IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 26 October 2023, accepted 29 November 2023, date of publication 5 December 2023,
date of current version 18 December 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3339555

TOPICAL REVIEW

Review on Sensors and Components Used in Robotic Surgery: Recent Advances and New Challenges

SHARAD DINESH[1], UMESH KUMAR SAHU[1], DAMESHWARI SAHU[2], SANTANU KUMAR DASH[3], AND UMESH KUMAR YADAV[4], (Member, IEEE)
[1]Department of Mechatronics, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal 576104, India
[2]Department of Electronics and Telecommunication, Bhilai Institute of Technology, Durg, Chhattisgarh 491001, India
[3]TIFAC-CORE, Vellore Institute of Technology (VIT), Vellore, Tamil Nadu 632014, India
[4]Department of Electrical Engineering, Malaviya National Institute of Technology, Jaipur 302017, India

Corresponding author: Umesh Kumar Sahu (umesh.sahu@manipal.edu)

This work was supported by the Open Access funding provided by the Manipal Academy of Higher Education, Manipal.

ABSTRACT Surgical robots have been used for many years in the field of medical sciences and engineering. With sophisticated technology governing the world in recent years, surgical robots have benefited from the addition of sensors, actuators, and intelligent control systems, allowing them to function at high precision along with more efficiency. The focus of this study is to present a brief review of sensors and components utilized in robotic surgery that have been studied in recent literature. In the present study, initially, a brief history of robotic surgery is presented, followed by a review on sensors and components in robotic surgery that can be informative for engineers or researchers while designing surgical robots for specific applications. Consequently, highlights of recent trends in the technological advancements in surgical robots have been presented. Further, the paper concludes with recent advances and new challenges in the development of surgical robots.

INDEX TERMS Actuators, minimally invasive surgery, surgical robots, robotic assisted surgery, sensors and components.

I. INTRODUCTION

Robotic surgery has emerged as one of the transformative tool in the field of medical science and cutting-edge engineering to serve for healthcare by offering unprecedented precision, higher dexterity, and minimally invasive capabilities. This review article is providing the comprehend review on significance and pivotal role played by sensors and components including mechanical sensors i.e. force/torque sensors, vision based sensors, haptic feedback systems, robotic arms, etc., in the domain of robotic surgery as an application of bio-medical engineering. The evolutionary implementation of sensors and bio-medical components drive the functionality and safety of robotic surgical systems very smoothly [1].

Surgery is a field of medicine that treats patients by making partial incisions or cuts on their bodies [2]. For thousands of years, the most prevalent operation, known as open surgery has been practiced worldwide. The major reason for using open surgery is to remove undesired elements of the body, such as tumors, or to treat diseases that damage the body. However, there are certain drawbacks of this procedure, including the risk of infection, significant blood loss, a longer recovery period, and the likelihood of traumatizing the patient. In order to address these limitations, surgeons have developed minimally invasive surgery (MIS) and laparoscopic techniques.

MIS involves executing procedures through small incisions and using visual imaging to precisely detect damaged areas or tumors. The primary goal is to give patients a safer and more efficient surgical experience. Although MIS has demonstrated advantages over open surgery, it has not

The associate editor coordinating the review of this manuscript and approving it for publication was Zheng H. Zhu.

completely eliminated the restrictions associated with it, such as the danger of infection and blood loss. Surgeons have developed techniques such as natural orifice transluminal endoscopic surgery (NOTES) to solve these issues. However, when dealing with complicated body components, the use of NOTES may be limited.

In recent years, medical robots have brought about a breakthrough in surgical practices. Following the pursuit of more advanced surgical interventions, the concept of robotic-assisted surgery emerged. The first surgical robot was introduced in 1982 and received approval for use in 2000 [3]. However, traditional rigid robots have limitations in meeting the requirements of highly precise surgical accuracy due to their lack of flexibility stemming from their rigid structure. This limitation is particularly evident when operating in internal positions within the human body. Rigid robots fail to match the flexibility of human organs and encounter difficulties in accessing circuitous body parts. The emergence of flexible robots offers a potential solution to this problem. Flexible robots can be classified into two categories: finite-degree-of-freedom robots with limited discrete joints and infinite-degree-of-freedom robots, also known as continuum robots (CRs), which exhibit elastic members rather than joint links. CRs, initially proposed in the 1960s, have garnered increasing attention due to their flexibility in movement resulting from infinite degrees of freedom. Researchers have proposed numerous bio-inspired ideas for CRs, and reviews on the application of continuum robots in the medical field have also surfaced. Advancements in robot technology have since led to significant improvements in surgical applications. These advancements have paved the way for refined and precise procedures, revolutionizing the field of surgery [4]. Figure 1 shows the overview on significant milestones in the history of surgery.

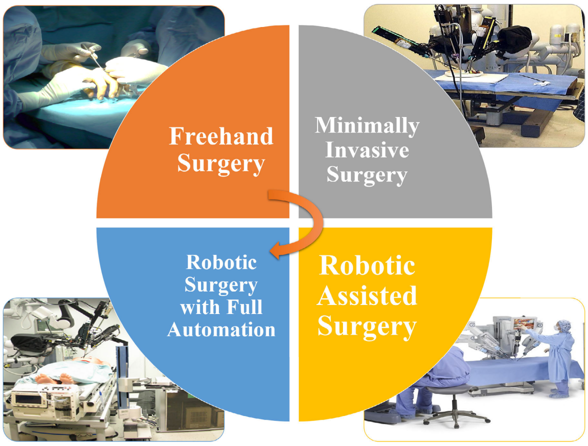


FIGURE 1. History of surgery (photos credit: commons.wikimedia.org).

The use of robotic surgery has the potential to improve surgical precision and accessibility within the human body even further. The purpose of this review is to highlight the pivotal role of sensors and components utilized in the field of robotic surgery by providing a glimpse on its wide applications, emerging trends, and future prospects that help essentially for healthcare professionals, bio-medical engineers, researchers working in robotic surgery domain. The contribution of this study is separated into four dimension.

- In the first dimension, systematic bibliometric data is analyzed using VOSviewer to select appropriate keywords for enhancing the impact of articles on the scientific community.
- In the second dimension, the history of surgery and popular surgical robots has been reviewed to provide information for engineers or researchers while designing surgical robots for specific applications.
- In the third dimension, prominent components and sensors have been analyzed with advantages and limitations to make the selection easier for the designer.
- Finally, the manuscript delves into a comprehensive analysis of the recent technological advancements, potential challenges, and obstacles that arise in the development of surgical robots in the healthcare sector.

This article presents the brief review on sensors and components used in robotic surgery. The review is organized as follows: Bibliometric analysis is presented in Section-II. Section-III discusses the types of robotic assisted surgery (RAS) systems. In Section-IV different components of RAS are presented. Section-V discusses the sensors used in RAS. SectionVI covers recent technological advancement in RAS. The Issue associated with RAS is presented in Section-VII, and some future research scope is highlighted in Section-VIII and the overall review is concluded in Section-IX.

II. BIBLIOMETRIC ANALYSIS

A. VOSVIEWER ANALYSIS

Initially, 10,144 articles in CSV format were extracted from the Scopus database using a single keyword (i.e., surgical robot and minimally invasive surgery). To acquire the optimum results, the keywords are combined interchangeably with minor modifications across several iterations of web search. Extracted articles contain all of the bibliometric data, which is then used as input for the VOSviewer analysis [5]. This analysis counts the number of times keywords and citation information appear in the selected articles. This data provides an efficient method for determining the impact of articles on the scientific community. The co-occurrence of the keywords has also been visualized. Some parameters were used for constructing the map, such as a threshold with a minimum number of co-occurrences of the keywords of 10. From a total of 12398 keywords, only 432 keywords meet with selected threshold criteria. As a result, 5 clusters have been drawn with the 29191 common links, and the total strength is 89185, as shown in Figure 2.

The size of the node represents the co-occurrence of terms (i.e., co-occurring keywords). The thickness of the association indicates the frequency of keyword co-occurrence (i.e., keywords that appear to occur and co-occur frequently).

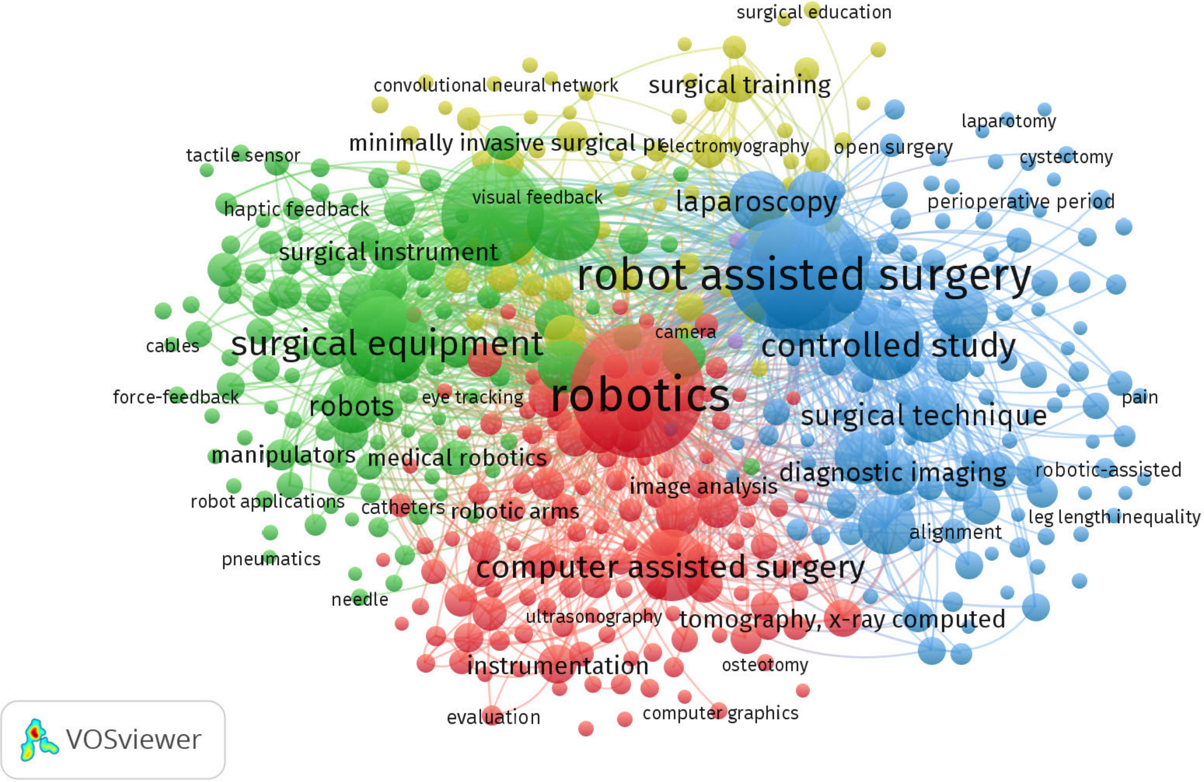


FIGURE 2. Keywords co-occurrence network visualization.

The connection describes the link between two items, while the node represents the strength of the items.

This analysis discovered 432 keywords out of 12398 to be significant. Furthermore, it is impossible to analyze all 432 keywords in a single study. As a result, some essential keywords from these keywords have been chosen, such as "robot-assisted" surgery, robotic surgical procedures, surgical equipment, minimally invasive surgery, sensor, haptic feedback, actuators, sensory feedback, etc." Maximum keywords were chosen based on their prevalence and connection strength in the literature. For example, the co-occurrence linkages for "robot-assisted surgery" were 172 with a strength of 710. The current study only focuses on the keywords with the highest keyword density.

B. PUBLICATION ANALYSIS

The publication of articles from 1982 to September 2023 is depicted in Figure 3 (bar graph) with reference to selected keywords. Since 2015, the number of publications has increased, and it can be seen that 80% of papers have been published in the last 9 years. In this review, sensors and components used in robotic assisted surgery is addressed. So, the year-wise publication of articles based on sensors and actuators is represented using the bar graph shown in Figure 4 and Figure 5, respectively. Similar trends have been observed in this analysis also, i.e. 80% of paper has been published in the last 9 years. Redundant articles with similar discussions on sensors and actuators have been discarded in this review.

C. GEOGRAPHICAL ANALYSIS

The geographical graph depicts the importance of robotic assisted surgery in many nations, including the United States, China, Italy, the United Kingdom, Germany, Japan, South Korea, France, Canada, the Netherlands, Spain, India, Belgium, Australia, and Turkey, etc. (Figure 6). Based on the findings, the United States has the greatest number of foreign publications in this field.

D. MOST CONTRIBUTED JOURNALS

For this analysis, journal information are taken from the Scopus database with the one keyword (i.e., surgical robot and minimally invasive surgery). Some periodicals are specifically related to robotic surgery. Surgical Endoscopy was the most relevant journal, followed by the Journal of Robotic Surgery. This comprehensive approach to publishing has contributed to their strong track record in sophisticated robotic surgery technologies, sensors, components, and actuators in the revived domain. Figure 7 depicts the contribution of the top ten journals.

III. ROBOTIC ASSISTED SURGERY

Robotic surgery was introduced in the year 1982 by a group of mechanical, mechatronics, and biomedical engineers in the

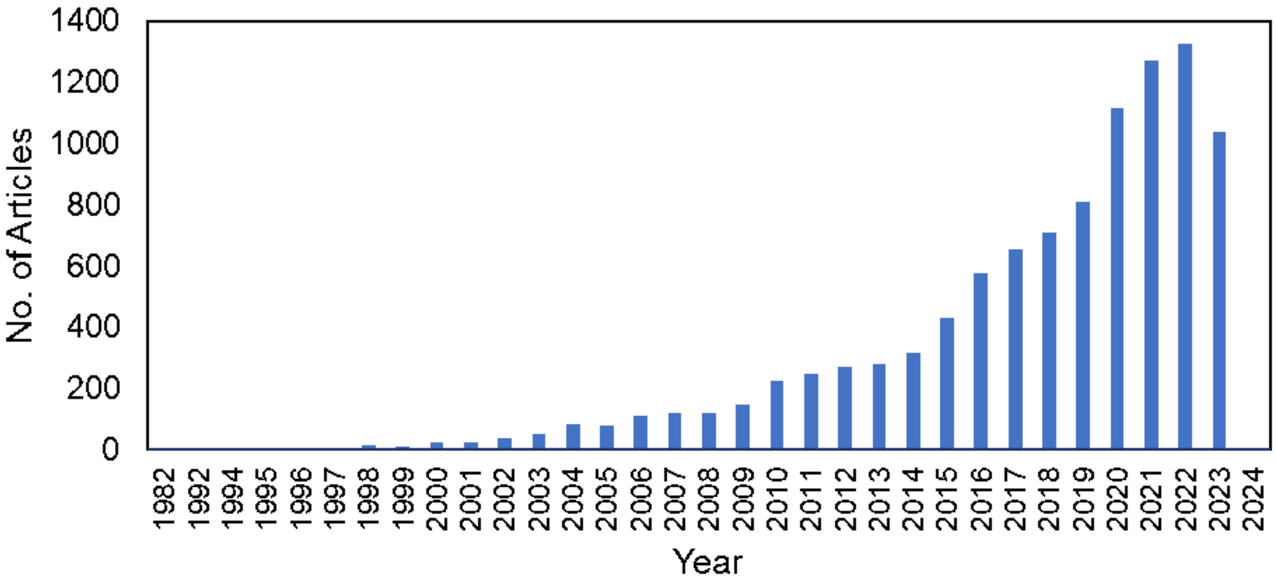


FIGURE 3. Published articles year wise.

