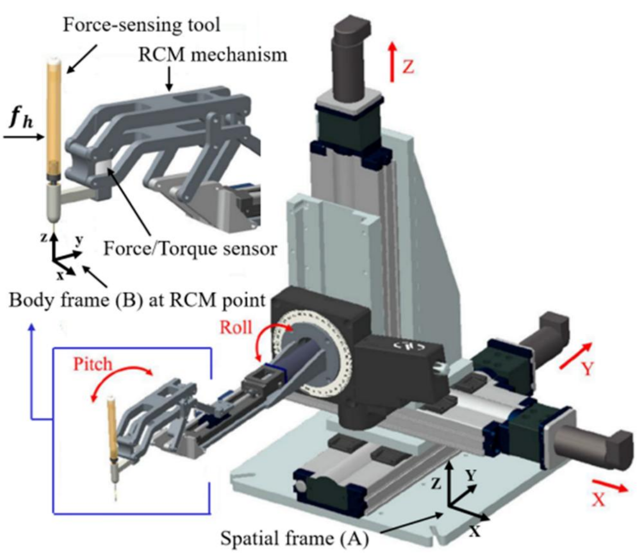

FIGURE 8 The Steady-Hand Eye Robot (SHER) with Remote Centre of Motion (RCM) mechanism.[61]

2.10 | ARAS-DIAMOND

ARAS-DIAMOND is a spherical parallel manipulator robot developed at K.N. Toosi University of Technology.[64] The RCM of ARAS-DIAMOND serves as the origin of the frames. This means that the RCM is located at a suitable point that is reachable by all the joints.[40] This robot is shown in Figure 9. One of the advantages of this robot is the use of visible light filters in front of the camera.[65] The parallel structure of the mechanism has two important features that provide the inherent stiffness, which is appropriate for sensitive and precise procedures required in eye surgery; dexterity and the compact size are further advantages.[66] The ARAS-DIAMOND has only two DoF, which is one of its disadvantages,[67] and it is not an automatic robot.[64–66]

2.11 | Cataract surgical system

In robotic cataract surgery, the accuracy and RCM mechanism of the robot play significant roles. A cataract surgical system was developed by Francom et al.[68] This system has seven DoF with sub-millimetre-size accuracy and a parallel RCM mechanism. This design enables the robot to reach all parts of the eye needed to perform cataract surgery. The study showed that sub-millimetre accuracy is sufficient for cataract surgery.[69]

3 | TYPES OF EYE DISEASES THAT REQUIRE SURGERY

3.1 | Cataract

One of the most common eye diseases particularly associated with ageing is cataract[70,71] and treatment to remove the cataractous lens

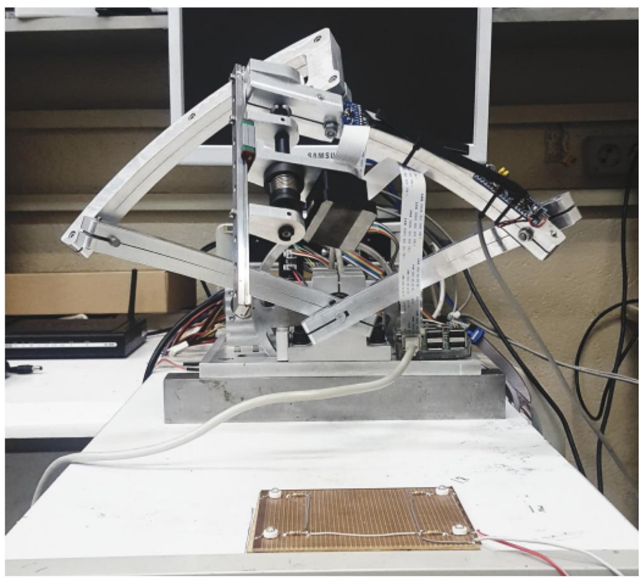

FIGURE 9 ARAS-DIAMOND.[65]

is the most frequent eye surgery performed globally. It lends itself to the application of robotic surgery by virtue of its relative simplicity. Yet, disadvantages of surgical robots, such as costs and learning curve, have thus far limited their use for cataract surgery.[46] Tristan et al. in46 have used the Da Vinci Xi surgical system for simulation in cataract surgery. In their study, the authors have mentioned that the Xi model has some limitations, such as the RCM being too proximal when compared with conventional manual surgery.

