Vol. 7, No. 3, November 2025 (Special Issue), pp. 241~263, p-ISSN 2685-2381, e-ISSN 2715-2626
http://dx.doi.org/10.28989/avitec.v7i3.2941

A Systematic Review of Surgical Robots and Controls for Teleoperations

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Article Info

Article history:
Submitted April 17, 2025
Accepted May 28, 2025
Published August 19, 2025

ABSTRACT

The advancements in healthcare technology have transformed the landscape of medical practice, with robotics emerging as a prominent feature. The use of teleoperation, particularly in remote robot-assisted surgeries, has obtained significant attention and acclaim for its potential to enhance surgical outcomes and expand access to specialized care. Despite the increase in research in this domain, there remains a need for a thorough and systematic review to consolidate the diverse findings and conclusions. This work presents an organized synthesis of existing related works using Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA), facilitating easier access to vital information for researchers, practitioners, and innovators. To achieve this, the historical development of surgical robots were explored. Furthermore, different types of surgical robots with various architecture were extensively examined to highlight the relevance of their application. Imperatively, advancements in teleoperability and control systems of surgical robots were comprehensively discussed underscoring its growing influence in current healthcare delivery. Moreover, practical challenges faced by teleoperated surgical robots were highlighted and elaborated to point out their limitations. Additionally, future directions aimed to tackle the identified shortfalls in robotic surgery and teleoperation were considered. In this regard, this work provided an impactful contribution that positively influences growth in the area of robotic surgery and teleoperation by consolidating several insights into a cohesive framework which ultimately seek to improve patient care.

Keywords:
Surgical robotic architecture;
teleoperability and control systems;
robot-assisted surgery.

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1. INTRODUCTION

Robotic systems have the capability of performing functions and activities for people to make their lives easier and to manage the typical work process [1]. Robots improve productivity and efficiency in so many different fields. They can perform repetitive tasks for lengthy periods, are very accurate as well as useful in operations that may be hazardous to humans. Among many fields, robotics has also greatly influenced health care. In 1985, Shao et al. utilized industrial robot to conduct a neurosurgical biopsy. The success of the procedure positively impacted and altered the course of robotic surgery. Since its inception, surgical robotics have gone through several phases as many procedures conducted with robot assistance have become less intrusive and more complicated [2].

Teleoperations, which involves controlling systems from a distance, is a key part of this progress [3][4]. Many more advances have taken place and notable among them is the Da Vinci [5]. Employing a tele-operative system with haptic feedback gives users the chance to immerse themselves in a distant environment and execute tasks without being physically present [6]. Originally used in aerospace and defense, teleoperation has become crucial in health care, particularly in surgery. Surgical Robotics with Teleoperations has been crucial as it allows precise control of surgical instruments from afar. This capability improves the surgeon's ability to perform delicate tasks with greater accuracy. It is also useful in emergency operations when the surgeon cannot be physically present. This study covers a systematic and comprehensive review of teleoperations and robotics especially of surgical robots that have been developed to date. This work also seeks to provide an elaboration on the operations of surgical robots, the various types of surgical robots, the advantages and disadvantages as well as the challenges faced in the use of these robots in the medical field.

The outline for this paper is as follows: Section 2 offers a comprehensive overview of the data collection process for this review. It outlines the specific search criteria employed, and the journals that were reviewed, and details the quantity, number, and types of literature studies that contributed to the development of this research paper. Section 3 discusses the various types of surgical robots, delving into their system architecture and the actuation mechanisms that power these advanced technologies. This discussion aims to clarify the design and functional capabilities of these innovative robotic systems in the field of surgery. Section 4 focuses on teleoperation in surgical robotics, examining the various feedback methods utilized, as well as the control modes and algorithms that govern their operation. This section aims to provide a detailed understanding of how remote operation enhances surgical precision and effectiveness through advanced technology. Section 5 explores the different surgical procedures that have benefited from the use of robotic systems to prioritize future investments. Section 6 addresses the challenges that surgical robots face in the medical field. It examines the various obstacles, including technical limitations, cost considerations, and the need for specialized training, that can impact the implementation and effectiveness of robotic systems in surgery. This section aims to provide a balanced perspective on the hurdles to surmount in order to fully realize the potential of robotic technology in healthcare. Section 7 highlights the future directions of the technology and summarizes the key findings of our study, presenting the main insights and conclusions reached throughout our research. This section seeks to underscore the importance of these results and their potential impact on the future of robotic surgery. Holistically, the rationale for selecting and addressing these respective sections is to provide detailed understanding of the current states of surgical robotics while exploring vital theoretical, practical and future-oriented areas.

2. RESEARCH METHODS

In this study, a structured procedure involving Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) framework was utilized to perform and report on the systematic search that incorporates major virtual databases recognized in research and academia. Due to its transparency in reliable search and identification of primary journals coupled with thorough examination of important reference studies, this work adopted PRISMA in the methodology to ensure reliable and reproducible review in this field of critical interest. The investigation focuses on various instances where the application of surgical robots in medicine has been suggested or implemented. For the scoping analysis, the PRISMA flow diagram, as depicted in Figure 1 was utilized.

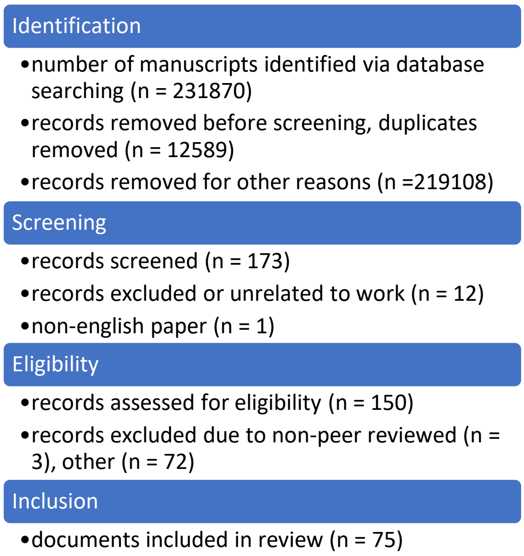

Figure 1. Search criteria

2.1 Data source

A systematic search strategy was executed between June and October 2024. This process involved rigorous scans of prominent digital repositories, along with targeted searches for key articles from reputable sources. The electronic files were examined using a combination of primary keywords and relevant topic headings. This review focused exclusively on papers written in English. A considerable number of the collected articles were discarded as their titles did not satisfy the specific criteria set after an extensive examination of the various databases. This review focused exclusively on papers written in English. A considerable number of the collected articles were discarded as their titles did not satisfy the specific criteria set after an extensive examination of the various databases, and a systematic search strategy was implemented. This included comprehensive scans of major electronic archives, targeted searches of key articles, and hand searches of reference lists from prior systematic reviews and meta-analyses. The electronic files were examined using a combination of primary keywords and relevant topic headings.

Table 1. Search string selection

String	Batch 1(B1)	Batch 2 (B2)
String 1 (S1)	Surgical Robot	Teleoperations
String 2 (S2)	Surgical Robots	Teleoperations
String 3 (S3)	Surgical Robotics	Teleoperations
String 4 (S4)	Robotic surgery	Teleoperations
String 5 (S5)	Surgical Technology	Remote Surgery
String 6 (S6)		Telesurgery

Search String: ([S1, B1], [S4, B1], [S5, B1], [S1,B1] AND [S1,B2], [S4,B1] AND [S1,B2], [S5,B1] AND [S1,B2], [S1,B1] AND [S5,B2], [S1,B1] AND [S6,B2], [S6, B2].

Table 2. Inclusion and exclusion selection methods

Selection method	Inclusion Criteria	Exclusion Criteria
Technical presentation and impact of research paper	1. Written in English 2. Innovative and the novel contributions to the field 3. Methodological rigor	Closed access journals
Scope and relevance to the research question	Surgical Robotics and Teleoperations	Non-surgical healthcare robots
Timeline	Recency or present times of literature	Literature published 5-10 years ago
Quality of the publication or source	1. Research Gate 2. Academia edu 3. IEEE Xplorer 4. Google Scholar 5. Pubmed	Non-peer reviewed journals

Therefore, the structured approach summarized in Table 1 and Table 2 provided a bias-free and meticulous foundation on which the subsequent aspects of this review was extensively developed.

This section elaborated on all the key concepts that guided the scope and methodology of the research. Moreover, it offered a comprehensive overview of the system architecture of surgical robots. Each innovation or advancement existing in modern surgical robotic systems was identified and discussed Furthermore, limitations associated with current technologies were highlighted. Thus, this work explored and addressed the following research questions:

1. What are the theoretical foundations that support the development and control of surgical robots?
2. How do teleoperation improve surgeon-robot interaction in surgeries and what type of feedback systems are most efficient?
3. What are the most prevalent clinical applications of surgical robots, how they affect healthcare delivery and what emerging fields are most immensely impacted?
4. What are the technical and operational setbacks facing their broader design, cost, accessibility and utilization?

What are the long-term implications of improving teleoperation of surgical robotics with advanced sensor technologies, augmented reality and predictive machine learning models?

2.2 Evolution of Surgical Robots

The concept of robotic surgery came to light in the 1970s from robotics research funded by NASA and the U.S. Defense Advanced Research Projects Agency [7-10]. The main goal was to develop a system that could allow surgeries to be performed remotely, eliminating the need for surgeons to be physically present in dangerous or inaccessible locations like battlefields or spacecraft. In 1983, Dr. Yik San Kwoh and his team at the University of California designed the Arthrobot; a robot explicitly designed to assist a patient during surgery. It was operated together with the Programmable Universal Machine for Assembly (PUMA 560) for neurosurgical biopsies with incredible precision, down to 0.05mm. The technology developed and began to include urological as well as prostate procedures at the Imperial College. In 1988, ProBot was developed in Imperial College in London to aid transurethral prostatectomies. This robotic system introduced four axes to assist with movement, utilized high-speed rotating blade which enabled resection, and a compact design tailored for prostate surgery. In 1989, Yulun Wang founded Computer Motion Inc., which became a leading provider of surgical robots. Their robotic arm known as AESOP 1000 which had the feature of a pedal control, was approved in 1994 by the FDA, historically making it the first telepresence surgical robot for orthopedic surgery. Over time, it evolved into the voice-controlled AESOP 2000 and later had models that included features like operating room lighting control. The AESOP system was later upgraded and evolved into the ZEUS Robotic Surgical System [11], which featured three remotely controlled arms. In 1995 however, Intuitive Surgery, an American biotechnology company, designed the Lenny System which was an early prototype for robotic surgery and it laid the groundwork for the now famous and hugely successful da Vinci system. In 1998, Intuitive Surgical launched the initial da Vinci "Standard" surgical robot, which was first utilized at the Cleveland Clinic in Cleveland, Ohio. In 2003, Computer Motion discontinued the use of the ZEUS and joined Intuitive Surgical. This collaboration has caused massive advancements in the world of surgical robotics and since the FDA approved of da Vinci Standard System in 2000, newer generations with more advanced features have been designed: it includes the S system (2003) which is the first of the generations, the Si System (2009) as the second, and the Xi System (2014) as the third generation.