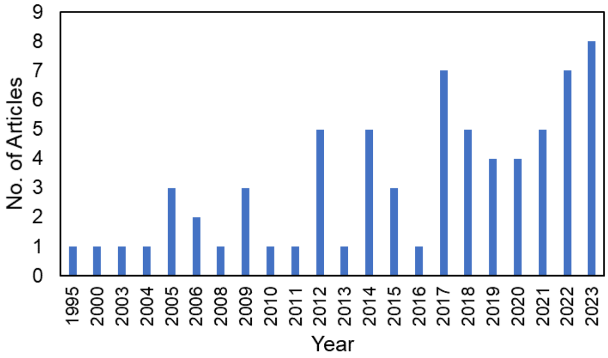


FIGURE 4. Sensor based published articles year wise.

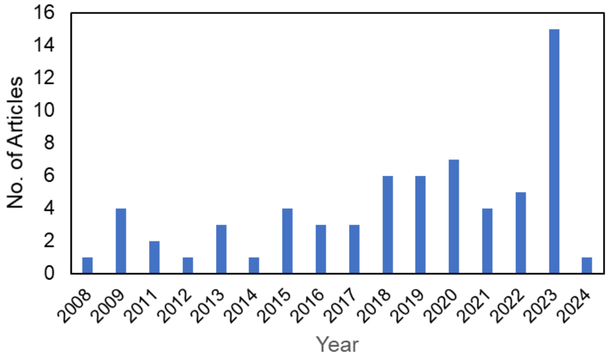


FIGURE 5. Actuator based published articles year wise.

United States. The initial robots, Arthrobot and Unimation Puma 200, played significant roles in manipulating patient's limbs and assisting in neurological procedures, respectively.

Robotic-assisted surgery refers to a surgical approach that leverages the assistance of robots. The primary objective behind introducing robots in surgery was to overcome the limitations associated with traditional approaches, such as open surgery and minimally invasive surgery, by aiding surgeons in navigating the complexities of the human body.

Robotic surgery involves making a small incision through which a robotic arm, equipped with visual 3D imaging and surgical tools is inserted. The surgeon operates the robotic arm using a console that telemanipulates its movements, enabling precise and controlled procedures. By merging visual feedback and advanced control systems, robotic surgery enhances the surgeon's capabilities and facilitates intricate surgical tasks.

Despite early successes, the approval for robotic surgery faced challenges in many countries due to concerns about robot safety and uncertainties. However, the introduction of the Da Vinci robot in 2000 revolutionized the field and became a resounding success, ultimately becoming the most commonly used surgical robot worldwide. The use of the Da Vinci robot marked a turning point, renewing interest in robotic surgery and inspiring the development of various other robotic surgical systems.

Numerous robotic surgical systems have been developed, with extensive clinical trials conducted across different countries. As the world enters the robotic era. Future studies will play a crucial role in evaluating the strengths and weaknesses of each robotic surgical system, thereby shaping the future of this rapidly evolving field [6].

Robotic surgery may be automatic or autonomous systems. Autonomic systems exhibit predictable behaviors based on established theories, either deterministic or probabilistic. Variations in behavior are typically minor adaptations

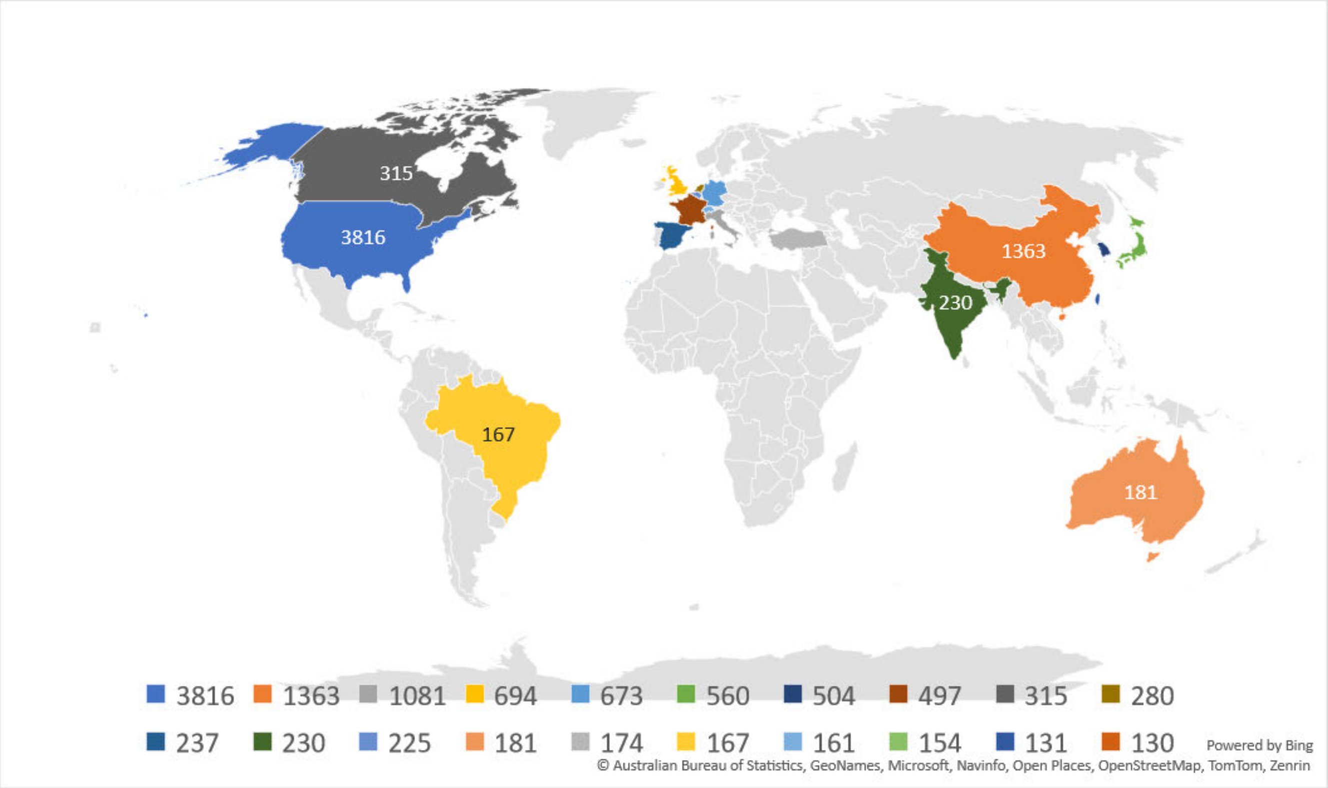


FIGURE 6. Geographical representation of literature for Top-20 regions.

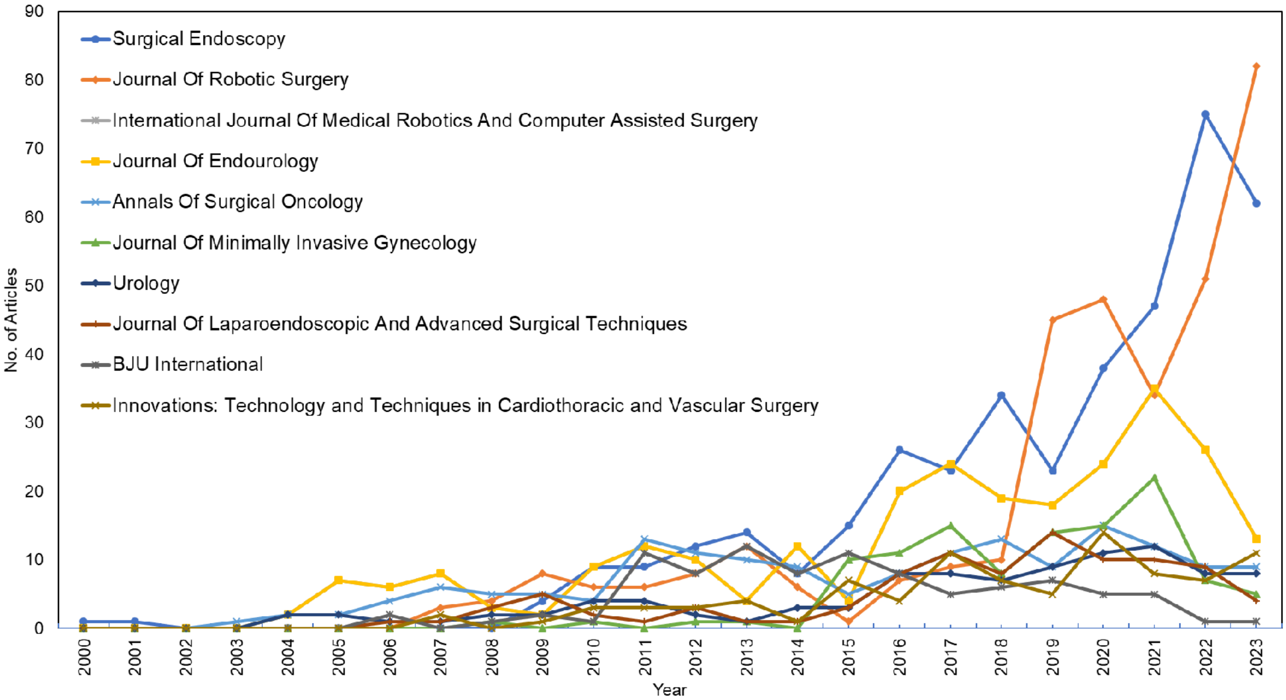


FIGURE 7. Top 10 Journals contribution.

of controller parameters to external conditions. However, if variations become too significant, automatic systems may fail to adapt. In contrast, autonomous systems possess the capability to make substantial adaptations to changes in external conditions through task planning. This planning function requires a broader domain knowledge and the utilization of cognitive tools, such as ontologies or logical rules, which are not inherent to automatic systems [7].

The primary-secondary surgical robot offers six degrees-of-freedom (DOF) of motion. The robot comprises a four-DOF arm located outside the abdominal cavity and a two-DOF wrist joint at the tip. This configuration enables the forceps tip to approach the target within the abdomen from any position and posture. Surgeons operate the remote secondary arms, connected via the wrist joint, using the primary console. The intuitive operation of the robot stems from the secondary arms reproducing the 6-DOF hand motion of the surgeon at the console. Furthermore, robotic systems facilitate neurosurgery through network connectivity and enable microsurgery by adjusting the motion scale between the primary and the secondary [8].

The increasing utilization of surgical robots has led to shorter operation times, reduced infection risks, and faster recovery rates. Robotic surgery has not only benefited patients but has also positively impacted surgeons. By employing robotic assistance, surgeons can enhance their physical and mental skills while performing procedures, enabling them to operate on complex parts of the human body more effectively [9].

There are various surgical robots that were being used in the world, but over the course of time, these surgical robots have been upgraded and these upgraded robots are now being used currently. The types of surgical robot system are depicted in Figure 8 and discussed below.

A. DA VINCI SURGICAL ROBOTS

The Da Vinci surgical system (Figure 9(a)) is a robotic surgery technology developed by Intuitive Surgical. It received Food Drugs administration (FDA) approval in the year 2000 and has since revolutionized surgical procedures. The system consists of a surgeon's console, a patient-side cart, and a vision system. By using this technology, surgeons can perform minimally invasive surgeries with enhanced precision and control [10]. The benefits of the Da Vinci Surgical System include reduced post-operative pain, shorter hospital stays, and faster recovery times for patients. Surgeons also experience improved precision, enhanced dexterity, and reduced fatigue. The robots have expanded the range of surgical interventions and are used worldwide [11], [12].

B. FLEX ROBOTIC SYSTEM

Medrobotics Corporation developed a flexible surgical robot (Figure 9(b)) designed for cardio and transoral surgeries. This robot has an improved 3D visualization, flexibility, and precise access to anatomical locations. It aims to perform surgeries without leaving visible scars and effectively identifies the challenges associated with rigid robots [20]. The main purpose of the flex robotic system is to locate and remove tumors, a task that can be challenging when done manually. The robot's enhanced flexibility, superior 3D imaging, and maneuverability enable surgeons to navigate intricate pathways and perform minimally invasive procedures. The Medrobotics surgical robot has the potential to significantly enhance surgical outcomes and can improve patient experiences in cardio and transoral surgeries [13], [21].

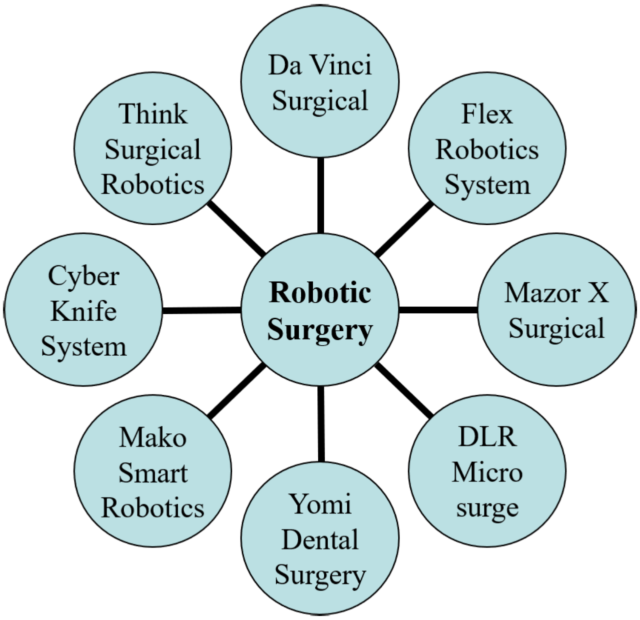


FIGURE 8. Types of surgical robot systems.