Nevertheless, the feasibility of using the Da Vinci Xi for cataract surgery was acknowledged.[46] Mature cataracts lead to the complete opacification of the lens.

The RCM is used to position the robot and to provide rotation around the incision point in order to prevent potential eye damage.[37] Spherical, parallel, and hybrid RCM mechanisms have been reviewed. The authors concluded that the hybrid RCM mechanisms are most suitable for eye surgery since these mechanisms have a greater number of DoF.[37]

Subsequent studies have reported results of semi-automated cataract surgery.[51,68] Wilson et al.[51] developed the RCM limitation using the IRISS surgical robot for cataract surgery. For complete robotic cataract surgery, two surgical manipulator arms that work simultaneously are required as well as a range of motion up to 180° around each rotational axis, two RCMs in close proximity and appropriate surgical instruments.[68]

3.2 | Pterygium

A pterygium is a wing-shaped, fleshy, fibrovascular overgrowth of subconjunctival connective tissue that extends across the limbus and over the cornea (Figure 10). The feasibility of pterygium surgery has been shown using the Da Vinci Si on twelve porcine eyes.[72] One of the major limitations of this study was that it was performed on non-living eyes.[72] In addition, the time taken for the surgery was 36 min which is longer than manual surgeries. The authors indicated that the RCM of Da Vinci Si was too proximal for this type of condition when compared to common manual surgery (non-robotic).[72]

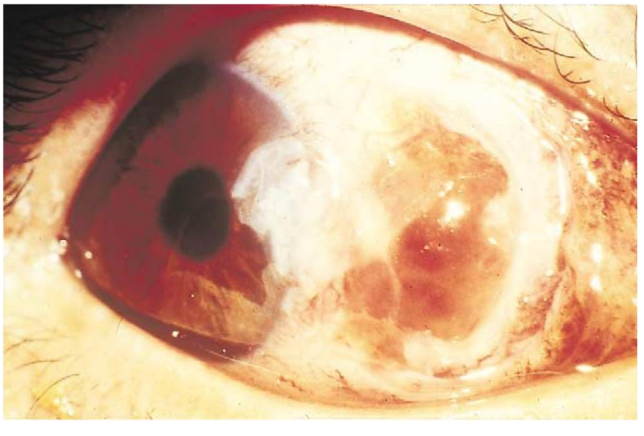

FIGURE 10 A pterygium encroaching onto the cornea surface.[73]

The first human pterygium surgery on a 73-year-old patient with nasal and temporal pterygia used the Da Vinci Si surgical system.[47] The operative time of this procedure was 60 min and 30 s, which was significantly longer than the time taken for manual (non-robotic) pterygium surgery and the patient was discharged within 24 h.[47]

The Da Vinci Si surgical system allows the surgeon to change the angles of the instruments during the surgery. This feature is one of the significant advantages of the Da Vinci robot for pterygium surgery.[47] In addition, sufficient DoF, the RCM mechanism of the robot, and millimetre-size accuracy render this system suitable for pterygium surgery.

3.3 | Vitreoretinal

Vitreoretinal disease affects either the vitreous, the retina or both. The retina is a light and sensitive layer behind the eye which focuses on images and transmits that information to the brain. This transmission is done via optic nerves. The vitreous also is a clear gel that fills the eye's posterior chamber.[74]

The first experimental robotic vitreoretinal eye surgery performed on a human eye demonstrated the successful removal of a 10-micron thick membrane from the retina.[75] One of the challenges is the time of surgery to minimise discomfort for both the surgeon and the patient and the prevention of damage to the delicate ocular system from a prolonged surgical procedure.[75] One of the challenges of robotic surgery for vitreoretinal conditions is that the surgical system must have micron-sized accuracy, and a suitable RCM and viewing system are vital.[75]

Vitreoretinal surgery was tested on a porcine eye model with a master-slave surgical system.[76] A 3D microscope view was employed for the surgeon to control the slave part by moving the master unit.[76] The results of this study showed superior operability compared with a traditional manual procedure.[76] One of the problems mentioned in the study was the time taken for the initial positioning of the tips of the surgical tools at the insertion points of the eye. This time was 8–10 min which should ideally be reduced to 1–2 min.[76]

3.4 | Corneal laceration

Corneal lacerations are the most common cause of unilateral blindness in the United States.[82] Tsirbas et al. performed an ocular microsurgery for repairing a corneal laceration in a porcine model with the Da Vinci surgical system.[5] Figure 11 shows corneal laceration on a canine eye 24 h after injury.