2.3 Classification of Surgical Robots

Robotics in this field can be classified into the following:

2.3.1 Robotic telesurgery

Here, the surgeon controls the robotic arm performing the surgery remotely from a master console. Several robotic platforms have been utilized for human telesurgery, with the ZEUS platform being the most extensively documented. Although the Da Vinci platform is widely used in clinical settings, it has not been employed for human remote telesurgery [12].

2.3.2 Image-Guided Surgical Robotics

Here, a human is not needed in the loop as images like CT, and MRI among others as the robots autonomously execute part or all of the surgery based on these images. Notwithstanding, a surgeon supervises the procedure. The patient data serves as a guide. For surgeries to occur in real time, the surgical robot needs to be able to navigate freely in the given environment and so they are integrated with machine vision. An existing structure known as Structure from Motion (SFM) exists which can derive 3D information from 2D images but there is a challenge of offline processing when handling low-resolution images as well as average blow performance. A visual odometer might work but it is not suitable for intracavity tissues in laparoscopic surgeries. Simultaneous Localization and Mapping technology (SLAM) is adopted to assist in navigation. It is unique due to its ability to perform simultaneous recursive completion of mapping and positioning and provide timely feedback to surgeons. The major issues brought about due to the SLAM technique are bad performance due to movement of equipment and data scarcity but it can be solved by adopting a system of dynamic object detection and image segmentation to reduce inefficiency based on movement. Data scarcity is solved by using a learning-based single-frame stereo depth estimation method that enhances the robustness of texture-less surfaces.

2.3.3 Cooperative Control in Surgery

Here, the surgeon directly uses robotic tools for the surgery especially because great precision is required. It has reshaped how medical services are viewed and delivered. Medical robots and surgical systems are a fast-expanding sector within service robotics.

2.3.4 Levels of autonomy

Table 3 provides levels of autonomy in robotic surgery [13-14].

Table 3. Surgical robot's autonomy levels

Level of Autonomy	Description	Example
LEVEL 0: NO AUTONOMY	At this level, the surgeon independently generates, selects, executes, and monitors all surgical actions. These tasks are performed entirely by the surgeon without any assistance from a robotic device	Traditional vehicles
LEVEL 1: ROBOT ASSISTANCE	At this level, the surgeon is responsible for generating, selecting, executing, and monitoring all surgical actions, while the surgical robot assists in execution and monitoring. The robot offers minimal support and does not significantly interfere with the surgeon's intended motion paths. About 86% of all robotic surgeries fall under level 1	Adaptive cruise control
LEVEL 2: TASK AUTONOMY	Task autonomy refers to the ability of surgical robots to independently perform and oversee predefined automated actions for a specific task after being chosen by the surgeon, removing the necessity for direct surgeon intervention.	Autopilot features in some cars
LEVEL 3: CONDITIONAL AUTONOMY	Surgical robots in this category can suggest patient-specific strategies for surgical tasks or procedures, which the surgeon can either approve or modify. Once approved, the robot autonomously executes and monitors the actions based on the surgeon-approved plan.	Self-driving taxis in specific areas
LEVEL 4: HIGH-LEVEL AUTONOMY	High-level autonomy in surgical robots allows the surgeon to approve the surgical plan and oversee the procedure, with the option to intervene if necessary or upon request. These robotic systems can independently perform the procedure on their own without requiring the surgeon's direct involvement. They are capable of generating and proactively selecting the most suitable surgical plan tailored to the patient, executing, and monitoring it autonomously once approved by the surgeon.	Fully autonomous vehicles in controlled environments
LEVEL 5: FULL AUTONOMY	As the name implies, surgical robots at this level operate autonomously, making decisions throughout the entire surgical process, including preoperative procedures. These advanced systems can create and choose the most suitable surgical plan tailored to the patient without requiring prior authorization from the surgeon, while independently carrying out and overseeing the procedure.	Hypothetical future self-driving cars that can drive anywhere.

2.4 Types of Surgical Robots

Surgical robots are categorized based on their operative functions or mode of operation. These categories include passive robots, active robots, synergistic systems, and master-slave systems.

2.4.1 Passive robots

They are used as tool-holders and do not perform any operative tasks. The main advantage is that they do not tire and can keep tools accurately in position for extended periods.

2.4.2 Active robots

These are designed to perform more complex motions than passive robots. They are tasked with carrying out specific operative functions autonomously. Most active robots are developed to handle one particular task within the overall surgical procedure [15].

2.4.3 Synergistic systems

Both the surgeon and a computer manage the controls of this system. The surgeon can operate the machine within set range of motion and force. While the surgeon performs the operational task, the synergistic system constrains the surgeon's actions to minimize the risk of errors while still utilizing the surgeon's skills and judgment.

2.4.4 Master-slave systems

There are also non-autonomous. The master side includes the surgeon, the master robot, and visual and haptic displays, all of which are controlled by the surgeon. On the slave side, there is the patient, the slave robot, and haptic sensors and cameras, with the slave robot being controlled based on the surgeon's input [16].

2.5 Examples of Surgical Robots

2.5.1 Soft robots

Minimally invasive surgery is a system that demands maximum flexibility. This is especially highlighted in complicated surgical interventions like otolaryngology, lung bronchoscopy as well as endovascular interventions. Hence the need for the slender and agile continuum and hyper-redundant robots. [17] investigated the bending behavior of a soft robot under single-degree deformation, focusing on the influence of activating a single air chamber. The study aimed to reduce the actuation effort required for movement. The bending motion was achieved by inflating one air chamber while simultaneously applying tension to a single tendon, resulting in a two-dimensional bending effect. To develop a mathematical model of this process, various factors were taken into account, including the applied air pressure, tendon force, and radial expansion of the soft structure. The research sought to identify an optimal configuration that would produce the intended mechanical response while minimizing the objective function.

2.5.2 Continuum robots

Continuum robots are modeled after natural structures like trunks, tentacles, and snakes, enabling them to move through tight spaces, handle objects in unpredictable settings, and follow flexible, curved trajectories [18]. Original medical robots are rigidly connected, but their limitations stem from their mutual connections. A continuum robot has three segments that enable it to move flexibly in small spaces. Most continuum robots are tendon-driven. However, new materials have been developed and applied to continuum robots. For example, there are robots embedded with ferromagnetic composite materials as a continuum robot, which can rotate over 180 degrees. Some continuum robots have also been developed by combining ionic liquid conductors and tendon-driving methods.

2.5.3 Hyper-redundant robots

Hyper-redundant robots are very similar to continuum robots possessing a high degree of freedom [19]. Their mechanical design can vary significantly based on the specific needs of an application. The control algorithm of these redundant manipulators includes inverse kinematics, which typically requires calculating the Jacobian pseudo-inverse. While these robots come with certain drawbacks, they are most effective in specialized applications. Nevertheless, the dexterity provided is an essential requirement for surgical robotics.

2.5.4 The Zeus system

The da Vinci and Zeus robotic surgery systems possess similar capabilities but differ in their approaches. Both function as advanced master-slave surgical robots, featuring multiple remotely controlled arms operated from a console with video-assisted visualization and computer-enhanced precision The da Vinci system has significantly transformed surgical procedures since receiving FDA approval in 2000. The Zeus system consists of a surgeon control console and three robotic arms mounted on the operating table, as depicted in Figure 2. The left and right robotic arms mimic the surgeon's hand movements, while the third arm, AESOP, is a voice-controlled robotic endoscope that aids in visualization. In the Zeus system, the surgeon sits in an ergonomically designed upright position, with the video monitor and instrument controls arranged to enhance dexterity and provide a comprehensive view of the operating room. This system employs both straight-shafted endoscopic instruments, similar to traditional ones, and jointed instruments with articulating end-effectors, offering 7 degrees of freedom [20].

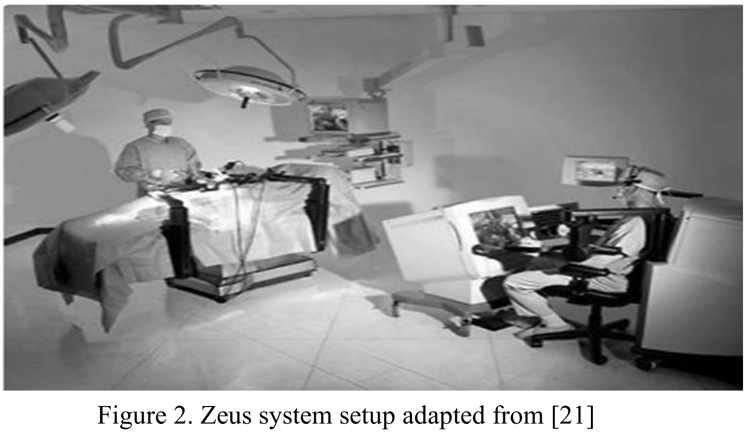

Figure 2. Zeus system setup adapted from [21]

2.5.5 DaVinci Robot

The daVinci robotic system is currently the most adaptable master-slave robotic system available [22]. It was approved by the FDA in 2000 and has significantly transformed surgical procedures since then [23]. Mona, a daVinci Prototype in 1997 performed the first human trials in Belgium [24]. The da Vinci Surgical system consists of three main structures. Table 4 contains the daVinci system parts and functions.