C. DLR MICROSURGE

The German Aerospace Centre's (DLR) surgical robot (Figure 9(c)) is a tele-manipulation-based device designed for minimally invasive procedures. It is made up of three robotic arms, each of which has seven degrees of freedom. One arm is equipped with 3D vision system, while the other two arms contain surgical equipment [22]. The technology has contact-free interfaces that allow surgeons to operate the robot arms via a console. It also offers excellent haptic feedback for instrument manipulation [14], [23].

D. MAZOR X SURGICAL

Medtronic's surgical robot (Figure 9(d)) is designed to aid surgeons during spinal surgeries by using a 3D simulation of the patient's spine to identify and change the surgical plan. The technology has an automatic robotic arm and left and right handed control. Its goal is to improve surgical precision and to aid the surgeon during the surgery [15], [24].

E. MAKO SMART ROBOTICS

The Mako surgical robot (Figure 9(e)) developed by Mako Surgical Corp® is based on the Robotics Arm Interactive Orthopaedic (RIO) technology. It is specifically designed to aid in partial and total knee replacement procedures.

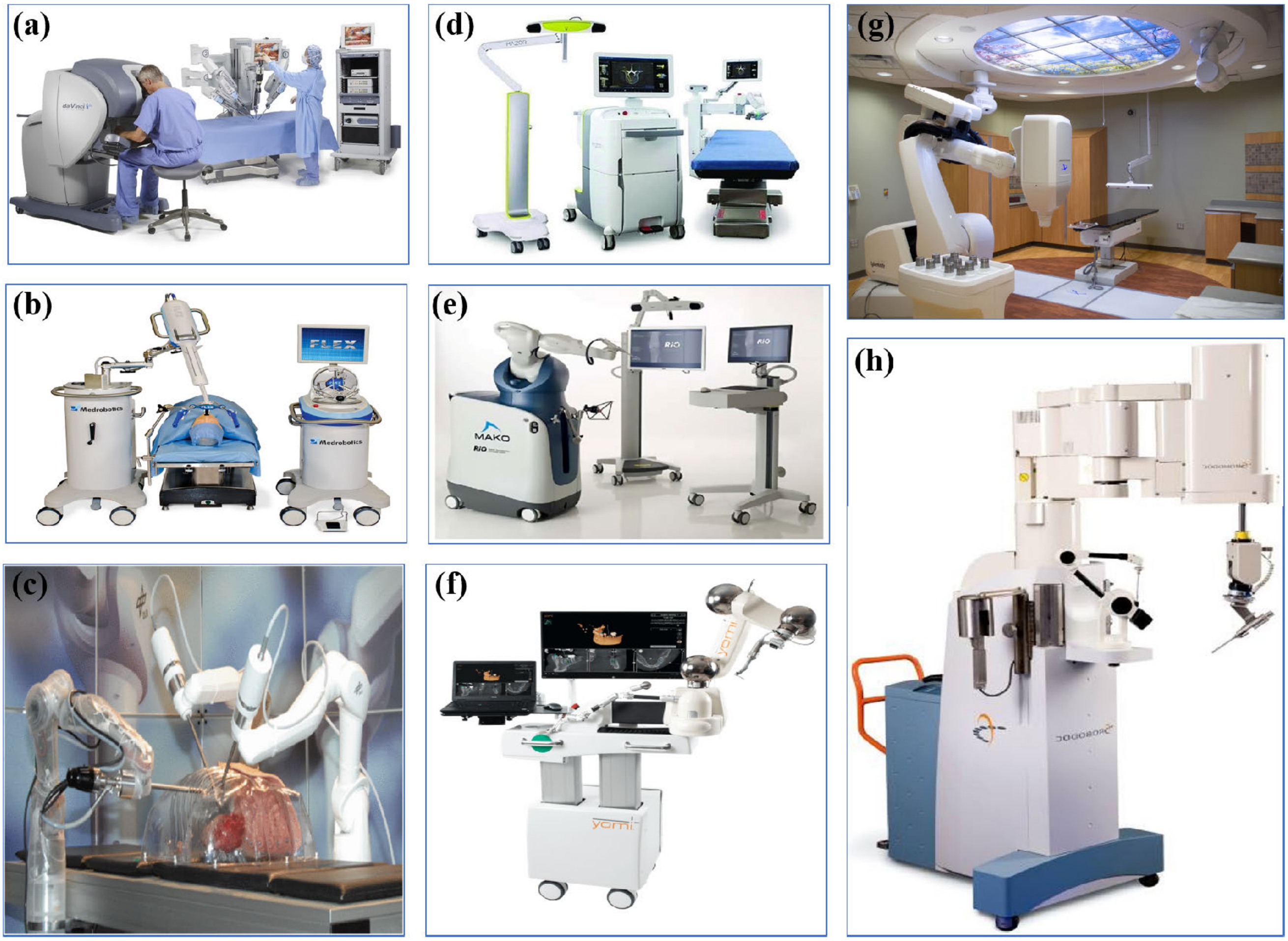


FIGURE 9. Surgical robots. (a) Da Vinchi® surgical system (photo credit: commons.wikimedia.org) [12]. (b) Medrobotics Flex system (photo credit: businesswire.com) [13]. (c) DLR microsurge robotic system [14]. (d) Mazor^{TM} X surgical [15]. (e) Mako surgical robot [16]. (f) Yomi surgical robot (photo credit: neocis.com) [17]. (g) Cyber Knife surgical robot (photo credit: commons.wikimedia.org) [18]. (h) Think surgical robot [19].

A computed tomography (CT) scan is used to build a 3D visual model of the patient's knee. The robotic arm then accurately removes the diseased bone and cartilage and replaces it with the knee model. The Mako surgical robot allows healthcare professionals to perform knee replacement surgery with more precision and accuracy [16], [25].

F. YOMI SURGICAL ROBOTS

The dental surgical robot (Figure 9(f)) is largely utilized in dentistry-related surgeries, assisting surgeons in implant planning and placement. The robot includes sensors that offer feedback on the position and angle of the implant, allowing surgeons to do the procedure with more safety and precision. This method improves implant placement precision, resulting in better outcomes for patients having dental implant procedures [26].

G. CYBER KNIFE SYSTEM

Radiosurgery surgical robots (Figure 9(g)) are used to treat tumors and other critical medical diseases in the human body. These robots use a 6-axis robotic arm that can move and bend around the patient, allowing precise radiation beams to be delivered to the damaged area from unusual angles. This technology enables very accurate and targeted radiation treatment, increasing the efficacy and precision of radiosurgery procedures [25].

H. THINK SURGICAL ROBOTICS

Think Solution's surgical robot is an image-based robot milling system (Figure 9(h)) meant to aid in procedures such as complete knee replacement. By offering 3D visualization and analysis of the surgical outcome, it enables the surgeon to accomplish consistent and correct implantation. The robot prepares the bone for implantation using precise 3D modeling, increasing the procedure's precision. This technology assists surgeons in obtaining greater precision and better surgical outcomes during complete knee replacement procedures [19].

IV. COMPONENTS IN RAS

To ensure a successful robotic surgical procedure, several crucial systems and components are required to meet specific

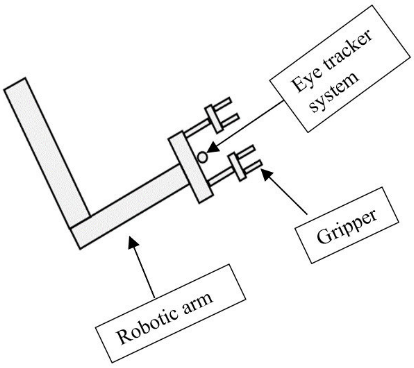


FIGURE 10. Surgical robot with eye tracking system.

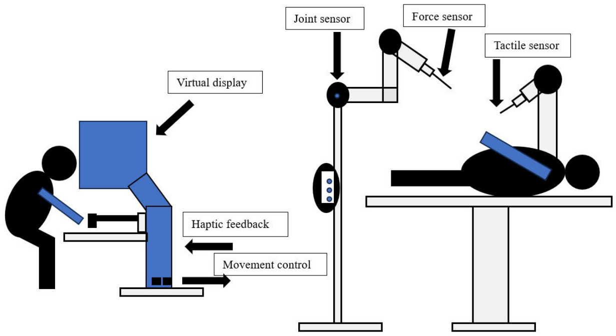


FIGURE 11. Haptic feedback in robotic assisted surgery.

conditions, including advanced visual imaging capabilities, precise haptic feedback mechanisms, and the utilization of various sensors. Failure to implement these techniques can hinder the effectiveness and performance of the surgical robot during the operation.

A. EYE TRACKING SYSTEMS IN RAS

Eye tracking systems, including 3D image videos, are being added into robotic surgery to enhance visual imaging. Initially, 2D visuals were used in procedures like laparoscopy and NOTES but had certain limitations [27]. Upgraded visuals allow surgeons to accurately visualize and locate surgical targets with camera movements controlled by the eye tracking system. Companies are actively advancing these systems to improve the surgeon's view and control during robotic-assisted surgeries such as Da Vinci and flex robots [28]. Cybernetic surgery had a good advantage for good image-guided visuals, enabling surgeons to enhance accuracy and safety during procedures [29]. Figure 10 demonstrates the eye tracking system enabled surgical robot.

B. HAPTIC FEEDBACK IN RAS

Haptic Feedback is defined as the real or the simulated touch interactions of a robot and human with a sense of touch. The purpose of haptic feedback is to make the surgeon feel that they are not operating but to make the robot to automatically operate on the patient [30]. Haptic feedback in robotic surgery aims to provide a sense of touch for the surgeon, but distinguishing touch sensations poses a challenge as it cannot distinguish the sense of touch except in the cases of prosthetics like artificial hands or legs, can be adapted touch feedback. While haptic feedback has been successful in virtual reality games and certain prosthetics, robotic surgery primarily utilizes force feedback and kinaesthetic techniques [31]. Haptic feedbacks have a greater precision. Surgeons estimate the force applied through specialized grippers and force sensors, but these methods have limitations in fidelity and usability. Tactile feedback, which involves detecting tissue properties, requires complex sensors and displays, making it a challenging approach in robotic surgery [32]. Figure 11 demonstrate the use of haptic feedback in RAS.

C. ACTUATORS USED IN RAS

Actuators are a part of device which achieves physical movements in a mechanical part in the robots. These are used as a joint of a robot arm to rotate or the grippers to hold and open. Actuators an integral component of robotic devices, plays a crucial role in enabling physical movements within mechanical parts, such as rotating joints in robot arms or grippers for holding and manipulating objects [3], [4]. In the context of surgical tools, actuators are strategically positioned remotely from the end effector and surgical sites, providing a safe and straightforward solution for lightweight instruments to operate within the confines of the human body. To meet the clinical requirements of smaller size and enhanced flexibility for surgical tools, various advanced actuation methods have been developed, including cable-driven mechanisms, flexible fluid actuators, smart material actuators, and magnetic actuators, all designed to effectively transmit force and motion from the actuator site to the end-effectors [33]. Despite the utilization of surgical robotics for several decades, certain intrinsic challenges still limit their applicability in specific surgical procedures that demand miniature size and high applied force for the surgical tools. This section aims to provide an overview of the actuation methods used in existing surgical robotic systems. There are five types of actuators that are being implemented is shown in Figure 12, and described in Table 1. Also, advantages and disadvantages of sensors used in RAS is summarized in Table 2.

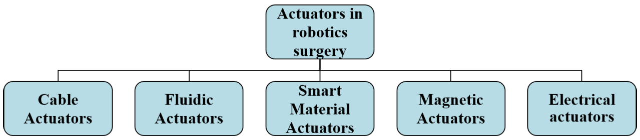


FIGURE 12. Actuators used in RAS.

TABLE 1. Actuators used in RAS.

Actuators	Description	Reference
Cable Driven Actuators	Cable driven actuators are used in robotic surgical applications to overcome the size and weight limitations. They transmit position or force through external actuators to distant joints via fixed points or flexible tubes improving robot motion control.	[34]–[53]
Fluidic actuators	Fluidic actuators are used in medical applications. This converts external fluid pressure into elongation or bending motion to actuate robotic joints or flexible bending parts, offering higher flexibility and power supply in the joints that enables bending through pressure in internal chambers and rigidity.	[54]–[69]
Smart Material Actuators	Smart material actuators are used in surgical robotics due to their ability to memorize and recover shapes. They offer high work density and bio-compatibility, finding applications in robotic endoscopes, and surgical graspers.	[70]–[76]
Magnetic Actuators	Magnetic actuators utilize magnetic fields to wirelessly control surgical tools and offers reliable force transmission. This can be implemented with external permanent magnets or electromagnetic coils. Magnetic actuation has been applied in various surgical procedures. Magnetic actuation provides remote control and has potential for precise and compact robotic systems in the medical field.	[77]–[94]
Electrical Actuators	Electrical actuators such as Dielectric Elastomer Actuators (DEAs), and Hydraulically Amplified Self-Healing Electrostatic (HASEL) actuators, are useful in Minimally Invasive Surgery (MIS) instruments but DEA face challenges such as high voltage requirements and slow response. HASEL actuators address these issues by combining the benefits of hydraulic and DEA actuators, making them suitable for future MIS applications.	[95]–[100]

V. SENSORS IN RAS

Sensors are main components in surgical robotics as they are important in detecting tissue interaction and providing essential force sensing information to surgeons. Various sensing techniques including strain gauges, capacitive sensors, piezoelectric sensors, and optical sensors, are extensively used in surgical robots to facilitate accurate haptic feedback and enhance the overall surgical experience [3]. Each sensor has certain advantages: strain gauges are highly effective in sensing strain and deformation in materials, capacitive sensors excel in providing force information by detecting changes in capacitance, piezoelectric sensors are renowned for their precise force detection capabilities, and optical sensors enable force measurement in multiple degrees of freedom [7]. In addition to force sensing, position sensing feedback also holds great significance in surgical robotics, allowing for precise tracking and control of the robot's position and orientation during surgical procedures. However, real-time feedback remains a challenge in achieving optimal performance and responsiveness. To estimate positions, orientations, and interaction forces accurately, it becomes important to add sensors within the body of the robot, enabling seamless and efficient communication between the robot and the surgical environment. This integration task poses challenges due to the diverse range of actuation types and size constraints inherent in surgical robotics, and the integration of new sensors into existing robotic systems can be a complex and costly process, often requiring meticulous redesign and adaptation of the overall system architecture and technology [101]. The use of sensors and actuators within the user interface holds immense potential to not only restore haptic sensation but also enhance the robot's ability to interpret and respond to the surgeon's intentions, leading to improved surgical outcomes and patient care. To increase the sensor accuracy, a combination of preoperative models and intra-operative tracking data is needed. Table 3 summarized the sensors used in RAS. In addition, advantages and disadvantages of sensors used in RAS is summarized in Table 4.