The Da Vinci surgical system has been employed to repair corneal laceration in a porcine model.[5] This successful experiment has shown that using the Da Vinci surgical system for corneal laceration surgery is feasible.

Some disadvantages of robotic surgery for corneal laceration are the price of the Da Vinci surgical system and the speed of suturing, which is slower than other surgical methods.[5] The average

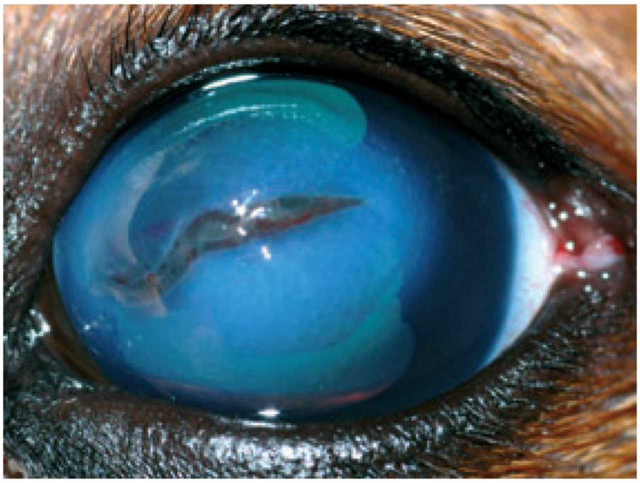

FIGURE 11 A corneal laceration on a canine eye 24 h after injury.[83]

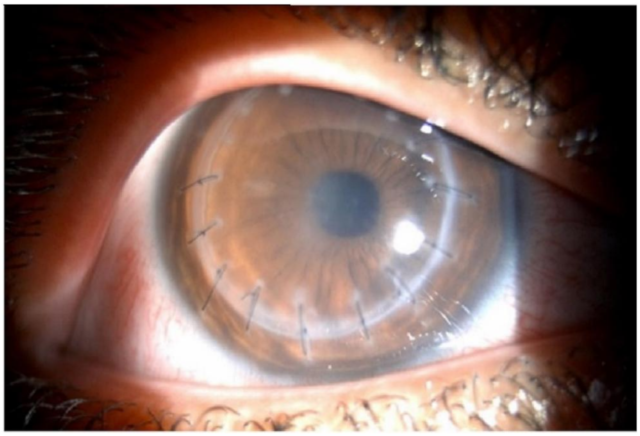

FIGURE 12 A corneal transplant in the right eye of an 18-year-old male.[87]

robotic surgical time for the placement of each suture is 207 s with the Da Vinci system compared to 62 s with conventional microsurgery.[5]

The feasibility of tele-robotic microsurgical repair of corneal lacerations in an animal eye model has been shown.[84] In this study, 5 mm central full-thickness corneal wounds were fashioned in five enucleated rabbit eyes and repaired remotely using the tele-robotic system, with five additional eyes also repaired by hand using a standard technique.[84] One of the challenges that were reported was the mean surgical time of 80 min for robotic surgeries (range 50-130) compared to 8 min (range 7–9) for surgeries conducted by hand and the required micron-sized accuracy.[84] A possible cause of such a discrepancy in time taken for surgery between robotic and manual procedures may be the relative inexperience of surgeons with robotic systems and the need for more training in robotic surgery. As the use of robots for surgery becomes more widespread, the duration of robotic surgical procedures may decrease.

3.5 | Corneal transplants

Corneal transplantation requires 16 sub-millimetre-sized sutures that are generated around the circular-shaped graft cornea.[85] Figure 12 shows a corneal transplant performed on the right eye of an 18-year-old male. The generation of uniformly shaped sutures is a challenge in corneal transplantation.[85] Eye surgical robots are a good choice for suturing the cornea because these robots are capable of conducting tasks repeatedly. A corneal suturing robot that can produce sutures of the desired shape with high uniformity has been described and shown to generate sutures with a standard deviation of 108 μm in length and 36 μm in-depth.[85] The results of this study indicated that the corneal suturing robot has the appropriate suture shape that can be generated for each patient.[85] Micron-size accuracy is one of the most essential features of these systems.

The Da Vinci surgical system was employed for penetrating keratoplasty in porcine and human eyes.[86] Surgery time, learning curve and surgical skills were the challenges mentioned in this study.[86]

3.6 | Eyelid surgery

Eyelid surgery is used for conditions like ptosis (drooping eyelids) or for cosmetic purposes.[88] Eye surgical robots can be employed for incision, fat removing and suturing. The ability of robots to suture with micron-size accuracy has been demonstrated,[85,86] also indicating the potential for performing eyelid surgery.