Table 4. daVinci System components

Part	Description	Image
Surgeon cart	With this tool, the surgeon gains a high-resolution 3D perspective and precise access to the surgical area. The advantages of the da Vinci system include less post-operative discomfort, shorter hospital stays, quicker patient recovery, improved maneuverability, and decreased surgeon fatigue. Thus, this system enables surgeons to perform minimal intrusive surgeries with improved precision and control	
Patient cart	This is positioned next to the patient's bed, where the camera and surgical instruments, operated by the surgeon during the procedure, are located.	
Vision cart	This device serves as a link between components, enabling the achievement of a high-quality image from the vision system	

The da Vinci robotic system features two advanced digital cameras equipped with dual lenses and three-chip technology. Each camera captures the surgical field from distinct perspectives, delivering separate images to each eye. This process enables the cerebral cortex of the brain to perceive a three-dimensional image. Additionally, the system incorporates a flexible endoscope with three degrees of freedom, enhancing synchronization between the visual display, the surgeon’s perspective, and the surgical instruments.

daVinci system can suffer the challenge of the lack of tangible feedback and also the issue of anatomical orientation. Surgeons must retain anatomical structures by studying preoperative imaging. To solve this, an IGSN is used. This provides the surgeon with a precise three-dimensional anatomical guide, offering real-time alignment with the surgical field. This IGSN system navigates using electromagnetic tracking (EMT). The very presence of the robot distorts the electromagnetic field and reduces accuracy. For this reason, two distinct electromagnetic field generators were utilized within a clinical surgical setting [22]: a Table Top Field Generator (TTFG) and a Planar Field Generator (PFG).

2.5.6 Hinotori Robot

Medicaroid developed the Hinotori surgical robot system and its related instruments [26]. The system has successfully performed complex procedures, such as a robotic spleen-preserving distal pancreatectomy, which is a significant achievement given the complexity of the procedure. The Hinotori has demonstrated its capabilities in highly advanced pancreatic surgery.

Both the Hinotori and daVinci systems are equipped with articulated arms that allow for meticulous and precise movements, featuring tremor filtering and motion scaling. Each system has four arms, and the console surgeon can perform the procedure in a similar manner with both. However, the Hinotori has some features that distinguish it from the daVinci system. Notably, the Hinotori offers greater degrees of freedom for each arm, which enhances the flexibility of its movements compared to the da Vinci system.

Despite these advantages, Hinotori lacks adjustability in its axes, unlike daVinci system, which includes a patient clearance feature to prevent the robotic arms from colliding with the patient’s body. This feature allows the patient-side surgeons to resolve any arm interference without interrupting the console surgeon’s work. In contrast, with Hinotori, the console surgeon must pause the procedure and adjust the arm position under the guidance of the patient-side surgeons. Regardless of the system used, it is crucial to manage potential interference between the robotic arms and collisions with the patient’s body throughout the operation. Additionally, when the axes are fully extended, Hinotori’s robotic arm movements are significantly restricted. This presents a disadvantage compared to the daVinci system, especially during procedures in the ventral abdomen or on the opposite side of the lateral arms, where the full extension of the arms can hinder maneuverability. Careful port placement is essential with the Hinotori to avoid the need for arm extension.

The most significant difference between the Hinotori and daVinci systems is that the Hinotori's software determines the pivot position for each arm without requiring the attachment of a trocar. Table 5 shows a comparison.

Table 5. daVinci vrs Hinotori

Surgical system	Hinotori surgical system	da Vinci surgical system
Manufacturer	Medicaroid Corporation, Kobe, Japan	Intuitive Surgical, Inc, Sunnyvale, CA, USA
Regulatory approval(year)	Japanese Ministry of Health, Labor and Welfare (2020)	US Food and Drug Administration (1998)
Camera	Three-dimensional high-definition	Three-dimensional high-definition
Motion scaling	Yes	Yes
Tremor filtering	Yes	Yes
Number of robotic arms	4	4
Number of axes	8	7
Adjustability of the axes	No	Yes, with patient clearance button
Docking	Docking-free design	Docking design
Center of motion	Pivot position by software	Remote center by dedicated trocar
Instrument types	11	39

2.5.7 Flex robotic system

Medrobotics Corporation developed a flexible surgical robot designed for cardio and transoral surgeries. This robot offers improved 3D visualization, enhanced flexibility, and precise access to anatomical locations. Its primary aim is to perform surgeries without leaving visible scars, addressing the limitations posed by rigid robots [27]. The main purpose of the flexible robotic system is to locate and remove tumors, a task that is often difficult when performed manually.

The robot's advanced adaptability, high-resolution 3D imaging, and precise maneuverability enable surgeons to navigate intricate pathways and carry out minimally invasive procedures. The Medrobotics surgical system holds promise for greatly enhancing surgical results and improving patient experiences in both cardio and transoral surgeries [28][29].

2.5.8 DLR Microsurge

The surgical robot developed by the German Aerospace Centre (DLR) operates on a tele-manipulation system for minimally invasive surgeries. It features three robotic arms, each offering seven degrees of freedom. One of these arms is equipped with a 3D imaging system, while the remaining two are designed to handle surgical instruments. [30]. The system features contact-free interfaces, enabling surgeons to control the robotic arms via a console. Additionally, it provides excellent haptic feedback for instrument manipulation, enhancing the surgeon's tactile experience during the procedure [31][32].

2.5.9 Mazor X Surgical

Medtronic's robotic system is built to assist surgeons in spinal procedures by utilizing a 3D model of the patient's spine to assess and adjust the surgical approach. This advanced technology features an automated robotic arm and ambidextrous controls. Its primary objective is to enhance surgical accuracy and support the surgeon throughout the operation [33][34].

2.5.10 Marko Smart Robotics

The Mako surgical robot, designed by Mako Surgical Corp®, utilizes Robotics Arm Interactive Orthopaedic (RIO) technology. It is designed to aid in both partial and total knee replacement surgeries. A CT scan generates a three-dimensional model of the patient's knee, allowing the robotic arm to precisely remove damaged bone and cartilage. The robotic arm then replaces the removed tissue with the knee model. The Marko surgical robot allows medical professionals to carry out knee replacement procedures with enhanced accuracy and precision.

2.5.11 Actuation Mechanisms of Surgical robots

Actuation enables surgical instruments to move and perform manipulations [35]. Minimally Invasive Surgery (MIS) offers numerous advantages to patients, including less trauma due to smaller incisions, reduced hospital stays and recovery periods, as well as fewer post-operative complications and pain. Various types of soft robots have been designed for MIS, utilizing different actuation techniques such as cable-driven, fluid-powered, and magnetically controlled mechanisms.

2.5.12 Cable driven surgical robots

Cable-driven actuation is the most popularly technique employed in recent modern multi-joint rigid surgical instruments. n this approach, cables function as the medium for force transmission, conveying motion and force from either an electric motor or a human hand to the regions along the cable's path. [35]. Most surgical robots employ tendon-sheath structures due to their flexibility, compact size, and ease of control. However, there are some challenges related to the friction characteristics of long-distance cable tension estimation. The Cable-Conduit Mechanism (CCM) is preferred over other transmission systems because it can operate effectively in confined workspaces and navigate long, narrow, and tortuous paths [36]. An innovative solution proposed by [37] involves a miniature tension array designed to integrate sensors into the distal end of long and flexible surgical instruments.

The design is a scaffold constructed through a laser welding process that fuses thermoplastic sheet laminates together, forming airtight compartments. This design enables it to collapse into a compact size when deflated. However, when the compartments are filled with air and pressurized, the scaffold’s framework expands into a prismatic form. The sensor design Involved a force compensation strategy. It utilizes the Capstan equation to account for friction and bending angles in the cables. This way, errors in force perception can be minimized resulting in more accurate measurements of the external forces acting on the robot’s end-effector during operation. This was validated after a series of experiments undertaken. These tests aimed to analyze the ability of the sensors to differentiate between various tissue stiffness levels. The sensor array achieved an average error of 0.173 N in force estimation, showcasing its reliability in real-time applications, which is essential for enhancing surgical outcomes.

2.5.13 Fluid Actuation

Minimally invasive surgery (MIS) imposes various challenges for designing robotic systems intended to aid medical practitioners during procedures. The drawbacks of traditional rigid robotic devices have spurred interest in soft robotics for medical use. Although rigid structures provide greater accuracy, their restricted flexibility and comparatively larger size hinder the expansion of the operational space and the reduction of trauma during operations. Despite their advantages, soft robotic actuators still face challenges related to force exertion and positioning capabilities, alongside the size restrictions necessary for MIS [38].

To address these challenges, surgical robots must enhance tool maneuverability and precision. Many existing systems depend on large external robots that control cable-driven instruments. Among the various actuation methods in soft robotics, fluidic actuation is widely adopted due to its ease of implementation and low cost. This technique is classified into pneumatic-driven and hydraulic-driven systems, depending on the fluid medium used. Both actuation types involve regulating fluid pressure within soft chambers to induce or generate the desired movement or shape deformation in soft devices. Various methods, such as asymmetry in chamber distribution, material stiffness variations, embedding non-stretchable materials, and regulating actuation sequences, have been proposed to achieve the desired performance.

Hydraulic surgical instruments typically exhibit greater output stress and better control accuracy compared to pneumatic systems, thanks to hydraulics' advantages in power density and incompressibility. These characteristics make hydraulic actuation more suitable for embedding surgical robotics endoscopically, and it helps avoid the friction issues associated with long Bowden cables [39]. However, the significant nonlinear behavior of soft actuators, combined with their intricate geometries, poses major obstacles to developing precise mathematical models. The hyper-elastic nature of soft materials introduces one layer of complexity, which is further compounded by the nonlinear characteristics of pneumatic actuation—such as air compressibility, the nonlinear correlation between pressure and flow in valves, and inherent time delays. Regardless of the specific actuator type, pneumatic systems play a crucial role in shaping the pressure dynamics of soft actuators, making precise pressure regulation essential for optimizing the overall performance of soft robots [40].

2.5.14 Multimodal Image fusion

The popularity gained by surgical robots over the years is due mainly because of the reduced risks such surgeries provide. Current surgical robotic systems however, rely on unimodal computed tomography and this limits their visualization. To address this inherent limitation, [41] proposed a software system based on multimodal image fusion. Multimodal image fusion is a technique that integrates multiple imaging modalities to create a single composite image that contains more comprehensive information as compared to individual images from different modalities. Simply, it is an image processing and computer vision that combines multiple images from different modalities. For instance, Computed tomography scans (CT) are used to obtain information about the bones while Magnetic Resonant Imaging (MRI) gives information on soft tissues. Fusing the two allows medical personnel to view the bones and tissues in a single structure. Medical analysis becomes more efficient and practical as compared to both providing individual information. It can also improve accuracy in pedicle screw placement, percutaneous kyphoplasty and other surgical operations. It also shortens the duration of surgeries and helps reduce complications.