VI. TECHNOLOGICAL ADVANCEMENT IN RAS

With the rapid progress of modern science and futuristic advancements, there is a vast realm of possibilities in surgical and medical applications, including the integration of artificial intelligence into surgical science and the introduction of soft robotics in robot-assisted spinal surgery. These innovations clearly illustrate the profound impact that technology can have, defying previously held beliefs about what was once considered unachievable in the field of medicine.

A. ROBOTIC ASSISTED SPINAL SURGERY

Robotic surgery has proven to be versatile, capable of performing operations on various parts of the human body, including spinal surgery. Computer-assisted navigation (CAN) is a surgical technique employed in robotic spinal surgeries, with applications such as tumor identification and spinal procedures [169]. Brainlab's CT-based CAN platform, approved in the US in the year 2013, offers mobility and is utilized after the patient is anesthetized and positioned on the operating table for a CT scan [170]. The safety precautions are well noted to have a successful operation and they are well studied with over 20 clinical trials using various manufacturer platforms. Safety precautions have been extensively studied through numerous clinical trials with different manufacturer platforms, demonstrating

TABLE 2. Advantages and disadvantages of actuators used in RAS.

Actuators	Advantages	Disadvantages	Reference
Cable Driven Actuators	1. Can generate high forces at the distal end, for precise and forceful movements. 2. Safer as they use bio-material cables, have fail-safe mechanisms, avoids risks of cable failure. 3. Can provide stiffness enhancements to surgical tools.	1. Complex to design and implement, leading to potential challenges in manufacturing and maintenance. 2. Repeated bending of steel cables over pulleys can lead to fatigue. 3. Achieving optimal stiffness in surgical tools as excessive stiffness leads to tissue damage.	[34]–[53]
Fluidic Actuators	1. Made of bio-compatible materials having no energized parts, reduces risks with electrical components. 2.The compliant nature enables to interact with delicate tissues without damage, enhancing safety. 3.They are successfully used in micro-scale surgeries, can operate in small spaces, and handle delicate procedures.	1. They can be bulky and complex, requires careful design and integration and maintenance. 2. They need power supplies to achieve desired performance levels. 3. The unique properties of flexible materials can make it difficult to develop accurate models and efficient control strategies, and the precision and reliability.	[54]–[69]
Smart Material Actuators	1. They possess properties like corrosion resistance, bio-compatibility, and non-magnetism. 2. Can offer high work density, strength, significant displacement, and large force output. 3. Can be shaped into various forms, such as cables, springs, plates, tubes, and rings.	1. They exhibit a relatively small strain during actuation restricting range of motion 2. They often have a low actuation frequency, which may limit their speed of operation. 3. They require cooling time after actuation, leading a narrow bandwidth of operation as it depends on factors on size, shape, and design.	[70]–[76]
Magnetic Actuators	1. They enable wireless transmission of forces and torques through the abdominal wall, eliminating the need for connection cables or linked mechanisms, simplifying the system and reduces its weight. 2. The elimination of physical connections allows for simpler and more lightweight robotic systems, with precision and maneuverability are crucial. 3. They are driven by powerful external magnets or MRI machines, can lead to surgical tools with high speed, capacity, and dexterity. enabling complex and precise maneuvers.	1. They exhibit hysteresis, non-linearity, and uncertainty in their models, which will be complicated. 2. Multiple-DOF (Degree of Freedom) systems that use coupled magnets require careful consideration of their interactions and positioning. 3. The technology associated with magnetic actuation can be expensive to implement.	[77]–[94]
Electrical Actuators	1. They provide accurate and precise control over position, velocity, and force, making them well-suited for delicate surgical procedures where precision is crucial. 2. They can offer high-speed and high-force capabilities, enabling them to perform complex movements and tasks required in surgical procedures. 3. They can be designed in compact sizes, allowing for minimally invasive surgical procedures and better access to confined spaces.	1. They need a continuous power source, which can lead to challenges in terms of power management, battery life, and safety. 2. Depending on the actuator type and power requirements, electric actuators might be heavier and bulkier compared to some other actuation methods. 3. Needs careful consideration of electrical safety, insulation, and grounding to prevent any harm to patients, surgeons, and the surgical environment.	[95]–[100]

good accuracy, precision, and minimal complications [171]. Ongoing research aims to improve upon the existing CAN concept, with the Mazor X surgical robot being a notable advancement in this field [172].

B. ARTIFICIAL INTELLIGENCE IN RAS

Despite the slower acceptance of advanced technologies, the combination of artificial intelligence (AI) and robots holds the potential to revolutionize society in the coming years [173]. Engineers are actively working on integrating AI, big data, and machine learning to create intelligent robots capable of autonomously performing surgical tasks, improving efficiency, safety, and decision-making [174]. Machine learning algorithms are being applied in surgical robotics, including speech recognition, to enhance patient care [175]. However, ensuring safety is crucial, with a focus on safety-critical systems and cybersecurity measures to prevent data hacking and protect patient lives [176]. AI and machine learning offer the potential to overcome haptic feedback challenges, reducing suture breakage and knot slippage reported in manual human-assisted robotic surgery. These breakthroughs in surgical technology hold significant promise for both patients and surgeons [177].

C. SOFT ROBOTICS FOR RAS

Although robotic surgery has demonstrated effectiveness under human supervision, rigidity remains a significant drawback. Soft robotics, inspired by animals like snakes

TABLE 3. Sensors used in RAS.

Sensors	Description	Reference
Capacitive sensors	Capacitive sensors detect force by measuring changes in capacitance resulting from the deformation of a dielectric layer between two electrodes, and has good reproducibility, and stability in warm and wet environments.	[95], [102]–[111]
Biofeedback sensors	Biofeedback sensors can be integrated into surgical tools to monitor tissue oxygen saturation levels and alert surgeons if levels fall below acceptable thresholds, and strain gauges are used to measure the applied force of surgical tools.	[112]–[114]
Optical sensors	Optical sensing enables force measurement in up to six degrees of freedom (DOFs) by detecting changes in the intensity or phase of light passing through a flexible tube to a compliant structure reducing hysteresis and reproducibility in magnetic environments.	[115]–[125]
Thermal sensors	Thermal sensors are combined into thin and flexible elastomer platforms that is attached to target tissues or organs, providing data on thermal distribution, blood flow, contact pressure, and other physiological parameters. These sensors, comprising micro-thermistors enables a real-time monitoring of temperature and thermal distribution during medical procedures.	[126]–[129]
Force sensors	Force sensors are very effective for measuring forces and torques in many teleoperation applications. Adding force sensors to existing robotic surgical instruments is challenging due to constraints such as size, geometry, cost, biocompatibility, and sterilizability. Specialized grippers design can enable the use of force sensors.	[32], [130]–[144]
Tactile sensors	Tactile feedback systems in robotic minimally invasive surgery (RMIS) require both a sensor and a display. Tactile sensing aims to detect mechanical properties of tissue or provide feedback to the operator, but sensor design constraints include cost, size, geometry, biocompatibility, and surface finish. Various tactile sensors, such as capacitive sensors and force-sensitive resistors can be used.	[74], [120], [145]–[153]
Proprioception Sensors	Proprioception sensors involves in monitoring the state and position of surgical instruments which is crucial in robotic surgery. Parameters such as strain and end position are commonly monitored. Strain information aids in closed-loop motion control, while end-position information assists in precise navigation.	[154]–[158]
Environmental Perception Sensors	Environmental perception in robotic surgery currently focuses on image perception of the surgical environment. Medical image-sensing technologies are categorized into structure-based imaging (e.g., fluoroscopy and ultrasound) and surface-based optical imaging.	[159]–[164]
Interactive Perception Sensors	Interactive perception sensors in robotic surgery involves collecting information about the magnitude and distribution of force between surgical instruments and surrounding tissues. Thin-film pressure sensors and flexible, stretchable tactile sensors are commonly used for this purpose.	[165]–[168]

and octopuses, offer a potential solution by employing compliant materials and pneumatic networks for operation [178]. Soft robots are cost-effective, readily available, easy to handle, and notably safer than traditional approaches. Their ability to deform and regain shape makes them suitable for complex areas of the human body [179]. The initial soft robotics model, OctArm, drew inspiration from the muscular hydrostats of octopus arms and tentacles. Engineers have addressed the stiffness challenge by encasing granular material within an elastic membrane, allowing for a transition from soft to stiff through the application of vacuum [180]. Various techniques and models, such as inflatable robots and octopus-inspired designs, are being implemented to upgrade soft robotics stiffness and intelligence for medical applications. By introducing inflatable robots, the octopus inspired robot for actuation, sensing modelling and control and by upgrading, they can be used to make an intelligent soft robot in medical science [98].

VII. PROBLEMS FACED IN RAS

Despite the significant success and positive feedback surrounding surgical robots, there are several challenges that still need to be addressed. These include high equipment costs, limited lifespan requiring upgrades, the equipment cost of surgical robots is considerably high and that may have a limited lifespan i.e., they need to be upgraded. Since robotic surgery operation is done manually, extensive training is required as the surgeon needs to control it via console, so that they can handle that surgical robot. Improper training would lead to failure in procedure [181]. Accuracy, visual clarity, haptic feedback, and procedure time are additional concerns. Device failure and hygiene issues can occur if the robot is not properly maintained [182]. These factors prevent surgical robots from performing autonomous tasks, and some surgeons still prefer traditional approaches due to these challenges [183].

VIII. FUTURE RESEARCH SCOPE IN RAS

Despite the existing drawbacks in surgical robots, continuous efforts are being made through studies, demonstrations, and inventions to enhance their performance. Medical robots, including Da Vinci, Mazor X, verb surgical, and Henson medicals, are undergoing upgrades for improved usability and have received FDA approval [184]. Additionally, robots

TABLE 4. Advantages and disadvantages of sensors used in RAS.

Sensors	Advantages	Disadvantages	Reference
Capacitive sensors	1. Capacitive sensors enable multi-axis tactile feedback for clinical applications of robotic surgery. 2. Capacitive sensors have better stability, high precision and accuracy.	1. They have limitation on certain environmental factors regarding temperature, humidity. 2. They have issue in signal processing complexity.	[95], [102]–[111]
Biofeedback sensors	1. Surgeons can adjust their surgical techniques in response to real-time data. 2. Biofeedback sensors are designed to resist electromagnetic interference in the electrically noisy environment.	1. Maintaining and servicing the sensors can add ongoing expenses 2. Interpreting biofeedback data requires training and expertise, potentially causing delays in decision-making.	[112]–[114]
Optical sensors	1. High spatial resolution. 2. Some optical sensors offer real-time imaging, aiding surgeons in visualizing tissue and anatomy more clearly.	1. Requires precise alignment and packaging of fibers to maintain the calibration 2. Sensitive changes in light intensity due to cables bending.	[115]–[125]
Thermal sensors	1. Thermal sensors provide real-time temperature data, allowing surgeons to monitor tissue and instrument temperatures during surgery. 2. Thermal sensors can help manage and dissipate heat to prevent overheating and system malfunctions. 3. Thermal sensors can adapt robotic surgery systems to maintain consistent performance.	1. Thermal sensors require regular calibration and maintenance to ensure accuracy.	[126]–[129]
Force sensors	1. Force sensors help robots detect unexpected forces during surgery, caused by environmental factors, enhancing patient safety. 2. Force sensors allow the robot to adapt, compensate for the temperature variations, ensures consistent surgical outcomes. 3. Force sensors help robots apply just the right amount of force to tissues, reducing the risk of tissue damage.	1. Force sensors may have a limited sensing range, where a wide range of forces is applied. 2. There may be limited space for sensors, making it challenging. 3. Environmental factors, such as electromagnetic interference from other medical devices, can disrupt the operation of force sensors.	[32], [130]–[144]
Tactile sensors	1. Tactile sensors help robots to detect unexpected obstacles in their environment, avoids accidents. 2. Tactile sensors adapt to different environmental conditions, such as variations in surface texture, temperature, or humidity. 3. They provide immersive and realistic experience in virtual reality and teleoperation systems.	1. They may require regular maintenance to ensure their accuracy and reliability over time. 2. High-quality tactile sensors can be expensive.	[74], [120], [145]–[153]
Proprioception Sensors	1. Proprioception sensors improve surgical safety by providing real-time feedback on instrument positioning and forces. 2. They enable precise control of surgical instruments, even in dynamic and complex environments, improving surgical outcomes. 3. Proprioception sensors can adapt to changing environmental conditions, ensuring consistent performance.	1. Integrating proprioception sensors into robotic systems can be complex and time-consuming. 2. High-quality proprioception sensors can be expensive. 3. Some sensors may have a limited sensing range, which can be a drawback in procedures requiring a wide range of motion.	[154]–[158]
Environmental Perception Sensors	1. Environmental proprioception sensors provide awareness of the surgical environment beyond visual perception, including factors like temperature, humidity, and PH. 2. They contribute to enhanced patient safety by monitoring environmental conditions that can impact the success of surgery.	1. These sensors may require frequent calibration to ensure accurate data, which can be time-consuming. 2. Environmental factors like electromagnetic interference can disrupt sensor operation, potentially affecting surgical procedures.	[159]–[164]
Interactive Perception Sensors	1. Interactive perception sensors help protect delicate tissues from damage by surgical instruments by providing feedback on force distribution. 2. These sensors are highly sensitive, enabling the detection of subtle forces and pressure variations. 3. Interactive perception sensors provide real-time feedback to surgeons, allowing them to make immediate adjustments.	1. Integrating interactive perception sensors into surgical instruments can be complex. 2. Regular maintenance may be necessary to ensure the reliability and accuracy of these sensors over time.	[165]–[168]

are being utilized in various applications such as bone reduction fracture surgery, featuring different structures for intra-operative positioning, adaptability, minimal invasion, and simplified manipulation [185].

In the context of the COVID-19 pandemic, companies and engineers are exploring artificial intelligence and machine learning to enable autonomous robotic performance, minimizing the risk of infection for patients and doctors [186]. In hospitals and similar circumstances, such as quarantine, the main uses of these robots are to minimize human-to-human interaction and to provide cleaning, sterilization, and assistance. This will reduce the risk to medical personnel's lives, and physicians will be able to actively participate in the COVID-19 pandemic management process [187]. Through these advancements, the goal is to reduce errors, achieve easier handling, and enhance efficiency in surgical robots, ultimately envisioning a future where robots can perform surgeries independently under the supervision of medical professionals, potentially saving lives [188].