3.7 | Extra-ocular muscles

The human eye has six muscles which allow the eye to move and rotate. Extra-ocular muscle surgery is used to correct strabismus or squint.[89] The Da Vinci Xi surgical system was employed to investigate the feasibility of strabismus surgery.[90] In this study, strabismus surgeries were performed on six strabismic eye models. The authors reported that all six procedures were performed successfully.[90] Similar to cataract surgery, the required accuracy for extraocular muscle surgery is sub-millimetre size.

4 | AVAILABLE TECHNOLOGIES

4.1 | Sensors

One of the most important parts of each robot is the sensors. Sensor technologies have advanced in recent years and have been employed for a wide range of purposes. Table 2 shows the variety of applications of sensor technology in surgical robotics.

TABLE 2 The used sensors for surgical robots.[91–93]

Vision	Touch			Position	Motion	Speech	Sound
CMOS	Force feedback	Pressure sensors	EMG	Inertial devices	LIDAR	Micro speakers	Microphones
CCD image sensors	Haptics sensors		Neural probes	Encoders	GPS		
				Gyroscopes	Laser ranger		
				Accelerometers	Torque sensors		
					Ultrasonic sensors		

During surgery, the surgeon needs excellent eyesight requiring a correctly placed sensor that provides the requisite high-quality vision. The human eye is delicate, and any surgical tool needs to apply the right amount of pressure to permit the surgery to be performed without damaging the eye. Hence, touch sensors are very important for robotic eye surgery, as are accurate position sensors and motion sensors. For example, torque sensors are beneficial for minimally invasive surgeries. One of the most important challenges in eye surgery is the time delay in data transfer. In some cases of remote eye surgery, speech and sound sensors may also be required but have not been used widely in robotic eye surgery.

One of the most important sensors in eye surgical systems are force sensors. Given the need for the surgical robot to make contact with the eye, force sensors are of critical importance.[94,95] A force sensor with four DoF has been developed and described with experimental validation.[94] This sensor consists of four capacitive transducers, and all the transducers, including analog signal processing units, are embedded in small surgical instrument tips.[94] Force sensors placed at the instrument's tip can measure accurate force information without any notable concerns. Hence, the sensor can read multidimensional contact forces accurately because there is direct contact with the tissue.[94] Table 3 shows the types of force sensors used in various studies.

4.2 | Actuators

Actuators are critical components of surgical robots. One of the technical challenges in robotic eye surgery has been developing the quality of actuators.[96–98] An important aspect that should be mentioned when considering robotic eye surgery is the overall size of the eye compared to the surgical system; the impact of actuators on the overall size of the eye surgical robots and their role in the DoF of the robots are vital.[99]

A Shape Memory Alloy (SMA) is considered to be one of the most suitable actuators for robotic eye surgery where high-performance output is required.[99] This type of actuator is reviewed in detail.[99] One of the most important aspects of SMA is that it can generate forces 400 times higher than magnetic actuators and 150 times higher than hydraulic actuators. However, SMAs have a slow response time and low power density. The speed of response in the SMAs depends upon its bias force, size and shape.[99]

The cable-driven parallel mechanisms (CDPMs) use a plurality of actuation cables that act as part of a parallel kinematic structure in order to manipulate an end-effector in space. Changing the length of the actuation cables controls the end-effector pose.[100] The CDPM actuators have some important features that can be useful in robotic eye surgery, such as efficient force transmission, high end-effector payloads, and a sizeable configurable instrument workspace. These types of actuators and some of the advantages and disadvantages of their applications have been reviewed.[100] These actuators are unsuitable for eye surgery because cable stretch causes them to lack sufficient accuracy.

The transmission systems in all surgical techniques and all types of actuators such as SMA, cable, and fluidic types need a connection to the power supply in order to drive the surgical tools; the means of transmission is one of the challenges in all robotic surgical systems.[98] A magnetic actuator does not require a link for the actuation of the surgical tools because it uses the magnetic field.[98] This offers one of the most significant advantages of magnetic actuators because the linkage between the power supply and the actuator is a significant challenge. Hence, magnetic actuators are a suitable choice for eye surgery.