The construction of spine models using multimodal image fusion technology requires different critical techniques, including vertebral bone segmentation, nerve extraction, and multimodal image registration and integration, along with the assessment of interconnected facet joints. While advancements have been achieved in deep learning-driven vertebral segmentation, challenges remain in terms of long processing times and low accuracy levels. To address these issues, an interactive dual-output vertebral instance segmentation algorithm was developed. The training and refinement of this algorithm resulted in consistently high accuracy for both overall and localized segmentation. Compared to existing approaches, the algorithm's training process was accelerated by 2.7 times, while its segmentation speed was enhanced by a factor of four. Studies have shown that while conventional CT-based vertebral segmentation methods can achieve accurate segmentation for basic vertebral regions, but several challenges still exist. Figure 3 depicts different types of multimodal medical images.

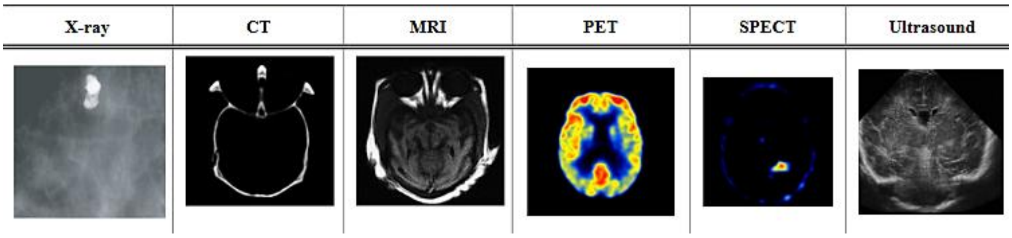

Figure 3. Image adapted from Ref. [42]

2.6 Advantages of Surgical Robots to Surgeons

Surgical robots provide exceptional abilities like repeatability with fewer mistakes, stability and accuracy, tolerance of ionizing radiation, as well as manage multiple simultaneous tasks. These capabilities somewhat come as a challenge to humans and therefore surgeons. Surgeons have challenges like tremors, fatigue, and ineffectiveness at the submillimeter scale. Surgical robots therefore complement surgeons to achieve a more successful surgical procedure when these qualities are needed [43]. Table 6 contains some areas where surgical robots are applied.

Table 6. Surgical robot applications

Task	Application
Decision making	During the surgical process, robots assist in major decision-making. An example is imaging modalities such as ultrasound providing more information on organs being operated on. Again, autonomous systems when fed with the necessary information can make decisions based on their program and input.
Navigation	Navigation inside the human body with developments like augmented and mixed reality, navigation during minimally invasive surgery is enhanced.
Object recognition	Haptic feedback, force feedback together with the experience of the surgeon make object recognition in hard-to-reach places more effect.
Orthopedic Surgery	TSolution-One and Mako Robotic Arm. It enables precision during joint replacements and hip arthroplasty.
Cardiac Surgery	Robotic Catheters and Soft Robotic Heart Support Devices. The former helps in heart leakage closure whereas the latter serves as heart support for patients with heart failures.
Head and Neck Surgery	Flex System. This system's joystick-controlled endoscope provides easy maneuvering in restricted places like the pharynx and skull base. [44]

Bilateral control is an essential aspect of surgical teleoperations. It comprises of different architectural designs that couple the master and slave robots as illustrated in Figure 4. The master robot, controlled by the surgeon, receives sensory data. This data is transferred to the slave robots which mimics the master robot's movements [57]. Below is a brief explanation of the different types.

2.7 Position-Position Architecture

Under this design, both robots are instructed to track each other. It makes use of a tracking controller called a proportional-derivative (PD) controller and it does so with the following command in Equation (1).

$$F_m = -K_m(x_m - x_{md}) - B_m(\dot{x}_m - \dot{x}_{md}) \quad (1)$$
$$F_s = -K_s(x_s - x_{sd}) - B_s(\dot{x}_s - \dot{x}_{sd})$$

If the position and velocity gains are the same, so that,

$$(K_m = K_s = K, B_m = B_s = B) \quad (2)$$

Then the two forces are the same and the system effectively provides force feedback. On the other hand, if the robots differ significantly, the forces will be distorted, Assuming the slave is under impedance control and back-drivable, the system operates normally. However, in situations where the slave is not back-drivable, environmental forces may be hidden from the user thereby defeating the purpose of force feedback. To address this, the position-force architecture in Figure 5 is chosen.

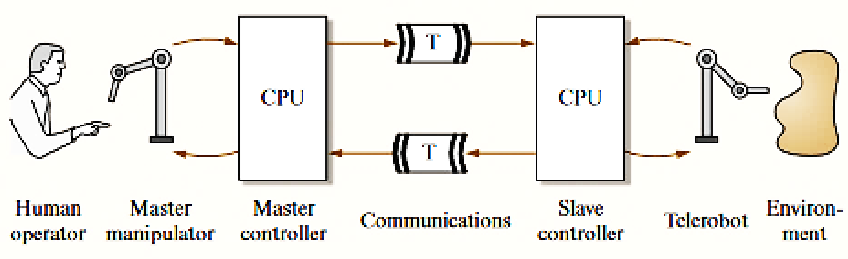

Figure 4. A bilateral teleoperator is viewed as a chain of elements reaching from user to environment [57]

2.8 Position-Force Architecture

The position-force architecture uses a force sensor at the slave robot's tip providing direct feedback of external forces between slave and environment. The system is controlled by Equation (3).

$$F_m = -F_{sensor} \quad (3)$$
$$F_s = -K_s(x_s - x_{sd}) - B_s(\dot{x}_s - \dot{x}_{sd})$$

This design is unstable, and the control loop passes from master motion to slave motion to environment forces and then back to master forces.

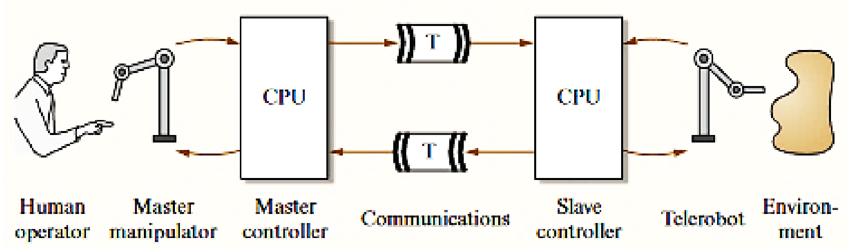

Figure 5. A position-position architecture effectively creates a spring and a damper [57]

This section explores the mechanisms involved in Teleoperations. It delves deep into the system architecture, control modes, and technologies driving it as well as how it is applied in surgery.

2.9 Teleoperations and various parts

From Ref. [45], a teleoperated system refers to a system that allows for a human operator to control a machine or robot from a distance while giving real-time feedback. The word comes from 'Tele' (which means distant) and 'Operation' (which means control) signifying the remote control of a system. Unlike autonomous machines which require no effort from a human being i.e., they are independent of human effort, teleoperated systems require guidance throughout the decision-making process in carrying out tasks.

The teleoperation system is made of two parts: an interface that takes the actions of a human operator and a manipulator that responds to the actions of the interface. [46]. These systems are mostly used where human presence at the control site is risky, dangerous, or inefficient. AI and robotics use for surgical teleoperations especially during the COVID-19 era also brought many advantages. Unlike the Conventional Laparoscopy which relies on 2D imaging which offers limited dexterity with rigid instruments, and requires surgeons to compensate for restricted movements, Robotics-Assisted MIS has brought enhancement providing 3D imaging, greater dexterity with wristed instruments among others. Since with teleoperation, the operator is now able to perform the operation without direct contact with the patient. Also, during long hours of surgery, the surgeon has a more comfortable space behind the console. The 3D offers better visualization. It also comes with more dexterity.[47] The integration of AI into teleoperation also enables us to have a semi-automated system where the pre-trained system is able to recognize and perform tasks autonomously. It reduces cognitive stress on the surgery. Again, haptic feedback integrated into the RAMIS improves surgery.

The teleoperations system comprises of many parts:

1. **The Operator (Human Controller)**: This refers to the human who directly controls the actions of the system. This person can be close to the machine or miles away and can rely on control interfaces like joysticks, consoles, keyboards or specialized control panels. Advanced systems like haptic feedback where the operator can "feel" what the machine is doing are used to enhance precision.
2. **Controller Interface**: This is the device or system used by the human operator to send commands to the **teleoperated** system. It translates the operator's inputs into actionable signals that control the machine's movement and functions. Depending on the complexity of the task, this could range from a simple remote control to an advanced simulation-based environment.
3. **Remote Machine/System**: The actual device being controlled, such as a robot, a drone, a vehicle, or another type of mechanical system. This machine carries out the tasks or operations dictated by the human operator.
4. **Communication Link**: The connection between the human operator and the remote machine, which can be via radio waves, satellite links, or the internet.
5. **Feedback System**: The feedback data, consisting of position, velocity, interaction force, and visual input, is supplied to facilitate intuitive control for surgeons during remote surgery. A reduction in the quality of this feedback may result in errors and failures when carrying out complex and delicate surgical procedures. [48]. A feedback system provides the operator with sensory information in real-time. This includes, visual, auditory or haptic feed backs and even temperature or pressure data. The immediate the feedback, the more effective the remote system can be controlled.

2.10 Types of feedback

In the fast-advancing area of surgical robotics, the role of feedback mechanisms is crucial to ensuring both precision and safety during procedures. Feedback systems provide critical information that allows surgeons to make informed decisions in real time, enhancing the effectiveness of robotic-assisted surgeries. These feedback mechanisms can be broadly categorized into various types, including visual, haptic, and auditory feedback, each contributing uniquely to the surgical experience.

2.10.1 Haptic feedback

From Ref. [49] Haptic feedback in surgical teleoperations is simply the technology that allows surgeons to receive tactile sensations. The feedback mimics the sense of touch, pressure and resistance and is very useful in performing surgical operations especially ones as delicate as endometriosis. Haptic technologies address this issue by allowing virtual objects to deliver perceptible feedback to the user [50]. Haptic feedback helps surgeons in many ways. It enhances their spatial awareness and helps minimize tissue damage. It has been revealed that this can minimize the dangers involved in intra-operative injury for Minimally Invasive Surgery (MIS) [51]. Haptic feedback can be grouped into three primary types: force feedback, kinesthetic feedback and tactile feedback.