IX. CONCLUSION

Robotic surgery remains a vast concept that requires in-depth research to fully comprehend its potential. Clinical studies have shown its superiority over traditional approaches, but there is a need to delve deeper into aspects such as rigidity, haptic feedback, visualization, and other features to enhance its efficiency further. As new technologies continue to advance, there is a possibility that surgical robots will eventually gain the capability to autonomously perform any surgical procedure under the supervision of surgeons. While the cost of these upgrades may be high, patient safety remains the utmost priority for surgeons. In inclusion, this review also highlights the pivotal role of sensors and components utilized in the field of robotic surgery by providing glimpse on its wide applications, emerging trends, and future prospects that help essentially for healthcare professionals, bio-medical engineers, researchers working in robotic surgery domain, etc., since this study ultimately lead to more precise, and accessible healthcare solutions. In conclusion, robotic surgery stands as a remarkable gift to mankind, combining the realms of medical science and technology.

REFERENCES

[1] N. Bandari, J. Dargahi, and M. Packirisamy, "Tactile sensors for minimally invasive surgery: A review of the state-of-the-art, applications, and perspectives," *IEEE Access*, vol. 8, pp. 7682–7708, 2020.

[2] S. M. Hussain, A. Brunetti, G. Lucarelli, R. Memeo, V. Bevilacqua, and D. Buongiorno, "Deep learning based image processing for robot assisted surgery: A systematic literature survey," *IEEE Access*, vol. 10, pp. 122627–122657, 2022.

[3] M. T. Thai, P. T. Phan, T. T. Hoang, S. Wong, N. H. Lovell, and T. N. Do, "Advanced intelligent systems for surgical robotics," *Adv. Intell. Syst.*, vol. 2, no. 8, pp. 1–33, Aug. 2020.

[4] Y. Zhong, L. Hu, and Y. Xu, "Recent advances in design and actuation of continuum robots for medical applications," *Actuators*, vol. 9, no. 4, p. 142, Dec. 2020, doi: 10.3390/act9040142.

[5] N. J. van Eck and L. Waltman, "Software survey: VOSviewer, a computer program for bibliometric mapping," *Scientometrics*, vol. 84, no. 2, pp. 523–538, Aug. 2010.

[6] C. Gosrisirikul, K. Don Chang, A. A. Raheem, and K. H. Rha, "New era of robotic surgical systems," *Asian J. Endoscopic Surg.*, vol. 11, no. 4, pp. 291–299, Nov. 2018.

[7] A. Attanasio, B. Scaglioni, E. De Momi, P. Fiorini, and P. Valdastri, "Autonomy in surgical robotics," *Annu. Rev. Control, Robot., Auto. Syst.*, vol. 4, no. 1, pp. 651–679, May 2021.

[8] K. Kawashima, T. Kanno, and K. Tadano, "Robots in laparoscopic surgery: Current and future status," *BMC Biomed. Eng.*, vol. 1, no. 1, pp. 1–6, May 2019.

[9] A. Mirbagheri, F. Farahmand, S. Sarkar, A. Alamdar, M. Moradi, and E. Afshari, "The sina robotic telesurgery system," in *Handbook Robotic Image-Guided Surgery*, M. H. Abedin-Nasab, Ed. Amsterdam, The Netherlands: Elsevier, 2020, pp. 107–121, doi: 10.1016/B978-0-12-814245-5.00007-4.

[10] A. Ibrahim and K. H. Rha, "New surgical robotics," in *Smith's Textbook Endourology*, 4th ed., A. D. Smith, G. M. Preminger, L. R. Kavoussi, and G. H. Badlani, Eds. Hoboken, NJ, USA: Wiley, 2019, pp. 881–886. [Online]. Available: www.wiley.com/go/smith/textbookofendourology

[11] H. Ashrafian, O. Clancy, V. Grover, and A. Darzi, "The evolution of robotic surgery: Surgical and anaesthetic aspects," *Brit. J. Anaesthesia*, vol. 119, pp. i72–i84, Dec. 2017. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0007091217541173

[12] W. C. Contributors, Wikimedia Commons. *File:Da Vinci Sistema Kirurgikoa.jpg*. Accessed: Oct. 10, 2023. [Online]. Available: https://commons.wikimedia.org/w/index.php?title=File:Da_Vinci_Sistema_Kirurgikoa.jpg&oldid=507776947

[13] M. Corp., businesswire.com. *Medrobotics FLEX System*. Accessed: Oct. 10, 2023. [Online]. Available: https://www.businesswire.com/news/home/20150722006524/en/Medrobotics®-Corporation-Receives-FDA-Clearance-to-Market-Flex®-Robotic-System

[14] R. Konietschke, U. Hagn, M. Nickl, S. Jorg, A. Tobergte, G. Passig, U. Seibold, L. Le-Tien, B. Kubler, M. Groger, F. Frohlich, C. Rink, A. Albu-Schaffer, M. Grebenstein, T. Ortmaier, and G. Hirzinger, "The DLR MiroSurge—A robotic system for surgery," in *Proc. IEEE Int. Conf. Robot. Autom.*, Kobe, Japan, May 2009, pp. 1589–1590.

[15] M. Huang, T. A. Tetreault, A. Vaishnav, P. J. York, and B. N. Staub, "The current state of navigation in robotic spine surgery," *Ann. Transl. Med.*, vol. 9, no. 1, p. 86, Jan. 2021.

[16] R. Shenoy and D. Nathwani, "Evidence for robots," *SICOT-J*, vol. 3, no. 38, pp. 1–6, May 2017.

[17] I. Neocis, neocis.com. *The Yomi Robot*. Accessed: Oct. 11, 2023. [Online]. Available: https://www.neocis.com/products-and-services/yomi-robot/

[18] W. C. Contributors, Wikimedia Commons. *File:Robotic CyberKnife at St. Marys Of Michigan.jpg*. Accessed: Oct. 11, 1023. [Online]. Available: https://commons.wikimedia.org/wiki/File:Robotic_CyberKnife_at_St._Marys_Of_Michigan.jpg

[19] M. H. L. Liow, P. L. Chin, H. N. Pang, D. K. J. Tay, and S. J. Yeo, "THINK surgical TSolution-one(Robodoc) total knee arthroplasty," *SICOT-J*, vol. 3, pp. 4–9, Oct. 2017.

[20] F. Barbara, F. Cariti, V. De Robertis, and M. Barbara, "Flexible transoral robotic surgery: The Italian experience," *Acta Otorhinolaryngolog. Italica*, vol. 41, no. 1, pp. 24–30, Feb. 2021.

[21] K. R. Sheth and C. J. Koh, "The future of robotic surgery in pediatric urology: Upcoming technology and evolution within the field," *Frontiers Pediatrics*, vol. 7, pp. 1–9, Jul. 2019.

[22] J. Dwivedi, "Robotic surgery—A review on recent advances in surgical robotic systems," in *Proc. Florida Conf. Recent Adv. Robot.*, Boca Raton, FL, USA, 2012, pp. 1–7. [Online]. Available: http://www.eng.fau.edu/conf/fcrar/papers/FCRAR_2012_2_1_Dwivedi_Mahgoub_FAU.pdf

[23] T. E. O'Connor, M. M. O'Hehir, A. Khan, J. Z. Mao, L. C. Levy, J. P. Mullin, and J. Pollina, "Mazor x stealth robotic technology: A technical note," *World Neurosurg.*, vol. 145, pp. 435–442, Jan. 2021, doi: 10.1016/j.wneu.2020.10.010.

[24] M. D'Souza, J. Gendreau, A. Feng, L. H. Kim, A. L. Ho, and A. Veeravagu, "Robotic-assisted spine surgery: History, efficacy, cost, and future trends," *Robotic Surg., Res. Rev.*, vol. 6, pp. 9–23, Nov. 2019.

[25] T. Ginoya, Y. Maddahi, and K. Zareinia, "A historical review of medical robotic platforms," *J. Robot.*, vol. 2021, pp. 1–13, Jan. 2021.

[26] M. Natarajan, "A review of robotics in dental implantology," *J. Indian Dental Assoc.*, vol. 5, no. 1, pp. 14–17, Mar. 2018.

[27] I.-H.-A. Chen, A. Ghazi, A. Sridhar, D. Stoyanov, M. Slack, J. D. Kelly, and J. W. Collins, ''Evolving robotic surgery training and improving patient safety, with the integration of novel technologies,'' *World J. Urol.*, vol. 39, no. 8, pp. 2883–2893, Aug. 2021, doi: 10.1007/s00345-020-03467-7.

[28] B. Rosa, V. Bordoux, and F. Nageotte, ''Combining differential kinematics and optical flow for automatic labeling of continuum robots in minimally invasive surgery,'' *Frontiers Robot. AI*, vol. 6, pp. 1–7, Sep. 2019.

[29] R. Muradore, D. Bresolin, L. Geretti, P. Fiorini, and T. Villa, ''Robotic surgery,'' *IEEE Robot. Autom. Mag.*, vol. 18, no. 3, pp. 24–32, Sep. 2011.

[30] M. Ershad, R. Rege, and A. Majewicz Fey, ''Automatic and near real-time stylistic behavior assessment in robotic surgery,'' *Int. J. Comput. Assist. Radiol. Surg.*, vol. 14, no. 4, pp. 635–643, Apr. 2019, doi: 10.1007/s11548-019-01920-6.

[31] L. Cheng and M. Tavakoli, ''Switched-impedance control of surgical robots in teleoperated beating-heart surgery,'' *J. Med. Robot. Res.*, vol. 3, nos. 3–4, Sep. 2018, Art. no. 1841003.

[32] A. M. Okamura, ''Haptic feedback in robot-assisted minimally invasive surgery,'' *Current Opinion Urol.*, vol. 19, no. 1, pp. 102–107, Jan. 2009.

[33] H. M. Le, T. N. Do, and S. J. Phee, *A Survey on Actuators-Driven Surgical Robots*, vol. 247. Amsterdam, The Netherlands: Elsevier, Aug. 2016, doi: 10.1016/j.sna.2016.06.010.

[34] Z. Wang, S. Bao, B. Zi, Z. Jia, and X. Yu, ''Development of a novel 4-DOF flexible endoscopic robot using cable-driven multisegment continuum mechanisms,'' *J. Mech. Robot.*, vol. 16, no. 3, pp. 1–15, Mar. 2024.

[35] J. Li and Q. Jiang, ''Optimal design and experiment of cable-driven puncturing surgery robot for soft needle,'' *J. Med. Devices*, vol. 17, no. 2, pp. 1–12, Jun. 2023.

[36] J. Colan, A. Davila, Y. Zhu, T. Aoyama, and Y. Hasegawa, ''OpenRST: An open platform for customizable 3D printed cable-driven robotic surgical tools,'' *IEEE Access*, vol. 11, pp. 6092–6105, 2023.

[37] J. Yang, Z. Sun, J. Chen, and Y. Guo, ''A cable-driven highly compact single port laparoscopic surgical robot with sequentially inserted arms,'' *Int. J. Med. Robot. Comput. Assist. Surg.*, vol. 19, no. 2, pp. 1–12, Apr. 2023.

[38] J. Hao, K. Zhang, Z. Zhang, S. Wang, and C. Shi, ''An online model-free adaptive tracking controller for cable-driven medical continuum manipulators,'' *IEEE Trans. Med. Robot. Bionics*, vol. 5, no. 3, pp. 623–635, Aug. 2023.

[39] K. Nojima, K. Tadano, and D. Haraguchi, ''Application and mechanical evaluation of polyarylate fiber rope in wire drive mechanism of robotic surgical instruments,'' *J. Robot. Mechatronics*, vol. 35, no. 2, pp. 461–469, Apr. 2023.

[40] Z. Wang, G. Liu, S. Qian, D. Wang, X. Wei, and X. Yu, ''Tracking control with external force self-sensing ability based on position/force estimators and non-linear hysteresis compensation for a backdrivable cable-pulley-driven surgical robotic manipulator,'' *Mechanism Mach. Theory*, vol. 183, May 2023, Art. no. 105259, doi: 10.1016/j.mechmachtheory.2023.105259.

[41] R. Li, F. Chen, W. Yu, T. Igarash, X. Shu, and L. Xie, ''A novel cable-driven soft robot for surgery,'' *J. Shanghai Jiaotong Univ. Sci.*, pp. 1–13, Sep. 2022, doi: 10.1007/s12204-022-2497-3.

[42] Y. Yan, L. Yu, C. Li, X. Gu, and H. Ren, ''UKF-based motion estimation of cable-driven forceps for robot-assisted surgical system,'' *IEEE Access*, vol. 8, pp. 94912–94922, 2020.

[43] W. Liu, Z. Yang, S. Jiang, D. Feng, and D. Zhang, ''Design and implementation of a new cable-driven robot for MRI-guided breast biopsy,'' *Int. J. Med. Robot. Comput. Assist. Surg.*, vol. 16, no. 2, pp. 1–15, Apr. 2020.

[44] M. Runciman, J. Avery, M. Zhao, A. Darzi, and G. P. Mylonas, ''Deployable, variable stiffness, cable driven robot for minimally invasive surgery,'' *Frontiers Robot. AI*, vol. 6, pp. 1–16, Jan. 2020.

[45] S. Jin, S. K. Lee, J. Lee, and S. Han, ''Kinematic model and real-time path generator for a wire-driven surgical robot arm with articulated joint structure,'' *Appl. Sci.*, vol. 9, no. 19, p. 4114, Oct. 2019.

[46] F. Qi, F. Ju, D. Bai, Y. Wang, and B. Chen, ''Kinematic analysis and navigation method of a cable-driven continuum robot used for minimally invasive surgery,'' *Int. J. Med. Robot. Comput. Assist. Surg.*, vol. 15, no. 4, pp. 1–12, Aug. 2019.

[47] F. Qi, F. Ju, D. Bai, Y. Wang, and B. Chen, ''Motion modelling and error compensation of a cable-driven continuum robot for applications to minimally invasive surgery,'' *Int. J. Med. Robot. Comput. Assist. Surg.*, vol. 14, no. 6, Dec. 2018, Art. no. e1932.

[48] H. Li, W. Liu, K. Wang, K. Kawashima, and E. Magid, ''A cable-pulley transmission mechanism for surgical robot with backdrivable capability,'' *Robot. Comput.-Integr. Manuf.*, vol. 49, pp. 328–334, Feb. 2018.

[49] S. S. Cheng, X. Wang, and J. P. Desai, ''Design and analysis of a remotely-actuated cable-driven neurosurgical robot,'' in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Sep. 2017, pp. 1685–1690.

[50] A. Tzemanaki, L. Fracczak, D. Gillatt, A. Koupparis, C. Melhuish, R. Persad, E. Rowe, A. G. Pipe, and S. Dogramadzi, ''Design of a multi-DOF cable-driven mechanism of a miniature serial manipulator for robot-assisted minimally invasive surgery,'' in *Proc. 6th IEEE Int. Conf. Biomed. Robot. Biomechatronics (BioRob)*, Singapore, Jun. 2016, pp. 55–60.