Some smart materials have been used for developing actuators. Piezoceramics are a type of smart material that expand or contract when an electrical voltage is applied.[101] The piezoelectric actuators were built by piezoceramics and are a type of common actuator in robotic surgery.[101] A micro positioning piezoelectric actuator has been described, and a Long Short-Term Memory artificial neural network algorithm has been designed to control these actuators in robotic eye surgery.[101]

The cable-driven mechanism, flexible fluidic, smart material, and magnetic actuators have been reviewed, and their advantages and disadvantages have been discussed[98] and are summarised with SMA actuators in Table 4. A further detailed description of actuators can be found in the literature.[102–105]

4.3 | Communication protocols

Since many surgical robots use the master-slave concept, communication protocols are very important in robotic surgery. One of the challenges that may occur during robotic surgeries is the time delay, and communication protocols play a key role in minimising time

TABLE 3 Force sensors for robotic surgical systems.[91,94,120,125–144]

Authors	Year	Range	Error/Accuracy	Features
Eltaib et al.[127]	2000	0–75 mV	*	Capacitive, capacitance <60 pF, robust against surgeon's hand tremors
Dargahi et al.[126]	2000	2 N	Error = 0.2 N	Piezoelectric, sensitive
Kattavenos et al.[133]	2004	245–1080 kPa	*	Piezoresistive, sensitive, small, lightweight, inexpensive
Ottermo et al.[139]	2004	10 N	*	Piezoelectric, mechanical robustness
Qasaimeh et al.[140]	2008	0.01–4 N	*	Piezoelectric
Trejos et al.[143]	2009	Lateral = ±5 N Axial = ±25 N Rotation = ±80 Nm	RMSEforce = 0.35 N RMSEtorque = 1.5 Nmm	Piezoresistive, force and torque sensor
Golpaygani et al.[145]	2009	0.1–0.7 N	Sensitivity = 0.83 kHz/N	Capacitive, low mass, low size and low power
Jalkanen et al.[130]	2010	2–10 kPa	*	Piezoelectric
Kalantari et al.[132]	2011	0.1–2.5 N	RMSE = 0.611 N	Piezoresistive
Baki et al.[125]	2012	2 N	Resolution = 5 mN	Piezoresistive, 3 DoF, Bandwidth>1 kHz
Talasaz et al.[142]	2012	Palpation = ±4–5 N Gripping = ±0.5 N	*	Capacitive, 3 DoF
Hwang et al.[129]	2013	0–3 N	Error = 0.4%	Piezoresistive, linearity >99.6%, good resolution, low cost, high accuracy, easy calibration of temperature change
Lee et al.[137]	2014	3–30 kPa	Sensitivity = 0.38 mV/kPa	Piezoelectric, excellent linearity, force and Pressure sensor
Li et al.[138]	2015	Axial = ±3 N Radial = ±1.5 N	Resolutionaxial = 5% Resolutionradial = 1%	Piezoresistive, 3-axis
Kim et al.[94]	2015	x = ±2.5 N y = ±5 N z = ±2.5 N Grasping = ±5 N	RMSEx = 0.0837 N RMSEy = 0.0732 N RMSEz = 0.114 N RMSEgrasping = 0.0957 N	Capacitive, 4 DoF
Hessinger et al.[128]	2016	10 N	Maximal = 4.92% Random = 1.13%	Piezoresistive, 6-axis, diameter 12 mm, force and torque sensor
Zhang et al.[144]	2017	<500 kPa	*	Piezoelectric, simple structure
Kim et al.[134]	2017	±1.5 N	Average relative error of force = 5.5%	Capacitive, 6-axis force and torque sensor, diameter 10 mm, height 10 mm, weight 1.25 g
Rado et al.[141]	2018	0.01–20 N	*	Piezoresistive, diameter 0.5 mm, 3D
Ju et al.[131]	2019	0–1.7 MPa	Error <2.5%	Piezoelectric, Width = 1 mm, Thickness = 0.2 mm Diameter = 8 mm
Kim et al.[135]	2020	x = ±0.3 N y = ±0–0.5 N z = ±0–0.9 N Gripping = ±0–0.9 N	Error = 1.9%	Capacitive, 4 DoF, force and torque sensor
Lai et al.[136]	2021	x = 0–6 N y = −3.5–3 N z = ±4.5 N	Error = 4.50–6.18%	6 DoF force and torque sensor, Diameter = 0.4 mm
Girerd et al.[120]	2021	2–8 N	Error = 0.01 N	Wireless, Width = 9.85 mm, Length = 80 mm, Height = 0.64 mm, trace width = 2.5 mm

Note: *This information is not available.

delays. Because communication protocols incorporate a wide range of concepts and definitions, the full extent of these protocols and their applications is beyond the scope of this paper.