2.10.2 The force feedback.

The most common type of haptic feedback is the force feedback. [49] It mimics the sensation of touching physical objects and enables the user to feel the pressure, weight and texture of the procedure. It is very commonly used in video gaming. An example is force-feedback steering wheels which enhance the gaming experience by providing more realistic resistance. Devices like joysticks also utilize haptic feedback. [53] Research actually indicates that gamers outperform non-gamers in surgical simulation tasks which is no surprise as the technology of force feedback is utilized more by gamers on a regular basis. The force feedback can be controlled using Position-Exchange Controller. This method employs the positions of both the master manipulator (controlled by the surgeon) and the slave robot (the surgical instrument). To generate force feedback, the tool-tissue interaction forces is accurately measured on the slave side and fed back to the user in real time with the same intensity as measured. Sensors are not required. When working with flexible robots, it becomes a problem as both stiffness of the environment and the robots are both transmitted as signals giving a false impression of a tissue. An example is determining a palpation which requires determine very subtle differences in tissues. To address this, another approach which involves calculating the force applied to the master manipulator by measuring the difference between the positions of the master and the slave robot's tip. This way, the quality of force feedback is improved making it more effective in force feedback [54].

2.11 Classifications of force feedback

A challenge with force feedback is how precise the measurements are. This has resulted in three categories of force feedback.

2.11.1 Sensor based force measurement.

This is further divided into two. Namely, Proximal sensing and Distal sensing. Their difference has to do with the position of the sensors on the devices. With proximal sensing, the sensor is placed on the tool shaft or within the device to measure the force interaction away from the tip. Due to friction in the tools, it suffers from limitations. For distal sensing, the sensors are placed at the tips of the device. The downside of this is sterilization requirements as well size. There is a need for resizing. Both methods have made strides.

2.11.2 Contact-less force measurement.

This method was developed to address the limitations of the traditional force systems: size, accuracy and sensing range. In this pursuit, RGB-D cameras, lasers, ultrasound etc. were employed. Ultrasound elastography has proven promising. Further research is necessary to ensure they can function effectively in diverse conditions without relying on pre-established models.

2.11.3 Force estimation.

This technique utilizes known dynamic models, including joint torques and motor currents, to estimate forces. Recent studies have shown that having information on the contact point geometry and joint torques will achieve high accuracy. Identifying the contacts remain a challenge. Also, actuators and strain gauges have been proposed for force estimation. Challenges being encountered are precise tool-tissue interaction force sensing, especially regarding sterilization and cost and the lack of thorough performance in many studies. [49]

2.11.4 Tactile feedback.

This type of haptic feedback is more focused on transmitting vibrations or pressure to the user's skin. Some examples of tactile feedback devices include Electroactive polymer (EAP) displays as well as the vibration motors used in mobile and wearable devices.

2.11.5 Kinesthetic feedback.

Kinesthetic feedback provides sensations related to movement and position. It enhances spatial awareness and simulates joint and muscle tension. It is commonly used in rehabilitation and physical therapy. It must be noted, however, that a number of surgical robotic systems utilize a hybrid of the three types.

2.11.6 Virtual feedback.

Virtual feedback enhances the surgeon's ability to interact with robotic systems and the surgical environment. Virtual feedback includes various types of information, such as visual cues that show what the robot is doing, haptic feedback that allows the surgeon to feel the tissue, and sound alerts that provide important updates during surgery. Skilled robotic surgeons can rely on visual indicators, such as tissue deformation, as substitutes for force and haptic feedback, which the da Vinci robotic system does not provide. Vision-based techniques for estimating force can also incorporate data from surgical instruments, including tool-tip movement patterns, speed, and grasper state [55]. Integrating information from multiple sensory sources is crucial for effective interaction with the surroundings [56]. The combination of feedbacks help surgeons make better decisions and perform procedures with greater accuracy.

2.12 Sensing via the internet

This teleoperation system operates over a network and utilizes a wireless mobile robot, incorporating TCP/IP, socket communication, and file caching technology. The operator remotely monitors dynamic real-time sensor data and manages the robot's movements via the internet using a control protocol. A wall-following experiment conducted in an indoor setting showcased the system's efficiency. **Wall-following** is a navigation technique used primarily by mobile robots, where the robot moves alongside a wall or a similar surface by maintaining a fixed distance from it. This method allows the robot to traverse an environment by following the contours of walls, typically in situations where other navigational aids, such as GPS or advanced mapping, are unavailable or unreliable. A human-machine system, remotely controls the module by sending motion commands to the robot and the robot executes the command. This involves gathering data about the robot, decision-making by a human operator, and executing actions through the robot. With the advent of HTTP, the earliest internet robots were primarily robotic arms or basic robots operated directly by humans, such as the Mercury Project, the telerobotic garden, and MAX wireless teleoperations. Currently, autonomous robots are being worked on to improve effectiveness and reduce delay caused by i.e. Xavier.

2.13 Human-centric evaluation of teleoperation

There are different teleoperation algorithms for controlling robotically steered needles. The algorithms used are:

1. **Joint Space Control**: The robot is controlled directly by manipulating the joints.
2. **Steering Control**: Controls mimics the steering of a driving wheel i.e. hub -centered steering.
3. **Cartesian Space Control:** The user uses the x, y, z co-ordinates to control the robots in a straight line, tested with or without force feedback.

These methods were evaluated based on performance, user experience and human-centric metrics. The cartesian space control was most preferred as it led to faster needle insertion, higher targeting accuracy, smoother movements, and lower cognitive load [47].

2.14 Module Description

Hardware architecture includes the client, host and a Wireless Mobile Robot (WiRobot). To teleoperate the robot via the internet a manipulator controls the panel on the client side. Master and slave robot are connected to the internet with a standard ethernet card for communication. The host computer interacts with the mobile robot using Bluetooth. The server connects to the Bluetooth wireless communication system through serial and USB ports, as illustrated in Figure 6, enabling wireless teleoperation.

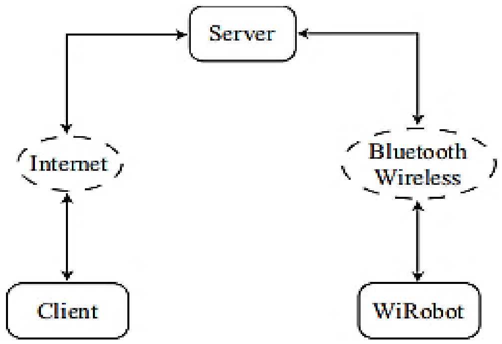

Figure 6. Structure of remote control

2.15 Software description

The server program as shown in Figure 7, runs on Win200 program and the client connects with the server using a TCP/IP protocol. The system is made up of independent modules which perform specific functions which each consisting of a server-side module and a client-side module. A firmware in the embedded controller controls the data acquisition, fast-loop low level motion control, image capture and wireless communication. The data between WiRobot hardware and the 'WiRobot SDK Active X' module is managed and transferred by WiRobot Gateway Program. The handshaking technology ensures stable image transmission between a server and client. The process starts with the client sending a "REQ" signal to request an image. The server instructs WiRobot to capture and save the image as a BMP file, which is then converted to a JPG to reduce transmission load. The client receives the image size via a "FIS" signal and, after confirming readiness with an "ACK" signal, the server sends the image data through a socket port. The transmission completes with an "SFC" signal from the client, and the cycle concludes when the server sends a "DON" signal, readying for the next image transfer with shared memory. Interaction is made easier with a client-side user interface made up of 4 displays.

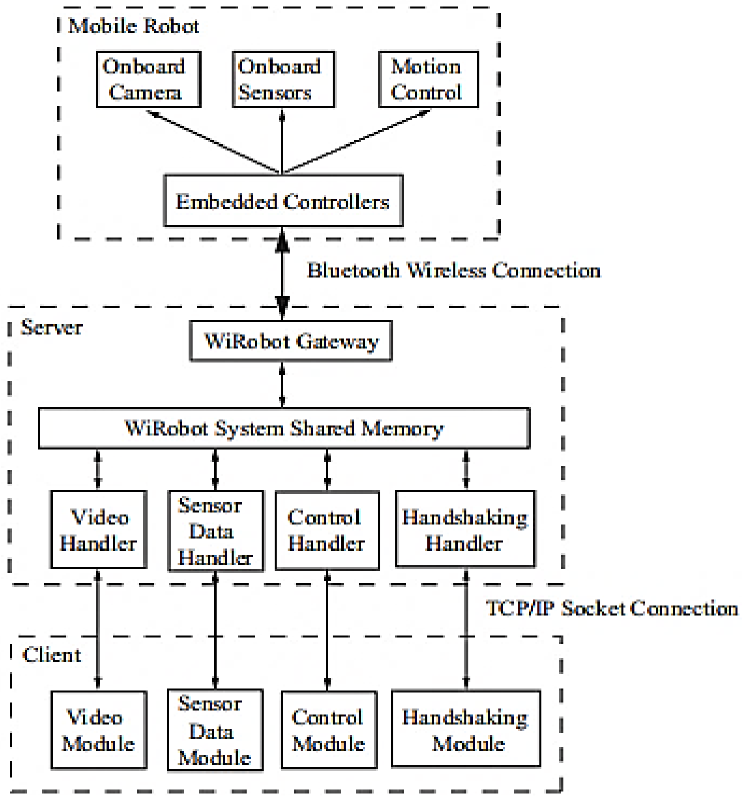

Figure 7. Software architecture

2.16 Data transmission: Solution to time delays

Telesurgery has achieved quite a lot in the industry but it faces issues of time lags. The biggest problem of telesurgeries is time delay. Time delay in surgical teleoperations is simply the lag between the surgeons' actions and the response on the surgical instruments. When the video feed is not real time, the surgeon is unable to gauge the position of the instruments precisely and that can be problematic in delicate surgical procedures. Figure 8 shows a typical delay response.

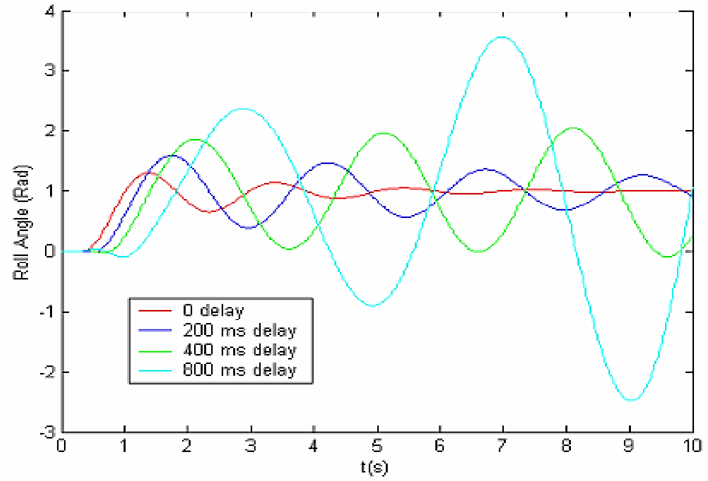

Figure 8. Responses with different delays

From the graphs, it can be seen that as delay increases, response lags input with greater amount.