[51] A. L. Orekhov, C. E. Bryson, J. Till, S. Chung, and D. C. Rucker, ''A surgical parallel continuum manipulator with a cable-driven grasper,'' in *Proc. 37th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*. Milan, Italy, Aug. 2015, pp. 5264–5267.

[52] M. D. M. Kutzer, S. M. Segreti, C. Y. Brown, M. Armand, R. H. Taylor, and S. C. Mears, ''Design of a new cable-driven manipulator with a large open lumen: Preliminary applications in the minimally-invasive removal of osteolysis,'' in *Proc. IEEE Int. Conf. Robot. Autom.*, Shanghai, China, May 2011, pp. 2913–2920.

[53] C. Direkwatana, J. Suthakorn, and C. Wilasrusmee, ''Development of wire-driven laparoscopic surgical robotic system,'' 'MU-LapaRobot,''' in *Proc. IEEE Int. Conf. Robot. Biomimetics (ROBIO)*, Phuket, Thailand, Dec. 2011, pp. 485–490.

[54] K.-W. Kwok, H. Wurdemann, A. Arezzo, A. Menciassi, and K. Althoefer, ''Soft robot-assisted minimally invasive surgery and interventions: Advances and outlook,'' *Proc. IEEE*, vol. 110, no. 7, pp. 871–892, Jul. 2022.

[55] L. Lindenroth, J. Merlin, S. Bano, J. G. Manjaly, N. Mehta, and D. Stoyanov, ''Intrinsic force sensing for motion estimation in a parallel, fluidic soft robot for endoluminal interventions,'' *IEEE Robot. Autom. Lett.*, vol. 7, no. 4, pp. 10581–10588, Oct. 2022.

[56] J. Liu, L. Yin, J. H. Chandler, X. Chen, P. Valdastri, and S. Zuo, ''A dual-bending endoscope with shape-lockable hydraulic actuation and water-jet propulsion for gastrointestinal tract screening,'' *Int. J. Med. Robot. Comput. Assist. Surg.*, vol. 17, no. 1, pp. 1–13, Feb. 2021.

[57] L. Lindenroth, S. Bano, A. Stilli, J. G. Manjaly, and D. Stoyanov, ''A fluidic soft robot for needle guidance and motion compensation in intratympanic steroid injections,'' *IEEE Robot. Autom. Lett.*, vol. 6, no. 2, pp. 871–878, Apr. 2021.

[58] G. Decroly, B. Mertens, P. Lambert, and A. Delchambre, ''Design, characterization and optimization of a soft fluidic actuator for minimally invasive surgery,'' *Int. J. Comput. Assist. Radiol. Surg.*, vol. 15, no. 2, pp. 333–340, Feb. 2020, doi: 10.1007/s11548-019-02081-2.

[59] A. Pourghodrat and C. A. Nelson, ''Disposable fluidic actuators for miniature in-vivo surgical robotics,'' *J. Med. Devices*, vol. 11, no. 1, pp. 1–8, Mar. 2017.

[60] A. Devreker, B. Rosa, A. Desjardins, E. J. Alles, D. Stoyanov, A. L. David, T. Vercauteren, J. Deprest, A. Devreker, B. Rosa, A. Desjardins, E. J. Alles, A. Devreker, B. Rosa, A. Desjardins, E. J. Alles, and E. Maneas, ''Fluidic actuation for intra-operative in situ imaging,'' in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Hamburg, Germany, Sep. 2018, pp. 1415–1421.

[61] G. Gerboni, T. Ranzani, A. Diodato, G. Ciuti, M. Cianchetti, and A. Menciassi, ''Modular soft mechatronic manipulator for minimally invasive surgery (MIS): Overall architecture and development of a fully integrated soft module,'' *Meccanica*, vol. 50, no. 11, pp. 2865–2878, Nov. 2015.

[62] A. J. M. Moers, M. F. L. De Volder, and D. Reynaerts, ''Integrated high pressure microhydraulic actuation and control for surgical instruments,'' *Biomed. Microdevices*, vol. 14, no. 4, pp. 699–708, Aug. 2012.

[63] D. B. Comber, E. J. Barth, R. J. W. Iii, J. E. Slightam, and V. R. Gervasi, ''Design and precision control of an MR-compatible flexible fluidic actuator,'' in *Proc. ASME/BATH Symp. Fluid Power Motion Control*, Oct. 2013, pp. 1–9.

[64] M. Cianchetti, T. Ranzani, G. Gerboni, I. De Falco, C. Laschi, and A. Menciassi, ''STIFF-FLOP surgical manipulator: Mechanical design and experimental characterization of the single module,'' in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Tokyo, Japan, Nov. 2013, pp. 3576–3581.

[65] A. Devreker, ''Towards fluidic actuation for catheter-based interventions,'' in *Proc. Actuator*, Bremen, Germany, 2014, pp. 173–176.

[66] J. E. Slightam and V. R. Gervasi, "Additively manufactured flexible fluidic actuators for precision control in surgical applications," in *Proc. 24th Int. SFF Symp. An Additive Manuf. Conf. (SFF)*. Austin, TX, USA: Univ. Texas at Austin, 2013, pp. 777–790.

[67] O. Ivlev, "Soft fluidic actuators of rotary type for safe physical human-machine interaction," in *Proc. IEEE Int. Conf. Rehabil. Robot.*, Jun. 2009, pp. 1–5.

[68] A. De Greef, P. Lambert, and A. Delchambre, "Towards flexible medical instruments: Review of flexible fluidic actuators," *Precis. Eng.*, vol. 33, no. 4, pp. 311–321, Oct. 2009.

[69] N. Yu, C. Hollnagel, A. Blickenstorfer, S. Kollias, and R. Riener, "FMRI-compatible robotic interfaces with fluidic actuation," in *Proc. Robot., Sci. Syst. IV*, Zurich, Switzerland, Jun. 2008, pp. 199–205.

[70] F. J. A. Oliver, "Construction and improvement of surgical gripper controlled with actuators based on intelligent materials," Undergraduate, Kaunas Univ. Technol., Kaunas, Lithuania, Tech. Rep., 2023. [Online]. Available: http://hdl.handle.net/10317/12609

[71] Q. Jacquemin, Q. Sun, D. Thuau, E. Monteiro, S. Tence-Girault, S. Doizi, O. Traxer, and N. Mechbal, "Design and control of a new electrostrictive polymer based continuum actuator for endoscopic robot," *J. Intell. Mater. Syst. Struct.*, vol. 34, no. 12, pp. 1355–1365, Jul. 2023.

[72] F. Arab Hassani, Q. Shi, F. Wen, T. He, A. Haroun, Y. Yang, Y. Feng, and C. Lee, "Smart materials for smart healthcare–moving from sensors and actuators to self-sustained nanoenergy nanosystems," *Smart Mater. Med.*, vol. 1, pp. 92–124, Aug. 2020, doi: 10.1016/j.smaim.2020.07.005.

[73] S.-R. Kang, S.-W. Cha, Y.-H. Hwang, Y.-S. Lee, and S.-B. Choi, "Controllable magnetorheological fluid based actuators for 6-degree-of-freedom haptic master applicable to robot-assisted surgery," *Sens. Actuators A, Phys.*, vol. 279, pp. 649–662, Aug. 2018, doi: 10.1016/j.sna.2018.06.057.

[74] F. Ju, Y. Wang, Z. Zhang, Y. Wang, Y. Yun, H. Guo, and B. Chen, "A miniature piezoelectric spiral tactile sensor for tissue hardness palpation with catheter robot in minimally invasive surgery," *Smart Mater. Struct.*, vol. 28, no. 2, Jan. 2019, Art. no. 025033.

[75] Y.-H. Hwang, S.-R. Kang, S.-W. Cha, and S.-B. Choi, "A robot-assisted cutting surgery of human-like tissues using a haptic master operated by magnetorheological clutches and brakes," *Smart Mater. Struct.*, vol. 28, no. 6, Jun. 2019, Art. no. 065016.

[76] Y.-H. Hwang, S.-R. Kang, S.-W. Cha, and S.-B. Choi, "An electrorheological spherical joint actuator for a haptic master with application to robot-assisted cutting surgery," *Sens. Actuators A, Phys.*, vol. 249, pp. 163–171, Oct. 2016, doi: 10.1016/j.sna.2016.08.033.

[77] D. A. Aubeeluck, C. Forbrigger, S. M. Taromsari, T. Chen, E. Diller, and H. E. Naguib, "Screen-printed resistive tactile sensor for monitoring tissue interaction forces on a surgical magnetic microgripper," *ACS Appl. Mater. Interface*, vol. 15, no. 28, pp. 34008–34022, Jul. 2023.

[78] X. Du and J. Yu, "Image-integrated magnetic actuation systems for localization and remote actuation of medical miniature robots: A survey," *IEEE Trans. Robot.*, vol. 39, no. 4, pp. 2549–2568, Aug. 2023.

[79] C. Forbrigger, E. Fredin, and E. Diller, "Evaluating the feasibility of magnetic tools for the minimum dynamic requirements of microneurosurgery," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, London, U.K., May 2023, pp. 4703–4709.

[80] H. Sun, J. Liu, and Q. Wang, "Magnetic actuation systems and magnetic robots for gastrointestinal examination and treatment," *Chin. J. Electr. Eng.*, vol. 9, no. 1, pp. 3–28, Mar. 2023.

[81] H. Nadour, A. B. Grayeli, G. Poisson, and K. Belharet, "CochleRob: Parallel-serial robot to position a magnetic actuator around a patient's head for intracochlear microrobot navigation," *Sensors*, vol. 23, no. 6, p. 2973, Mar. 2023.

[82] T. L. Thomas, "Bending the rules: Magnetically-actuated surgical continuum manipulators," Ph.D. dissertation, Dept. Eng. Technol., Univ. Twente, Enschede, The Netherlands, 2023.

[83] M. Nica, C. Forbrigger, and E. Diller, "A novel magnetic transmission for powerful miniature surgical robots," *IEEE/ASME Trans. Mechatronics*, vol. 27, no. 6, pp. 5541–5550, Dec. 2022.

[84] J. Hwang, J.-Y. Kim, and H. Choi, "A review of magnetic actuation systems and magnetically actuated guidewire- and catheter-based microrobots for vascular interventions," *Intell. Service Robot.*, vol. 13, no. 1, pp. 1–14, Jan. 2020, doi: 10.1007/s11370-020-00311-0.

[85] M. Verra, A. Firrincieli, M. Chiurazzi, A. Mariani, G. Lo Secco, E. Forcignanò, A. Koulaouzidis, A. Menciassi, P. Dario, G. Ciuti, and A. Arezzo, "Robotic-assisted colonoscopy platform with a magnetically-actuated soft-tethered capsule," *Cancers*, vol. 12, no. 9, p. 2485, Sep. 2020.

[86] O. Onaizah and E. Diller, "Tetherless mobile micro-surgical scissors using magnetic actuation," in *Proc. Int. Conf. Robot. Autom. (ICRA)*, Montreal, QC, Canada, May 2019, pp. 894–899.

[87] C. Forbrigger, A. Lim, O. Onaizah, S. Salmanipour, T. Looi, J. Drake, and E. D. Diller, "Cable-less, magnetically driven forceps for minimally invasive surgery," *IEEE Robot. Autom. Lett.*, vol. 4, no. 2, pp. 1202–1207, Apr. 2019.

[88] C. Heunis, J. Sikorski, and S. Misra, "Flexible instruments for endovascular interventions: Improved magnetic steering, actuation, and image-guided surgical instruments," *IEEE Robot. Autom. Mag.*, vol. 25, no. 3, pp. 71–82, Sep. 2018.

[89] R. L. Steinberg, B. A. Johnson, and J. A. Cadeddu, "Magnetic-assisted robotic surgery: Initial case series of reduced-port robotic prostatectomy," *J. Robotic Surg.*, vol. 13, no. 4, pp. 599–603, Aug. 2019, doi: 10.1007/s11701-018-0889-z.

[90] H. Ren and H. Banerjee, "A preface in electromagnetic robotic actuation and sensing in medicine," in *Electromagnetic Actuation and Sensing in Medical Robotics*, H. Ren and J. Sun, Eds. Berlin, Germany: Springer, 2018, ch. 1, pp. 1–10.

[91] A. Mohammadi, D. Samsonas, F. Leong, Y. Tan, D. Thiruchelvam, P. Valdastri, and D. Oetomo, "Modeling and control of local electromagnetic actuation for robotic-assisted surgical devices," *IEEE/ASME Trans. Mechatronics*, vol. 22, no. 6, pp. 2449–2460, Dec. 2017.

[92] F. Leong, N. Garbin, C. D. Natali, A. Mohammadi, D. Thiruchelvam, D. Oetomo, and P. Valdastri, "Magnetic surgical instruments for robotic abdominal surgery," *IEEE Rev. Biomed. Eng.*, vol. 9, pp. 66–78, 2016.

[93] H. Gu, M. Bain, C. J. Yen, S. Fang, F. Leong, A. Mohammadi, P. Valdastri, and D. Oetomo, "Local magnetic actuation based laparoscopic camera for minimally invasive surgery," in *Proc. Australas. Conf. Robot. Autom. (ACRA)*. Canberra, ACT, Australia, 2015, pp. 1–6.

[94] C. Di Natali, J. Buzzi, N. Garbin, M. Beccani, and P. Valdastri, "Closed-loop control of local magnetic actuation for robotic surgical instruments," *IEEE Trans. Robot.*, vol. 31, no. 1, pp. 143–156, Feb. 2015.

[95] A. Arshad, M. M. Saleem, M. I. Tiwana, H. ur Rahman, S. Iqbal, and R. Cheung, "A high sensitivity and multi-axis fringing electric field based capacitive tactile force sensor for robot assisted surgery," *Sens. Actuators A, Phys.*, vol. 354, May 2023, Art. no. 114272, doi: 10.1016/j.sna.2023.114272.

[96] S. Chiba and M. Waki. (2023). *Dielectric Elastomer Multi-Sensors and Tactile Actuators for Robot Fingers in Human-Robot Interaction*. [Online]. Available: https://www.preprints.org/manuscript/202307.0286/v1

[97] H. Wang, S. Cui, and F. Niu, "Optimization and demonstration of two types of spring-roll dielectric elastomer actuators for minimally invasive surgery," *Frontiers Bioeng. Biotechnol.*, vol. 10, pp. 1–14, Oct. 2022.

[98] J. Zhu, L. Lyu, Y. Xu, H. Liang, X. Zhang, H. Ding, and Z. Wu, "Intelligent soft surgical robots for next-generation minimally invasive surgery," *Adv. Intell. Syst.*, vol. 3, no. 5, pp. 1–39, May 2021.