Briefly, these protocols consist of Constrained Application Protocol (CoAP), MQ Telemetry Transport (MQTT) and MQ Telemetry Transport for Sensor Nodes (MQTT-SN).[106] MQTT-SN was reported

TABLE 4 Advantages and disadvantages of actuators.[98,99]

Actuator type	Advantages	Disadvantages
Cable-driven mechanism	Range of pulley to cable, lightweight, miniature, flexibility, safe on the human body	Expensive replacement costs, steel cable failure, nonlinear friction, backlash hysteresis, poor force delivery, difficulties in modelling and control
Flexible fluidic	Made of biocompatible material, shave, flexibility, providing high force, small size	Bulky, complex, high power supply requirements, unsafety, difficulties in modelling and control
Smart material	High corrosion resistance, biocompatible-nonmagnetic, very high work density, significant displacement, large force	Small strain, low actuation frequency, difficulty in the accurate control, narrow bandwidth, long cooling time
Magnetic	Wirelessly, high speed, high capacity, large power	High hysteresis, nonlinearity, uncertainty, high cost, high risk of tissue damages
SMA	High-performance output, more generating force, good fatigue life	Slow response, low power density, high power for heating

to provide a 30% faster performance than CoAP when transmitting the same payload.[106]

A review of the telecommunication method for the Zeus surgical system with applications for tele-surgery has indicated that computers of the Zeus surgical system have standard ruggedised Pentium-based compact-PCI units with 100 base-T ethernets for attachment to a network.[107] These systems run the VxWorks real-time operating system.[107]

A communication protocol must have some requirements for robotic eye surgery; some of these requirements have been described, and the authors tried to reduce the complexity of a real-time communication protocol.[108] A CAP/CAB architecture was employed to evaluate some real-time communication protocols using robotic eye surgery as a case study for this research.[108] The requirements for a suitable communication protocol for robotic eye surgery include a cycle time of less than 1 ms, real-time video streaming, one Gigabit/s bandwidth for big data, wireless communication, and hot-plugging availability.[108] In this study, some of the protocols were evaluated in accordance with these requirements, and after evaluation, the Ethernet POWERLINK was found to fulfil them all. Further detail about the communication protocols can be found in the literature.[109–112]

Another suitable communication protocol for surgical robots is based on Transmission Control Protocol/Internet Protocol (TCP/IP) peer-to-peer network communication.[113] In this communication protocol, the minimum data transmission unit is defined as a message. Zhen et al. in[113] have developed this communication protocol and mentioned that this protocol is open, simple, and extensible, as well as meeting the requirements of delay of data transmission within a normal range of the real-time capability.[113]

TCP/IP is the most common communication protocol in tele-surgery.[114] The User Datagram Protocol (UDP) is a connectionless protocol that runs on top of IP networks. UDP is another common communication protocol in surgical robots.[114] One of the disadvantages of this communication protocol is that the UDP/IP does not provide error recovery services, offering instead a direct way to send and receive datagrams.[114]

4.4 | Control algorithms

The removal of surgeon hand tremors is critical for robotic eye surgery. In control engineering, this tremor is referred to as external disturbance, which should be robust against uncertainties. There are three types of uncertainties in nonlinear systems: unknown parameters, uncertain nonlinearities, and unmodelled dynamics.[115]

Another issue that needs to be considered in designing controllers for robotic eye surgery is reaching time. The reaching time indicates the stability speed of the system. Methods have been developed for setting the reaching time, and these consist of finite-time,[116] fixed-time[117] and predefined-time[118] methods.

Smooth tracking means that the surgical system tracks the desired trajectory without any overshoot. Smooth tracking is very important in robotic eye surgery because a single overshoot risk injuring the eye.

The chattering problem can be accrued when we use some functions, such as signum or saturation in the controller. This can be very dangerous for surgical system actuators due to high-frequency switching; it can also increase the system maintenance costs.[119]

The most critical conditions for a suitable control method, described at the beginning of this section, will be used to compare some developed control methods used for eye surgery. Table 5 shows the advantages and disadvantages of some control methods.