Teleoperation technology has drawn attention from robotic researchers. The problem is, in most cases is that the manipulator is a fixed robot which is impractical. A mobile robot seems more practical and adaptable but it implies that robots are directed by a single manipulator which would increase time delays due to communication. This can be solved by designing a distribution algorithm which is combined with a finite-time algorithm to make known and improve the convergence time ie. the time it takes a system to reach stability. The force distribution between operator and object can be optimized by an adaptive robust control.

A neuro-adaptive fixed time (NAFT) control is also adapted. NAFT control is a control strategy used in systems to achieve stability and convergence within a predefined, fixed-time, irrespective of the set-up's premier conditions. It uses a neuro-adaptive mechanism or neural networks to adapt to varieties in the setup as shown in Figure 9. The 'fixed time' aspect means the control system guarantees the performance criteria method are met in a specific known period which is crucial in achieving fast and predictable responses from the robot. This would reduce delays since the task environment of a tele-operative system is a networked system which requires exchange of information through a bidirectional communication channel between the robots involved.

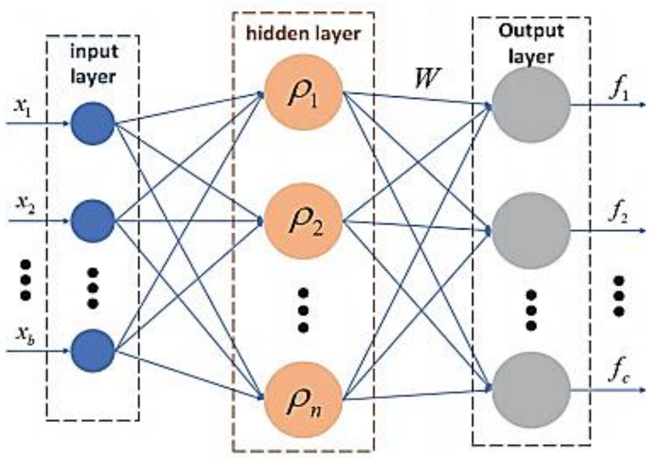

Figure 9. The Neural Structure

The time delays could also be tackled using a lag bipartite formation tracking system integrated with a matrix-weighted signed graph for communication. The multi-agent networks have been dived-into in robotics and such systems are interconnected with several parts to accomplish one or multiple tasks collectively. That system is known as Networked Robotic System with Local Interactions (NRSLI). The term local interactions signifies that each robot can only access a limited number of nearby robots, forming a small subset of the NRSLI.

These neighboring robots are identified based on factors such as communication range, transmission frequency, communication protocols, and hardware specifications. NRSLI introduces a lot of delay.

Using the Lag Bipartite Formation Tracking system implies that

1. The NRS robots are put in subgroups according to the signed graphs describing the coexistence of cooperative and antagonistic interactions.
2. The various states of each subgroup from a desired geometric pattern asymptotically in the local coordinate.
3. The geometric center of each subgroup is forced to track the same leader trajectory with different plus-minus signs and a time lag.

LBFT solves time delays by using a distributed tracking system, synchronization and formation control. Robots maintain a coordinated approach even in the presence of time delays and so teleoperated systems function more smoothly despite the communication lag. Matrix-weighted signed graphs enable efficient communication across networked systems by optimizing the flow of communication. The system is able to predict and adjust itself for delays in real-time which maintains synchronization between the master robot and the slave robot.

2.17 Challenges associated with teleoperation

A challenge associated with teleoperation is the bulkiness of the console. The console, although allows surgeons manipulate instruments and monitor procedures with enhanced precession, comes with the challenge of physical barriers and immobility which limits the interaction between surgeon and patient. An alternative solution: a Mixed Reality-based teleoperation system is suggested. The MR – based approach enables the surgeon to use hand gestures, head tracking and speech recognition to control the robots rather than the traditional console where the hand has to be used for everything. It replicates the functionality of the console with more flexibility, making remote and disaster -response surgeries possible [61].

3. RESULTS AND DISCUSSION

3.1 Neurosurgery

Stereotactic neurosurgical procedures demand high spatial accuracy and precise targeting to access specific anatomical structures while minimizing unintended damage. This section introduces three robotic systems designed for neurosurgical applications: (1) Minerva, developed at the University of Lausanne in Switzerland, was one of the earliest robotic systems created for accurate needle placement; (2) NeuroMate, a six-axis robotic system for neurosurgery, originated from research by Benabid, Lavallée, and their team at Grenoble University Hospital in France and was later developed by Integrated Surgical Systems in the United States; and (3) an MRI-compatible robotic system designed by Dohi and his collaborators in Japan. [63].

3.2 Laparoscopic surgeries

Laparoscopy is a surgical procedure in which small incisions are made in the abdomen or pelvis, allowing a camera to assist in the operation. It is a surgical procedure commonly used for cholecystectomy, appendectomy, hernia repairs and gynecological surgeries. Surgical robotics has become a pivotal element in laparoscopic surgery, enhancing precision, control, and ergonomics. With the use of robotic-assisted surgical systems (RASS) [64], surgeons can overcome the inherent limitations of conventional laparoscopic techniques. [65]

There are several advantages to using surgical robotics in laparoscopy. One of the standout benefits is enhanced precision and control. Robotic systems like the da Vinci SP model enable teleoperation of instruments with increased dexterity. The robotic arms are also designed to provide additional degrees of freedom (DoF), which allows surgeons to perform delicate movements that would be difficult or impossible with traditional laparoscopic tools. Ergonomics are also improved with RASS in laparoscopic surgeries as the surgeon consoles offer comfortable, seated operations. This reduces the fatigue and strain on the surgeon.

3.3 Spinal and neurosurgery

Neurosurgery and spinal surgery are closely related fields. Neurosurgery focuses on diagnosing and treating conditions affecting the brain and other parts of the nervous system, such as tumors, trauma, and neurological disorders. Spinal surgery, on the other hand, primarily addresses issues related to the vertebral column. Given the relationship between the spine and the brain, many surgical interventions, particularly those involving the cervical spine, can impact neurological function directly, making collaboration between these specialties essential. Robotic-assisted surgical systems (RASS) offer significant advantages in spine and neurosurgery by providing rigid guidance for neurosurgical instruments, such as biopsy needles and drills, as well as spinal implants.

Robotic systems, such as the Mazor X Stealth and the ROSA ONE systems, serve as rigid guides for high-precision insertion of tools and implants. This is crucial during procedures like biopsies or deep brain stimulation, where accurate placement can significantly influence outcomes. The systems utilize six degrees of freedom, allowing for intricate maneuvering in tight anatomical spaces.

3.4 Orthopedic surgery

Orthopedic surgery is a surgical specialty focused on diagnosing and treating disorders related to the bones, muscles, joints, and connective tissues. Orthopedic surgery with the help of robotic-assisted surgical systems (RASS) performs joint reconstruction procedures, particularly in knee and hip replacements. The success of robotic systems in orthopedics relies on detailed imaging data obtained from CT or MRI scans. During the procedure, intraoperative registration ensures that the robotic tools are accurately aligned with the patient's anatomy. Robotic-assisted surgical systems (RASS) in orthopedic surgery use different methods to help surgeons during operations. One important method is called the shared control model. In this approach, the surgeon manually guides a robotic tool, like an oscillating saw or milling machine. Initially, the robotic system helps by providing visual support for removing bone. As the tool gets close to important edges, it stops any extra bone from being removed. This helps make sure the implants are placed accurately and protects nearby tissues.

3.5 Vascular surgery

In vascular surgery, robotic-assisted surgical systems (RASS) are used for procedures like angioplasty. These systems include a surgeon's console, a holding arm, and a disposable catheter cassette. The setup allows the surgeon to operate the catheter remotely, moving it translationally and rotating it around its main axis. This steering capability helps navigate the catheter through the vascular system effectively. The **R-One system** from Robocath Inc is a RASS that integrates imaging systems to improve navigation. Another good example is the **CorPath GRX system**, which has FDA approval for both coronary and peripheral vascular procedures.

3.6 Vitreoretinal surgery

Robotic surgery is increasingly being applied in vitreoretinal procedures, particularly with the rise of minimally invasive ophthalmic surgery (MIOS). These advancements aim to enhance the treatment of retinal diseases while overcoming the limitations of traditional manual techniques. [66] designed a novel innovation that equips surgical robots with a Remote Center of Motion mechanism (RCM). The RCM minimizes unwanted movements thereby improving precision and stability in such delicate operations.

3.7 Thorascopic surgery

Robotic surgery has significantly enhanced thoracoscopic procedures, which are minimally invasive surgeries performed in the chest cavity. Complex thoracic interventions, such as lung resections, mediastinal biopsies, and esophageal surgeries can be performed with greater precision. There are ergonomic benefits for the surgeon. Robotic-assisted thoracic surgery involves smaller incisions, and this minimally invasive approach typically results in shorter hospital stays and quicker recovery times. Despite these advantages, robotic instruments may malfunction during surgery. [67] highlights a study on 544 patients who underwent robot-assisted thoracoscopic surgery. Out of these cases, 15 involved issues with the robotic surgical system. This highlights the importance of being well-acquainted with the robotic systems and instruments they use. Familiarity with these technologies can help with better identification and management of potential complications during surgery. As technology evolves, advancements in robotic systems for thoracoscopic surgery and other surgical processes are anticipated.