[99] J.-S. Plante, K. Tadakuma, L. M. DeVita, D. F. Kacher, J. R. Roebuck, S. P. DiMaio, F. A. Jolesz, and S. Dubowsky, "An MRI-compatible needle manipulator concept based on elastically averaged dielectric elastomer actuators for prostate cancer treatment: An accuracy and MR-compatibility evaluation in phantoms," *J. Med. Devices*, vol. 3, no. 3, pp. 1–10, Sep. 2009.

[100] F. Carpi, A. Khanicheh, C. Mavroidis, and D. De Rossi, "MRI compatibility of silicone-made contractile dielectric elastomer actuators," *IEEE/ASME Trans. Mechatronics*, vol. 13, no. 3, pp. 370–374, Jun. 2008.

[101] C. Wu, J. Cha, J. Sulek, C. P. Sundaram, J. Wachs, R. W. Proctor, and D. Yu, "Sensor-based indicators of performance changes between sessions during robotic surgery training," *Appl. Ergonom.*, vol. 90, Jan. 2021, Art. no. 103251, doi: 10.1016/j.apergo.2020.103251.

[102] L. Zhang, Z. Wu, H. Li, F. Wang, Z. Zeng, C. Hou, M. Gan, H. Liu, T. Chen, and L. Sun, "Force sensing and feedback system based on novel triaxial force capacitive sensor for minimally invasive surgical robot," *Adv. Sensor Res.*, vol. 2, no. 11, pp. 1–10, Nov. 2023.

[103] V. J. Vaitaitis, M. E. Dunham, Y. Kwon, W. C. Mayer, A. K. Evans, A. J. Baker, K. D. Walker, G. D. Cespedes, A. Stanley, and M. Opiri, "A surgical simulator for tympanostomy tube insertion incorporating capacitive sensing technology to track instrument placement," *Otolaryngol. Head Neck Surg.*, vol. 162, no. 3, pp. 343–345, Mar. 2020.

[104] Y. Dai, "Development of capacitive tactile sensors for surgical systems," Ph.D. dissertation, Dept. Elect. Eng., Univ. California, Los Angeles, CA, USA, 2019. [Online]. Available: https://escholarship.org/uc/item/5kb1z84z

[105] F. J. Mancillas, "Analysis of a micro-scale, tri-axial, capacitive-based, differential force sensor for haptic feedback system in robotic surgery," Ph.D. dissertation, Dept. Elect. Eng., Univ. California, Los Angeles, CA, USA, 2019.

[106] D. T. Vera, I. Lum, and A. T. Ohta, "Microporous capacitive sensors for use in surgical procedures," in *Proc. IEEE 7th Annu. Int. Conf. CYBER Technol. Autom., Control, Intell. Syst. (CYBER)*, Jul. 2017, pp. 607–610.

[107] Y. Dai, A. Abiri, S. Liu, O. Paydar, H. Sohn, E. P. Dutson, W. S. Grundfest, and R. N. Candler, "Grasper integrated tri-axial force sensor system for robotic minimally invasive surgery," in *Proc. 39th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, Jul. 2017, pp. 3936–3939.

[108] D. B. P. Tripp, "Force sensing surgical grasper with folding capacitive sensor," Ph.D. dissertation, Dept. Elect. Comput. Eng., Univ. Western Ontario, London, U.K., 2017.

[109] S. Yun, J. Yoo, S. Lim, J. Park, H.-K. Lee, and K.-S. Yun, "Three-axis pneumatic tactile display with integrated capacitive sensors for feedback control," *Microsyst. Technol.*, vol. 22, no. 2, pp. 275–282, Feb. 2016.

[110] O. H. Paydar, C. R. Wottawa, R. E. Fan, E. P. Dutson, W. S. Grundfest, M. O. Culjat, and R. N. Candler, "Fabrication of a thin-film capacitive force sensor array for tactile feedback in robotic surgery," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, Aug. 2012, pp. 2355–2358.

[111] T. Maier, T. Meschede, G. Strauss, T. Kraus, A. Dietz, and T. C. Lueth, "Joystick control with capacitive release switch for a microsurgical telemanipulator," in *Proc. IEEE Hum. Syst. Interact. Conf.*, Rzeszow, Poland, Jul. 2010, pp. 223–229. http://www.mimed.mw.tum.de/fileadmin/w00bhh/www/PDF_Archive/2010_HSI_Maier_223-229.pdf

[112] Q. Ouyang, J. Wu, S. Sun, J. Pensa, A. Abiri, E. P. Dutson, and J. W. Bisley, "Bio-inspired haptic feedback for artificial palpation in robotic surgery," *IEEE Trans. Biomed. Eng.*, vol. 68, no. 10, pp. 3184–3193, Oct. 2021.

[113] G. S. Fischer, J. Zand, M. Talamini, M. Marohn, T. Akinbiyi, K. Kanev, J. Kuo, P. Kazanzides, and R. Taylor, "Intra-operative ischemia sensing surgical instruments," in *Proc. Complex Med. Eng.* Japan: ICME, 2005, pp. 1–6.

[114] G. S. Fischer, T. Akinbiyi, S. Saha, J. Zand, M. Talamini, M. Marohn, and R. Taylor, "Ischemia and force sensing surgical instruments for augmenting available surgeon information," in *Proc. 1st IEEE/RAS-EMBS Int. Conf. Biomed. Robot. Biomechatronics*. Pisa, Italy, Feb. 2006, pp. 1030–1035.

[115] S. Dietsch, A. McDonald–Bowyer, E. Dimitrakakis, J. M. Coote, L. Lindenroth, A. Stilli, and D. Stoyanov, "Localization of interaction using fibre-optic shape sensing in soft-robotic surgery tools," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Kyoto, Japan, Oct. 2022, pp. 8057–8063.

[116] C. Shi, D. Song, D. Lai, and S. Wang, "Development of a high-sensitivity proximal force/torque sensor based on optical sensing for intravascular robots," *IEEE Trans. Med. Robot. Bionics*, vol. 4, no. 4, pp. 957–966, Nov. 2022.

[117] A. Issatayeva, A. Amantayeva, W. Blanc, D. Tosi, and C. Molardi, "Design and analysis of a fiber-optic sensing system for shape reconstruction of a minimally invasive surgical needle," *Sci. Rep.*, vol. 11, no. 1, pp. 1–12, Apr. 2021, doi: 10.1038/s41598-021-88117-7.

[118] J. Jivraj, C. Chen, D. Barrows, and V. X. D. Yang, "Optical coherence tomography for dynamic axial correction of an optical end-effector for robot-guided surgical laser ablation," *Opt. Eng.*, vol. 58, no. 5, pp. 1–8, May 2019.

[119] N. Haouchine, W. Kuang, S. Cotin, and M. Yip, "Vision-based force feedback estimation for robot-assisted surgery using instrument-constrained biomechanical three-dimensional maps," *IEEE Robot. Autom. Lett.*, vol. 3, no. 3, pp. 2160–2165, Jul. 2018.

[120] N. M. Bandari, R. Ahmadi, A. Hooshiar, J. Dargahi, and M. Packirisamy, "Hybrid piezoresistive-optical tactile sensor for simultaneous measurement of tissue stiffness and detection of tissue discontinuity in robot-assisted minimally invasive surgery," *J. Biomed. Opt.*, vol. 22, no. 7, Jul. 2017, Art. no. 077002.

[121] H. Xie, A. Jiang, H. A. Wurdemann, H. Liu, L. D. Seneviratne, and K. Althoefer, "Magnetic resonance-compatible tactile force sensor using fiber optics and vision sensor," *IEEE Sensors J.*, vol. 14, no. 3, pp. 829–838, Mar. 2014.

[122] R. Ahmadi, M. Packirisamy, J. Dargahi, and R. Cecere, "Discretely loaded beam-type optical fiber tactile sensor for tissue manipulation and palpation in minimally invasive robotic surgery," *IEEE Sensors J.*, vol. 12, no. 1, pp. 22–32, Jan. 2012.

[123] J. Ryu, J. Choi, and H. C. Kim, "Endoscopic vision based tracking of multiple surgical instruments in robot-assisted surgery," in *Proc. 12th Int. Conf. Control, Autom. Syst.*, Oct. 2012, pp. 2195–2198.

[124] H. Su, M. Zervas, G. A. Cole, C. Furlong, and G. S. Fischer, "Real-time MRI-guided needle placement robot with integrated fiber optic force sensing," in *Proc. IEEE Int. Conf. Robot. Autom.*, Shanghai, China, May 2011, pp. 1583–1588.

[125] S. Lavallée, P. Sautot, J. Troccaz, P. Cinquin, and P. Merloz, "Computer-assisted spine surgery: A technique for accurate transpedicular screw fixation using CT data and a 3-D optical localizer," *Comput. Aided Surg.*, vol. 1, no. 1, pp. 65–73, Jan. 1995.

[126] Q. Li, Z. Du, and H. Yu, "Temperature estimation for robotic bone milling surgery based on heat generation and conduction," *Measurement*, vol. 178, Jun. 2021, Art. no. 109411, doi: 10.1016/j.measurement.2021.109411.

[127] M. Sadeghi-Goughari and A. Mojra, "Intraoperative thermal imaging of brain tumors using a haptic-thermal robot with application in minimally invasive neurosurgery," *Appl. Thermal Eng.*, vol. 91, pp. 600–610, Dec. 2015, doi: 10.1016/j.applthermaleng.2015.08.032.

[128] M. Guiatni, V. Riboulet, C. Duriez, A. Kheddar, and S. Cotin, "A combined force and thermal feedback interface for minimally invasive procedures simulation," *IEEE/ASME Trans. Mechatronics*, vol. 18, no. 3, pp. 1170–1181, Jun. 2013.

[129] K. J. Rebello, "Applications of MEMS in surgery," *Proc. IEEE*, vol. 92, no. 1, pp. 43–55, Jan. 2004.

[130] H. Wang, Z. Du, L. Wang, Y. Zhang, X. Wang, Y. Gao, and H. Ren, "Design of a modular 3-D force sensor with fiber Bragg gratings for continuum surgical robot," *IEEE Trans. Instrum. Meas.*, vol. 72, pp. 1–11, 2023.

[131] Z. Chua and A. M. Okamura, "A modular 3-degrees-of-freedom force sensor for robot-assisted minimally invasive surgery research," *Sensors*, vol. 23, no. 11, p. 5230, May 2023.

[132] H. Zhang, C. Wang, M. Bai, H. Yi, J. Yang, Y. Zhu, and J. Zhao, "A micro-3-degree-of-freedom force sensor for intraocular dexterous surgical robots," *Adv. Intell. Syst.*, vol. 5, no. 7, pp. 1–9, Jul. 2023.

[133] C. Hou, K. Wang, F. Wang, H. Li, L. Lou, S. Zhang, Y. Gu, H. Liu, T. Chen, and L. Sun, "A highly integrated 3D MEMS force sensing module with variable sensitivity for robotic-assisted minimally invasive surgery," *Adv. Funct. Mater.*, vol. 33, no. 43, pp. 1–13, Oct. 2023.

[134] W. Lai, L. Cao, J. Liu, S. Chuan Tjin, and S. J. Phee, "A three-axial force sensor based on fiber Bragg gratings for surgical robots," *IEEE/ASME Trans. Mechatronics*, vol. 27, no. 2, pp. 777–789, Apr. 2022.

[135] J. Li, C. Wang, Z. Mao, Y. Liu, Z. Wang, and H. Liu, "A compact FBG-based triaxial force sensor with parallel helical beams for robotic-assisted surgery," *IEEE Trans. Instrum. Meas.*, vol. 71, pp. 1–9, 2022.

[136] G. A. Fontanelli, L. R. Buonocore, F. Ficuciello, L. Villani, and B. Siciliano, "An external force sensing system for minimally invasive robotic surgery," *IEEE/ASME Trans. Mechatronics*, vol. 25, no. 3, pp. 1543–1554, Jun. 2020.

[137] C. Gaudeni and D. Prattichizzo, "A mathematical model of the pneumatic force sensor for robot-assisted surgery," in *Proc. IEEE World Haptics Conf. (WHC)*, Tokyo, Japan, Jul. 2019, pp. 598–603.

[138] C. Gaudeni, L. Meli, and D. Prattichizzo, "A novel pneumatic force sensor for robot-assisted surgery," in *Haptics: Science, Technology, and Applications*, vol. 10894, 1st ed., D. Prattichizzo, H. Shinoda, H. Z. Tan, E. Ruffaldi, and A. Frisoli, Eds. Pisa, Italy, Cham, Switzerland: Springer, 2018, ch. 50, pp. 587–599, doi: 10.1007/978-3-319-93399-3_50.

[139] H. Su, I. I. Iordachita, J. Tokuda, N. Hata, X. Liu, R. Seifabadi, S. Xu, B. Wood, and G. S. Fischer, "Fiber-optic force sensors for MRI-guided interventions and rehabilitation: A review," *IEEE Sensors J.*, vol. 17, no. 7, pp. 1952–1963, Apr. 2017.

[140] U. Kim, D.-H. Lee, Y. B. Kim, D.-Y. Seok, J. So, and H. R. Choi, "S-surge: Novel portable surgical robot with multiaxis force-sensing capability for minimally invasive surgery," *IEEE/ASME Trans. Mechatronics*, vol. 22, no. 4, pp. 1717–1727, Aug. 2017.

[141] U. Kim, D.-H. Lee, W. J. Yoon, B. Hannaford, and H. R. Choi, "Force sensor integrated surgical forceps for minimally invasive robotic surgery," *IEEE Trans. Robot.*, vol. 31, no. 5, pp. 1214–1224, Oct. 2015.

[142] P. Puangmali, H. Liu, L. D. Seneviratne, P. Dasgupta, and K. Althoefer, "Miniature 3-axis distal force sensor for minimally invasive surgical palpation," *IEEE/ASME Trans. Mechatronics*, vol. 17, no. 4, pp. 646–656, Aug. 2012.

[143] P. J. Berkelman, L. L. Whitcomb, R. H. Taylor, and P. Jensen, "A miniature microsurgical instrument tip force sensor for enhanced force feedback during robot-assisted manipulation," *IEEE Trans. Robot. Autom.*, vol. 19, no. 5, pp. 917–922, Oct. 2003.

[144] P. J. Berkelman, L. L. Whitcomb, R. H. Taylor, and P. Jensen, "A miniature instrument tip force sensor for robot/human cooperative microsurgical manipulation with enhanced force feedback," in *Medical Image Computing and Computer-Assisted Intervention–(MICCAI)*, vol. 1935, S. L. Delp, A. M. DiGoia, and B. Jaramaz, Eds. Berlin, Germany: Springer, 2000, pp. 897–906.