The Proportional Integral Derivative (PID) controller is the most common control method in surgical robots. The standard PID is the main controller in IRISS and is employed for creating the command torque for servo motors of the IRISS surgical system.[68] The PID controller is a non-model-based method that can reduce hand tremors. This controller has three tunable parameters that are easy to tune. However, as mentioned, a suitable control method for eye surgery must have certain conditions such as reaching time, smooth tracking and robustness against internal and external disturbances that the PID does not provide, rendering the PID controller unsuitable for robotic eye surgery.

The Model Predictive Control (MPC) method is another common control algorithm used in robotic systems. The MPC has some

TABLE 5 Comparison of control algorithms of eye surgical robots.

PD H∞-based[64]	FOBSMC[148]	SSMC[149]	Observer-based impedance-control[147]	PD[146]	PID[68]	Controller
ARAS-diamond	Manipulator robots	Two-link manipulator robot	SMOS	RHAS	IRISS	Eye surgical robot
Experimentally	Simulation	Simulation	Simulation	Experimentally	Experimentally	Implementation
Robust, hand tremor reducing, easy for tuning, chattering-free, singular value reduced, good accuracy	Robust, hand tremor reducing, more control parameters, good tracking, lyapunov-based, smooth control, observer-based, velocity sensorless, chattering-free, disturbance observer, non-singular, good accuracy	Robust, hand tremor reducing, more control parameters, good tracking, lyapunov-based, smooth control, good accuracy	Robust, hand tremor reducing, more control parameters, observer-based, fewer number of used sensors, good tracking, adaptable, lyapunov-based, good accuracy	Non-model-based, robust, hand tremor reducing, easy for tuning, chattering-free, good accuracy	Non-model-based, robust, hand tremor reducing, easy for tuning, chattering-free, good accuracy	Advantages
Suitable for linear dynamics, model-based, knowledge needs about uncertainties and external disturbances, using derivative errors	Model-based, using derivative errors, hard to following mathematically, overshoots possible	Model-based, chattering, using derivative errors, hard to following mathematically, high gain output, unused of capacity integrator	Chattering, model-based, hard to following mathematically, singularity possible, overshoots possible, using derivative errors, knowledge needs about uncertainties and external disturbances	Setting the reaching time, slow tracking, overshoot, low number of control parameters, using derivative errors, unused of capacity integrator	Setting the reaching time, slow tracking, overshoot, low number of control parameters, using derivative errors	Disadvantages

benefits which can be helpful for robotic eye surgery. It was implemented for aiming the force control in teleoperated MIS with consideration given to the time delay.[93,120] The comparative robustness of the MPC is greater than that of the PID in MIS applications.[121] The MPC was tested successfully in some types of robotic surgeries[122–124] and it has capability and promise for eye surgery.

Abedloo et al. in[146] have mathematically modelled the RHAS robot. In this study, the authors used the PD controller for the experimental study, employing it to synchronize the slave RHAS robot with the movements of the master robot. Impedance control for Stereotaxic Micro-telemanipulator for Ocular Surgery (SMOS) robot has been conducted using the observer-based adaptive method.[147] Observer-based adaptive impedance control is a Lyapunov-based method that requires defining an error for estimation in order to use Lyapunov stability theory for proving the stability of the system. The tracking results were shown to be good, and the method was robust to system uncertainties.[147] The observer-based impedance control method has some features of a suitable controller for eye surgery, such as robustness and hand tremor reduction. However, the chattering problem and smooth control are the major disadvantages of this method.

Lyapunov-based methods are suitable for designing a good controller for robotic eye surgery. One of the control Lyapunov-based methods is the Sliding Mode Control (SMC), which is used in a variety of eye surgical systems.[148–150] An SMC-based method called the smoothing sliding mode control (SSMC) has been developed.[149] The difference between SSMC and SMC is that in SSMC, a saturation function was used in the control law.[149] SSMC has been compared with PID and SMC in a manipulator two-linked surgical robot.[149] This comparison showed that the SSMC could be used for robotic MIS surgery because of its accuracy. Also, the PID controller results in this study were not suitable for robotic surgery since this control method had some unwanted overshoots and did not demonstrate adequate performance.

The tracking trajectory results of SSMC were found to be suitable in simulations, but the method needs to be tested in practice. One of the problems that can accrue when using SMC is the chattering phenomenon. The SSMC has a reduced chattering phenomenon, but it is insufficient for surgical robots in practice that require a chattering-free controller.