Robotics is rapidly developing, but its application in healthcare often faces obstacles [69]. Surgical robotics face various challenges, particularly in terms of technological advancements. Some of these challenges are as follows:

3.8 Cost effectiveness

The costs associated with surgical robots are the main obstacle preventing their widespread use. The initial instalment of the DaVinci system is over a million dollars and a yearly service contract and frequent replacement of the costly laparoscopic instruments because they are semi-reusable. Such expenses make the DaVinci system unaffordable for many hospitals [70]. Industrial robots provide a way out since surgical robots are costly. Moreover, these systems were part of the early systems and not modern ones because of safety issues. It is worth paying some more attention to industrial robots as it offers a more cost-effective approach. Furthermore, the inclusion of advancement like seven degrees of freedom (DOF) and integrated torque sensors has limited the reduced safety that is associated minimally invasive surgery [71]

3.9 Safety issues

Medical robotics differs significantly from industrial robotics because it requires seamless collaboration with humans to achieve optimal performance. Consequently, it is essential for the broader community to establish and evaluate appropriate safety standards. To enhance safety, various measures can be implemented, such as incorporating redundant sensors, designing task-specific robots with specialized functionalities, and employing fail-safe mechanisms to ensure that, in the event of a malfunction, the robot can be safely removed and the procedure can be completed manually [63]. Additionally, the security of the system is another issue since it is possible to hack and attack robotic systems used for teleoperation hence the need for safety measures like: Out-of-Band Communication, Regular Software Updates, Data Distribution Service (DDS), Communication Robustness, Multi-Factor Authentication [72][77][78].

3.10 Technical and logistics issues

Robotic surgery presents additional technical and logistic challenges compared to traditional laparoscopic surgery. Surgeons identify the increased room requirements, inconvenience of rotating the patient, and device malfunctions as key issues in the design of robots that need addressing [79]. [80] collected and analyzed data from the FDA MAUDE database regarding adverse events in robotic surgery in America in the period 2000-2013, using a natural language processing tool. It was found out that 0.6 percent of surgeries reported an adverse event, of which 75.9 percent were device malfunctions, which suggests the manufacture and design of the surgical robots is unsatisfactory. Again, with teleoperated surgery, each member of the team is separated as everyone works in a different console. Spatial distribution as a result of teleoperated robots also has its own problems which include affective and cognitive gaps (where each team member has a different understanding.). This is because surgeons and nurses are no longer together in one operating room like in non-robotic surgery. It makes situational awareness and a common understanding, challenging. Again, the affective gaps created reduces emotional communication. Nurses and surgeons are unable to pick up another's stress, focus or facial expression which communicates something. It is therefore difficult to maintain a common grounds, and situational awareness. Communication barriers and resources also remains a challenge [74].

3.11 Software design

Regulatory agencies rightly demand proof that software governing potentially dangerous medical devices is designed following proper manufacturing standards. While this introduces an additional layer of requirements, a development approach that demonstrates compliance with IEC1508 is likely to be recognized by regulators as adhering to good manufacturing practices. [75]. This causes the creation of a software environment for medical robotics, particularly one that includes a real-time operating system, presents significant challenges. Many research efforts in developing robotic medical systems rely on commercially available software packages, which may not be fully compatible with the unique demands of surgical settings [81-83].

3.12 Future directions in robotics surgery

Over the years, studies concerning surgical robots have aggravated towards the interactions, healthcare and psychological fields. From this research paper, it makes it obvious that not all of the challenges are technical. Medical experts in robotic surgery lay emphasis on psychological and social issues when asked about the difficulties of working with a surgical robot. Humans have issues when it comes to trusting automated robots. Differences like their design, movement, appearance and often because they work without an operator, raise valid questions which leave humans confused as to whether they should trust the automated system. Notwithstanding, the introduction of robotic surgeries has led to new and improved ways of approaching healthcare in terms of cost. The use of telesurgery allows surgical procedures to be carried out in very remote conditions which overcomes the challenge of geographical barriers and allows patients to avoid travel in a minimally invasive surgery. Below are some major technological advancements that could positively improve the field.

3.13 Haptic feedback

Telesurgery has transformed wireless robotic surgical systems. It now enables the operators to feel tissue consistency, therefore providing real-time sensations. An upgrade worth looking at is the human-machine interface (HMI) and sensor-based instruments. Upgrading the HMI will enable more smoother and intuitive interactions. Advanced sensors can also measure forces in multiple directions [84-86].

3.14 Augmented reality in telesurgery

Augmented reality (AR) with telesurgery is a field that promises a safer, more efficient and accessible surgical operation. This really comes in handy in obscure areas where surgeons are not easily accessible as well as during emergencies. Augmented reality (AR) enables remote operation. Currently, studies aim at improving the remote operator's visualization and situational awareness in telesurgery using AR, bridging the gap between physical actions and the robot's movement. Another prospective future directive is AI integration to provide predictions during surgery. AI assisted haptics could help in tissue predictions [87-90].

3.15 Predictive maintenance for robotic surgeons

Robotic surgical systems have the tendency to fail and disrupt surgical workflows, compromise patient safety and incur substantial costs. Traditional maintenance approaches are not enough, that is, the schedule inspections and reactive repairs fall short in addressing real-time condition of the robotic systems. Unplanned breakdowns and unexpected failures can occur leading to delay in surgical procedures, increased patient risks, and financial burdens for healthcare providers. To overcome these challenges, a paradigm shift towards predictive maintenance has gained momentum in healthcare industry. Predictive maintenance leverages the power of AI and data analytics to analyze the vast amount of data collected from robotic surgical systems. Employing machine learning algorithms, anomaly detection techniques and predictive, modeling, AI can identify potential equipment failure before they happen, enabling proactive interventions and preventing costly downtime [91-95]. A key component of predictive maintenance is continuous monitoring of various parameters and performance indicators of the robotic system. Embedded sensors within the robot capture data related to motor performance, temperature, vibration, power consumption and other related variables. The data is fed into the AI module that employ sophisticated algorithms to analyze and interpret the information. Anomaly detection algorithms establish a baseline behavior and compare real-time data to the baseline. For instance, if a motor vibration level exceeds the normal temperature range, it may indicate a potential failure in the future [96-98]. Predictive maintenance also prolongs lifespan of the equipment. By addressing maintenance needs proactively, healthcare providers can minimize wear and tear on equipment reducing the likelihood of premature failures and extending the lifespan of the modules. Data analytics is crucial in a sense that, the vast amount of data generated into the robotic systems including sensor reading, performance metrics and operational parameters, provide valuable insights into the condition and performance of the equipment. Healthcare providers can make accurate predictions, extract meaningful patterns, and detect anomalies to ensure smoother operation and improved patient care [99-100].

4. CONCLUSION

This article presents a systematic review of surgical robots and control for teleoperations, beginning with an introduction that outlines their relevant history. It explores the various types of surgical robots and examines their system architectures as analysed by multiple researchers. The review also delves into the actuation mechanisms utilized in these robots, providing a comprehensive overview of their functioning. Additionally, the paper discusses teleoperation in surgical robotics, highlighting the different feedback methods employed to enhance surgeon-robot interactions. It further explores the diverse applications of surgical robots within the healthcare sector, illustrating their growing significance in modern medicine. Moreover, the review highlighted the challenges that surgical robots currently face in the medical field including economical implications, safety concerns and design lapses and regulatory issues. These findings emphasized the need for continued innovation and research to surrmount these drawbacks. While substantial progress has been made in the study of surgical robots, future advancements in surgical robotics are promising, particularly regarding accuracy and safety in surgical procedures. Thus, continuous improvement would ensure its broader adoption and application in improving healthcare delivery.

REFERENCE

[1] M.B. Asha Stebi and A. Jeyam, “A Study on Surgical Robots and Their Recent Developments,” *International Journal of Data Science and Artificial Intelligence*, vol. 1, no. 1, pp. 1-8, Oct. 2023.

[2] D. R. Berg et al., “Achieving Dexterous Manipulation for Minimally Invasive Surgical Robots Through the Use of Hydraulics,” in *Proc. IEEE Int. Conf. Robotics and Automation*, 2012, pp. 1234–1241. https://doi.org/10.1115/DSCC2012-MOVIC2012-8685

[3] P. Naughton and K. Hauser, “Structured Action Prediction for Teleoperation in Open Worlds,” *IEEE Robotics and Automation Letters*, vol. 7, no. 2, Apr. 2022. https://doi.org/10.1109/LRA.2022.3145953

[4] N. Feizi et al., “Robotics and AI for Teleoperation, Tele-Assessment, and Tele-Training for Surgery in the Era of COVID-19: Existing Challenges and Future Vision,” *Frontiers in Robotics and AI*, vol. 8, art. 610677, Apr. 2021. https://doi.org/10.3389/frobt.2021.610677

[5] A. Takács, D. Á. Nagy, I. J. Rudas, and T. Haidegger, “Origins of surgical robotics: From space to the operating room,” *Acta Polytechnica Hungarica*, vol. 13, no. 1, pp. 13–30, Jan. 2016.

[6] X. Xu, “Model Mediated Teleoperation: Toward Stable and Transparent Teleoperation Systems,” M.S. thesis, Dept. Control Eng., Tsinghua Univ., Beijing, China, Mar. 2016.

[7] Y. Rivero-Moreno et al., “Robotic Surgery: A Comprehensive Review of the Literature and Current Trends,” *J. Robot. Surg*., vol. 10, no. 3, pp. 123–145, Jul. 2023. https://doi.org/10.7759/cureus.42370

[8] E. George et al., “Origins of Robotic Surgery: From Skepticism to Standard of Care,” *JSLS*, vol. 22, no. 4, pp. e2018.00039, 2018. https://doi.org/10.4293/JSLS.2018.00039

[9] S. Kalan et al., “History of Robotic Surgery,” *Surg. Innov*., vol. 27, no. 1, pp. 10–19, Feb. 2020.

[10] A. L. G. Morrell et al., “The History of Robotic Surgery and Its Evolution: When Illusion Becomes Reality,” *Rev. Bras. Cir. Dig*., vol. 33, no. 2, pp. e0275, Oct. 2020. https://doi.org/10.1590/0100-6991e-20202798

[11] B. P. Stramiello, J. Funk, E. K. Richter, F. Yip, and M. C. Orosco, “Remote Telesurgery in Humans: A Systematic Review,” *Surgical Endoscopy*, vol. 36, no. 5, pp. 2771-2777, 2022. https://doi.org/10.1007/s00464-022-09074-4

[12] F. Ficuciello, G. Tamburrini, A. Arezzo, L. Villani, and B. Siciliano, “Autonomy in surgical robots and its meaningful human control,” *Paladyn, J. Behav. Robot.*, vol. 10, no. 1, pp. 30–43, 2019. https://doi.org/10.1515/pjbr-2019-0002

[13] K. Tomihara et al., “Robotic Spleen-Preserving Distal Pancreatectomy Using the First Domestic Surgical Robot Platform (the Hinotori Surgical Robot System): A Case Report,” Dept. of Surgery, Faculty of Medicine, Saga Univ., 2024.