[145] M. Rehan, M. M. Saleem, M. I. Tiwana, R. I. Shakoor, and R. Cheung, "A soft multi-axis high force range magnetic tactile sensor for force feedback in robotic surgical systems," *Sensors*, vol. 22, no. 9, p. 3500, May 2022.

[146] E. Rodr, A. P. Kypson, S. C. Moten, and L. W. Nifong, "A piezoresistive tactile sensor for tissue characterization during catheter-based cardiac surgery," *Int. J. Med. Robot. Comput. Assist. Surg.*, vol. 18, no. 4, pp. 211–215, Aug. 2006.

[147] M. A. Qasaimeh, S. Sokhanvar, J. Dargahi, and M. Kahrizi, "PVDF-based microfabricated tactile sensor for minimally invasive surgery," *J. Microelectromech. Syst.*, vol. 18, no. 1, pp. 195–207, Feb. 2009.

[148] A. S. Naidu, R. V. Patel, and M. D. Naish, "Low-cost disposable tactile sensors for palpation in minimally invasive surgery," *IEEE/ASME Trans. Mechatronics*, vol. 22, no. 1, pp. 127–137, Feb. 2017.

[149] S. Sareh, A. Jiang, A. Faragasso, Y. Noh, T. Nanayakkara, P. Dasgupta, L. D. Seneviratne, H. A. Wurdemann, and K. Althoefer, "Bio-inspired tactile sensor sleeve for surgical soft manipulators," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, Hong Kong, May 2014, pp. 1454–1459.

[150] P. Navalesi, C. M. Oddo, G. Chisci, A. Frosolini, P. Gennaro, V. Abbate, D. Prattichizzo, and G. Gabriele, "The use of tactile sensors in oral and maxillofacial surgery: An overview," *Bioengineering*, vol. 10, no. 7, p. 765, Jun. 2023.

[151] D. Zbyszewski, P. Polygerinos, L. D. Seneviratne, and K. Althoefer, "A novel MRI compatible air-cushion tactile sensor for minimally invasive surgery," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Oct. 2009, pp. 2647–2652.

[152] P. Goethals, M. M. Sette, D. Reynaerts, and H. Van Brussel, "Flexible elastoresistive tactile sensor for minimally invasive surgery," in *Haptics: Perception, Devices and Scenarios*, vol. 5024, 1st ed., P. Goethals, D. Reynaerts, H. V. Brussel, and M. M. Sette, Eds. Madrid, Spain, Berlin, Germany: Springer, 2008, pp. 573–579.

[153] K. Takashima, K. Yoshinaka, T. Okazaki, and K. Ikeuchi, "An endoscopic tactile sensor for low invasive surgery," *Sens. Actuators A, Phys.*, vol. 119, no. 2, pp. 372–383, Apr. 2005.

[154] J. Gafford, H. Aihara, C. Thompson, R. Wood, and C. Walsh, "Distal proprioceptive sensor for motion feedback in endoscope-based modular robotic systems," *IEEE Robot. Autom. Lett.*, vol. 3, no. 1, pp. 171–178, Jan. 2018.

[155] H. Huo, X. Liu, Z. Wu, Z. Tang, M. Tang, D. Chen, Y. Dong, X. Qiao, T. Liu, R. An, and Y. Fan, "Design of robot-assisted task involving visuomotor conflict for identification of proprioceptive acuity," *IEEE Trans. Instrum. Meas.*, vol. 70, pp. 1–10, 2021.

[156] N. Sornkarn, J. Konstantinova, P. Dasgupta, K. Althoefer, and T. Nanayakkara, "Palpation with controllable stiffness for robot-assisted minimally invasive surgery," in *Proc. Int. Conf. Robot. Autom. (ICRA)*. Hong Kong, 2014, pp. 1–5.

[157] Y. A. Chee, A. A. Bakir, and D. H. B. Wicaksono, "Proprioceptive sensing system for therapy assessment using textile-based biomedical micro electro mechanical system (MEMS)," in *Proc. IEEE SENSORS*, Taiwan, Oct. 2012, pp. 1–4.

[158] V. S. N. Sitaramgupta V, T. Sakorikar, and H. J. Pandya, "An MEMS-based force sensor: Packaging and proprioceptive force recognition through vibro-haptic feedback for catheters," *IEEE Trans. Instrum. Meas.*, vol. 71, pp. 1–11, 2022.

[159] Z. Li, A. Shaban, J.-G. Simard, D. Rabindran, S. Dimaio, and O. Mohareri, "A robotic 3D perception system for operating room environment awareness," in *Proc. 11th Int. Conf. Inf. Process. Comput.-Assist. Intervent.* Munich, Germany: Springer, 2020, pp. 1–14.

[160] A. M. Okamura, "Methods for haptic feedback in teleoperated robot-assisted surgery," *Ind. Robot, Int. J.*, vol. 31, no. 6, pp. 499–508, Dec. 2004.

[161] M. Tavakoli, R. V. Patel, and M. Moallem, "Haptic interaction in robot-assisted endoscopic surgery: A sensorized end-effector," *Internatioanl J. Med. Robot. Comput. Assist. Surg.*, vol. 1, no. 2, pp. 53–63, Jan. 2005.

[162] J. Konstantinova, A. Jiang, K. Althoefer, P. Dasgupta, and T. Nanayakkara, "Implementation of tactile sensing for palpation in robot-assisted minimally invasive surgery: A review," *IEEE Sensors J.*, vol. 14, no. 8, pp. 2490–2501, Aug. 2014.

[163] Y. Dai, Y. Xue, and J. Zhang, "Human-inspired haptic perception and control in robot-assisted milling surgery," *IEEE Trans. Haptics*, vol. 14, no. 2, pp. 359–370, Apr. 2021.

[164] Y. Li, F. Richter, J. Lu, E. K. Funk, R. K. Orosco, J. Zhu, and M. C. Yip, "SuPer: A surgical perception framework for endoscopic tissue manipulation with surgical robotics," *IEEE Robot. Autom. Lett.*, vol. 5, no. 2, pp. 2294–2301, Apr. 2020.

[165] C. Yang, Y. Xie, S. Liu, and D. Sun, "Force modeling, identification, and feedback control of robot-assisted needle insertion : A survey of the literature," *Sensors Rev.*, vol. 18, no. 2, pp. 1–32, Feb. 2018.

[166] R. Wen, C.-B. Chng, and C.-K. Chui, "Augmented reality guidance with multimodality imaging data and depth-perceived interaction for robot-assisted surgery," *Robotics*, vol. 6, no. 13, pp. 1–18, May 2017.

[167] A. Ehrampoosh, B. Shirinzadeh, J. Pinskier, J. Smith, R. Moshinsky, and Y. Zhong, "A force-feedback methodology for teleoperated suturing task in robotic-assisted minimally invasive surgery," *Sensors*, vol. 22, no. 20, p. 7829, Oct. 2022.

[168] F. Zhong, B. Li, W. Chen, and Y.-H. Liu, "Robot–camera calibration in tightly constrained environment using interactive perception," *IEEE Trans. Robot.*, to be published.

[169] S. C. Overley, S. K. Cho, A. I. Mehta, and P. M. Arnold, "Navigation and robotics in spinal surgery: Where are we now?" *Neurosurgery*, vol. 80, no. 3S, pp. S86–S99, Mar. 2017.

[170] R. B. Kochanski, J. M. Lombardi, J. L. Laratta, R. A. Lehman, and J. E. O'Toole, "Image-guided navigation and robotics in spine surgery," *Neurosurgery*, vol. 84, no. 6, pp. 1179–1189, Jun. 2019.

[171] A. Hussain, A. Malik, M. U. Halim, and A. M. Ali, "The use of robotics in surgery: A review," *Int. J. Clin. Pract.*, vol. 68, no. 11, pp. 1376–1382, Nov. 2014.

[172] H. Alfalahi, F. Renda, and C. Stefanini, "Concentric tube robots for minimally invasive surgery: Current applications and future opportunities," *IEEE Trans. Med. Robot. Bionics*, vol. 2, no. 3, pp. 410–424, Aug. 2020.

[173] M. Bhandari, T. Zeffiro, and M. Reddiboina, "Artificial intelligence and robotic surgery: Current perspective and future directions," *Current Opinion Urol.*, vol. 30, no. 1, pp. 48–54, Jan. 2020.

[174] J. Ruby, S. Daenke, Y. Yuan, W. Harry, J. Tisa, J. Nedumaan, Y. Yung, J. Lepika, T. Binford, P. S. J. Kumar, and W. Hu, "Robotic arm in surgery," *Amer. J. Clin. Surg.*, vol. 4, no. 1, pp. 10–18, Mar. 2020.

[175] S. O'Sullivan, N. Nevejans, C. Allen, A. Blyth, S. Leonard, U. Pagallo, K. Holzinger, A. Holzinger, M. I. Sajid, and H. Ashrafian, "Legal, regulatory, and ethical frameworks for development of standards in artificial intelligence (AI) and autonomous robotic surgery," *Int. J. Med. Robot. Comput. Assist. Surg.*, vol. 15, no. 1, pp. 1–12, Feb. 2019.

[176] V. Bellini, M. Guzzon, B. Bigliardi, M. Mordonini, S. Filippelli, and E. Bignami, "Artificial intelligence: A new tool in operating room management. Role of machine learning models in operating room optimization," *J. Med. Syst.*, vol. 44, no. 1, pp. 1–10, Jan. 2020.

[177] M. McKendrick, S. Yang, and G. A. McLeod, "The use of artificial intelligence and robotics in regional anaesthesia," *Anaesthesia*, vol. 76, no. S1, pp. 171–181, Jan. 2021.

[178] M. Runciman, A. Darzi, and G. P. Mylonas, "Soft robotics in minimally invasive surgery," *Soft Robot.*, vol. 6, no. 4, pp. 423–443, Aug. 2019.

[179] B. Mosadegh, P. Polygerinos, C. Keplinger, S. Wennstedt, R. F. Shepherd, U. Gupta, J. Shim, K. Bertoldi, C. J. Walsh, and G. M. Whitesides, "Pneumatic networks for soft robotics that actuate rapidly," *Adv. Funct. Mater.*, vol. 24, no. 15, pp. 2163–2170, Apr. 2014.

[180] C. Laschi, B. Mazzolai, and M. Cianchetti, "Soft robotics: Technologies and systems pushing the boundaries of robot abilities," *Sci. Robot.*, vol. 1, no. 1, pp. 1–10, Dec. 2016.

[181] A. Prasad, "Robotic Surgery in India," *J. Young Med. Researchers*, vol. 1, no. 1, pp. 1–13, Aug. 2013.

[182] B. T. Carpenter and C. P. Sundaram, "Training the next generation of surgeons in robotic surgery," *Robotic Surg., Res. Rev.*, vol. 4, pp. 39–44, Apr. 2017.

[183] A. Ahmad, Z. F. Ahmad, J. D. Carleton, and A. Agarwala, "Robotic surgery: Current perceptions and the clinical evidence," *Surgical Endoscopy*, vol. 31, no. 1, pp. 255–263, Jan. 2017.

[184] O. Yazicioglu and O. Borat, "Reflections on surgical robotics," *Quest J. J. Med. Dental Sci. Res.*, vol. 8, no. 9, pp. 37–44, Sep. 2021. [Online]. Available: www.questjournals.org

[185] B. S. Peters, P. R. Armijo, C. Krause, S. A. Choudhury, and D. Oleynikov, "Review of emerging surgical robotic technology," *Surgical Endoscopy*, vol. 32, no. 4, pp. 1636–1655, Apr. 2018, doi: 10.1007/s00464-018-6079-2.

[186] X. V. Wang and L. Wang, "A literature survey of the robotic technologies during the COVID-19 pandemic," *J. Manuf. Syst.*, vol. 60, pp. 823–836, Jul. 2021.

[187] Z. H. Khan, A. Siddique, and C. W. Lee, "Robotics utilization for healthcare digitization in global COVID-19 management," *Int. J. Environ. Res. Public Health*, vol. 17, no. 11, p. 3819, May 2020.

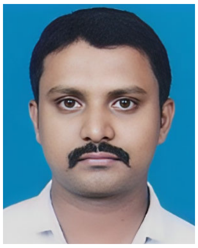
[188] G. N. Moawad, S. Rahman, M. A. Martino, and J. S. Klebanoff, "Robotic surgery during the COVID pandemic: Why now and why for the future," *J. Robotic Surg.*, vol. 14, no. 6, pp. 917–920, Dec. 2020, doi: 10.1007/s11701-020-01120-4.

SHARAD DINESH received the B.Tech. degree in mechanical engineering from the N.M.A.M. Institute of Technology (Nitte), Karnataka, India, in 2021, and the M.Tech. degree in industrial automation and robotics from the Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, India, in 2023. His research interests include robotics, machine learning and AI, automation, computer aided design, and surgical robot.

UMESH KUMAR SAHU received the B.E. degree in electronics and telecommunication engineering from Pt. Ravishankar Shukla University, Raipur, India, in 2007, the M.Tech. degree in instrumentation and control from the Bhilai Institute of Technology, Durg, India, in 2013, and the Ph.D. degree in electrical engineering from the National Institute of Technology Rourkela, Rourkela, India, in 2020. He is currently an Assistant Professor with the Department of Mechatronics, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka, India. His research interests include robotics and machine vision, image processing, instrumentation and control, network control systems, control of flexible robot manipulator, industrial automation, and intelligent robotic control.

DAMESHWARI SAHU received the B.E. degree in electronics and telecommunication engineering from Chhattisgarh Swami Vivekanand Technical University, Bhilai, India, in 2014, and the M.Tech. degree in instrumentation and control from the Bhilai Institute of Technology, Durg, India, in 2017. Her research interests include machine vision, image processing, and instrumentation and control.

SANTANU KUMAR DASH received the Ph.D. degree in electrical engineering from the National Institute of Technology Rourkela, India, in 2019. He is currently a Senior Assistant Professor with the TIFAC-CORE Research Center, Vellore Institute of Technology, India. His research interests include power quality, grid connected systems, distributed generations, and embedded system application for power converter control.



UMESH KUMAR YADAV (Member, IEEE) received the degree in electrical and electronics engineering, and the master's degree in power system engineering. He has more than ten years of teaching experience in academics. In his academic career, he has been associated with the Government Engineering College, Raipur, for two years, and with the Department of Electrical Engineering, NIT Raipur. Before joining the Ph.D. in MNIT, and with the Renewable Energy Department, Pt. RSSU Raipur. He is currently a Research Scholar with the Department of Electrical Engineering, MNIT Jaipur. His research interests include system modelling and control, order reduction and optimization, soft computing, machine learning, and systematic learning approach.

• • •

Open Access funding provided by 'Manipal Academy of Higher Education' within the CRUI CARE Agreement