Force feedback is very important for robots used in eye surgery. In all robotic eye surgeries, feedback from the force between the human eye and the robot needs to be calculated. The SMC method has been used in designing a bilateral controller for force feedback in surgical systems.[150] The experimental results of this study were good, and the controller worked very well; this controller was found to be robust against uncertainties and external disturbances.[150]

A robust SMC-based controller called FOBSMC (Fixed-time Observer-Based Sliding Mode Control) was designed and shown to use information about disturbance observer and state observer simultaneously using manipulator robots for testing of the controller.[148] Additionally, this controller was able to remove the effect of communication time delay.[148] The FOBSMC is a good choice for robotic eye surgery. In Table 5, some controller algorithms of eye surgical robots are compared. Briefly, the controllers[64,68,146,150] have been implemented experimentally in the real robots and have been tested only in simulation.[147–149,151]

The sclera force plays a fundamental role in robotic eye surgery, and this force is controlled by Adaptive Norm Control (ANC) and Adaptive Component Control (ACC) methods.[59] These methods have been used to control the scleral force of eye surgery with the SHER robot and the results show that the ANC method can maintain scleral force at a safe level.[59]

Other types of control methods have been designed for specified tasks in the robotic eye, surgery such as Kalman Filter,[152] deep imitation learning with optimal control,[153] adaptive force control,[58] and artificial intelligent algorithms.[154]

5 | COST-EFFECTIVENESS

Table 1 shows that the initial cost of buying robotic systems is high, and the cost of maintaining and repairing them is also substantial.[4]

There are currently two options in robotic eye surgery: a robot used for a specific eye disease or a robot that can be applied to treat a variety of eye conditions. There are advantages and disadvantages to each,[155,156] but some studies have suggested that using a surgical system for several eye diseases could improve the cost-effectiveness of robotic eye surgery.[155–157]

One of the features that can reduce the overall cost of robotic eye surgery is post-operative care. When overall costs, including post-operative care, were considered, robotic surgery was as cost-effective as conventional surgery.[4] A shorter hospital stay is one of the positive features that can reduce the overall cost of robotic surgeries. A shorter hospital stay for patients treated with robots for some surgeries has been shown.[156–158] Patient satisfaction and safety are fundamental to surgical success and may offer a further advantage of robotic surgery. An accurate and suitable robotic surgical system can provide a safer procedure.[159]

The conversion rate, which refers to the percentage of minimally invasive surgeries that need to be converted to open surgeries and indicates the efficiency of the surgical method, the complexity of the surgery and/or surgeon's experience and skills,[160,161] has been reported to be lower in robotic surgery than those in routine surgeries.[162,163] Hence, any excess expense required to purchase the robotic system is mitigated by the reduced cost of conversions. If the surgery costs can be further reduced by the implementation of robotics, this type of surgery will become even more attractive.

6 | CONCLUSION

This review has focused on some most important challenges of robotic eye surgery, such as costs, time of surgery, features of different robots and technologies, as well as control systems and algorithms. Some robotic systems, such as the Da Vinci surgical system, are technically excellent but very expensive. There is a need to improve the controllers and sensors of eye surgical robots without increasing their costs. A comparative analysis of sensors and a description of conditions of suitable control algorithms provided for eye surgical robots are given. The features of a suitable control method for robotic eye surgery are described. This should be robust, smooth, accurate, and chatter-free. Robotic eye surgery is a relatively new research field and is still advancing. Although several surgical robots have been designed for the eye, a system that is affordable and precise, with a simple design to reduce the learning curve and increase the speed of surgery with a suitable controller for a range of eye surgical procedures, is not yet available. Future studies need to consider the design and testing of a suitable control algorithm to be applicable specifically to eye surgery.

ACKNOWLEDGEMENTS

Andrew Ordys, Ali Soltani Sharif Abadi, and Krzysztof Kukielka acknowledge support from National Agency of Academic Exchange (NAWA), "Polish Returns", grant No: PPN/PPO/2018/1/00063/U/00001. Ali Soltani Sharif Abadi acknowledges support from Warsaw University of Technology (WUT), grant No: 504440200003.

CONFLICT OF INTEREST STATEMENT

The authors declare no potential conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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How to cite this article: Soltani Sharif Abadi A, Ordys A, Kukielka K, Pierscionek B. Review on challenges for robotic eye surgery; surgical systems, technologies, cost-effectiveness, and controllers. *Int J Med Robot*. 2023;19(4):e2524. https://doi.org/10.1002/rcs.2524