[14] M. F. Zaman, N. Buchholz, and C. Bach, "Robotic Surgery and Its Application in Urology: A Journey Through Time," *EMJ Urology*, pp. 72-82, Aug. 2021. https://doi.org/10.33590/emjurol/20-00278

[15] S. Galvan, D. Botturi, and P. Fiorini, "Perception and Computation in Miniature Surgical Robots," in *Int. Conf. Robot. Autom*., Osaka, Japan, 2022.

[16] M. Roshanfar, J. Dargahi, and A. Hooshiar, "Design Optimization of a Hybrid-Driven Soft Surgical Robot with Biomimetic Constraints," *Biomimetics*, vol. 9, no. 1, Jan. 2024. https://doi.org/10.3390/biomimetics9010059

[17] K. Li, Z. Qi, and X. Feng, "A review of continuum robots for surgical applications," in *Proc. 3rd Int. Conf. Signal Processing and Machine Learning*, China, 2023.

[18] G. S. Chirikjian and J. W. Burdick, "Hyper-Redundant Robot Mechanisms and Their Applications," in *IEEE/RSJ Int. Workshop on Intelligent Robots and Systems*, Osaka, Japan.

[19] K. Cheng et al., "A systematic review of image-guided, surgical robot-assisted percutaneous puncture: Challenges and benefits," *Math. Biosci. Eng*., vol. 20, no. 5, pp. 8375–8399, 2023. https://doi.org/10.3934/mbe.2023367

[20] A. R. Lanfranco, A. E. Castellanos, J. P. Desai, and W. C. Meyers, "Robotic Surgery: A Current Perspective," *Surg. Endosc*., vol. 17, no. 9, pp. 1471–1478, Sep. 2003.

[21] L. A. Aguilera Saiz, H. C. Groen, W. J. Heerink, and T. J. M. Ruers, "The influence of the da Vinci surgical robot on electromagnetic tracking in a clinical environment," *J. Robotic Surg*., vol. 18, art. 54, Jan. 2024. https://doi.org/10.1007/s11701-023-01812-7

[22] S. Dinesh, U. K. Sahu, D. Sahu, S. K. Dash, and U. K. Yadav, "Review on sensors and components used in robotic surgery: Recent advances and new challenges," *IEEE Access*, vol. 11, pp. 140722–140739, 2023. https://doi.org/10.1109/ACCESS.2023.3339555

[23] T. Haidegger, L. Kovács, B. Benyó, and Z. Benyó, "Spatial Accuracy of Surgical Robots," in *Proc. 5th Int. Symposium on Applied Computational Intelligence and Informatics* (*SACI*), 2009.

[24] K. J. Chu, "Current use of intraoperative ultrasound in modern liver surgery," *Oncology and Translational Medicine*, Jun. 2024. https://doi.org/10.1097/OT9.0000000000000005

[25] F. Cepolina and R. P. Razzoli, "An introductory review of robotically assisted surgical systems," *Robot. Comput.-Integr. Manuf*., Apr. 2022. https://doi.org/10.1002/rcs.2409

[26] F. Barbara, F. Cariti, V. De Robertis, and M. Barbara, "Flexible transoral robotic surgery: The Italian experience," *Acta Otorhinolaryngologica Italica*, vol. 41, no. 1, pp. 24–30, Feb. 2021. https://doi.org/10.14639/0392-100X-N0688

[27] M. Corp., "Medrobotics FLEX System," businesswire.com, accessed Oct. 10, 2023. Available: https://www.businesswire.com/news/home/20150722006524/en/Medrobotics%C2%AE-Corporation-Receives-FDA-Clearance-to-Market-Flex%C2%AE-Robotic-System

[28] K. R. Sheth and C. J. Koh, "The future of robotic surgery in pediatric urology: Upcoming technology and evolution within the field," *Frontiers in Pediatrics*, vol. 7, pp. 1–9, Jul. 2019. https://doi.org/10.3389/fped.2019.00259

[29] J. Dwivedi, "Robotic surgery—A review on recent advances in surgical robotic systems," in *Proc. Florida Conf. Recent Adv. Robot*., 2012, pp. 1–7.

[30] R. Konietschke et al., "The DLR MiroSurge—A robotic system for surgery," in *Proc. IEEE Int. Conf. Robot. Autom*., Kobe, Japan, May 2009, pp. 1589–1590.

[31] T. E. O'Connor et al., "Mazor X Stealth robotic technology: A technical note," *World Neurosurgery*, vol. 145, pp. 435–442, Jan. 2021. https://doi.org/10.1016/j.wneu.2020.10.010

[32] M. Huang et al., "The current state of navigation in robotic spine surgery," *Annals of Translational Medicine*, vol. 9, no. 1, p. 86, Jan. 2021. https://doi.org/10.21037/atm-2020-ioi-07

[33] M. D'Souza et al., "Robotic-assisted spine surgery: History, efficacy, cost, and future trends," *Robotic Surgery Research and Reviews*, vol. 6, pp. 9–23, Nov. 2019. https://doi.org/10.2147/RSRR.S190720

[34] 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, May 2021. https://doi.org/10.1002/aisy.202100011

[35] T. N. Do, T. Tjahjowidodo, M. W. S. Lau, and S. J. Phee, "Adaptive Control of Position Compensation for Cable-Conduit Mechanisms Used in Flexible Surgical Robots," in *Proc. 11th Int. Conf. Informatics in Control, Automation and Robotics* (*ICINCO*), Vienna, Austria, Sep. 2014, pp. 110–117. https://doi.org/10.5220/0005114701100117

[36] Z. Zhou, J. Yang, M. Runciman, J. Avery, Z. Sun, and G. Mylonas, "A tension sensor array for cable-driven surgical robots," *Sensors*, vol. 24, p. 3156, May 2024. https://doi.org/10.3390/s24103156

[37] M. Runciman, J. Avery, A. Darzi, and G. Mylonas, "Open loop position control of soft hydraulic actuators for minimally invasive surgery," *Appl. Sci*., vol. 11, no. 17, art. 7391, 2021. https://doi.org/10.3390/app11167391

[38] M. Runciman, J. Avery, M. Zhao, A. Darzi, and G. P. Mylonas, "Deployable variable stiffness cable driven robot for minimally invasive surgery," *Front. Robot. AI*, vol. 6, art. 141, 2019. https://doi.org/10.3389/frobt.2019.00141
[39] S. Yuan et al., "Development of a software system for surgical robots based on multimodal image fusion: Study protocol," *Front. Surg*., Jun. 2024. https://doi.org/10.3389/fsurg.2024.1389244
[40] S. Kumar, "Multimodal Medical Image Fusion Techniques – A Review," *Current Signal Transduction Therapy*, vol. 15, no. 1, pp. 1–15, Feb. 2020. https://doi.org/10.2174/1574362415666200226103116
[41] D. B. Camarillo, M. S. Thomas, M. Krummel, and J. K. Salisbury, Jr., "Robotic technology in surgery: past, present, and future," *Am. J. Surg*., vol. 188, no. 4 Suppl., pp. 2S–15S, Oct. 2004. https://doi.org/10.1016/j.amjsurg.2004.08.025
[42] E. Abdelaal, P. Mathur, and S. E. Salcudean, "Robotics In Vivo: A Perspective on Human–Robot Interaction in Surgical Robotics," *Annu. Rev. Control Robot. Auton. Syst*., vol. 3, pp. 9.1–9.22, 2020. https://doi.org/10.1146/annurev-control-091219-013437
[43] X. Xue, S. X. Yang, and M. Q.-H. Meng, "Remote Sensing and Teleoperation of a Mobile Robot via the Internet," Advanced Robotics and Intelligent Systems Lab, Univ. of Guelph, Tech. Rep., 2020.
[44] Y. Sheng et al., "Teleoperated Surgical Robot with Adaptive Interactive Control Architecture for Tissue Identification," in *Proc. IEEE Int. Conf. Robotics and Automation*, Paris, France, 2021, pp. 1234–1240.
[45] Z. Wang, I. Reed, and A. M. Fey, "Toward Intuitive Teleoperation in Surgery: Human-centric Evaluation of Teleoperation Algorithms for Robotic Needle Steering," in *Proc. IEEE Int. Conf. Robotics and Automation*, Brisbane, Australia, 2018, pp. 1–8. https://doi.org/10.1109/ICRA.2018.8460729
[46] G. S. Guthart and J. K. Salisbury, "The intuitive telesurgery system: Overview and application," in *Proc. IEEE Int. Conf. Robotics and Automation*, vol. 1, pp. 618–621, 2000. https://doi.org/10.1109/ROBOT.2000.845362
[47] E. Abdi, D. Kulić, and E. Croft, "Haptics in teleoperated medical interventions: Force measurement, haptic interfaces and their influence on user's performance," *IEEE Trans. Biomed. Eng*., vol. 67, no. 12, pp. 3438–3451, Dec. 2020. https://doi.org/10.1109/TBME.2020.2987603
[48] M. Gutierrez, R. Ott, D. Thalmann, and F. Vexo, "Mediators: Virtual Haptic Interfaces for Tele-operated Robots," in *Proc. ACM SIGGRAPH Symp. Appl. Percept. Graph. Vis*., 2004, pp. 123–130.
[49] H. Su et al., "Bilateral Teleoperation Control of a Redundant Manipulator with an RCM Kinematic Constraint," in *Proc. IEEE Int. Conf. Robotics and Automation*, Paris, France, 2020, pp. 4477–4482. https://doi.org/10.1109/ICRA40945.2020.9197267
[50] Rosser et al., "The impact of video games on laparoscopic skills in surgeons," *J. Surg. Educ*., vol. 69, no. 2, pp. 173–176, Mar.–Apr. 2012. https://doi.org/10.1016/j.jsurg.2011.10.008
[51] M. Mahvash and P. Dupont, "Bilateral Teleoperation of Flexible Surgical Robots," in *Proc. IEEE Int. Conf. Robotics and Automation* (*ICRA*), Pasadena, CA, May 2008, pp. 3851–3858.
[52] W. J. Jung, K. S. Kim, and S. C. Lee, "Vision-Based Suture Tensile Force Estimation in Robotic Surgery," *Sensors*, vol. 21, no. 1, Jan. 2021. https://doi.org/10.3390/s21010110
[53] S. W. Wong and P. Crowe, "Visualisation ergonomics and robotic surgery," *J. Med. Eng. Technol*., 2023. https://doi.org/10.1007/s11701-023-01618-7
[54] G. Niemeyer, C. Preusche, and G. Hirzinger, "Telerobotics," in Springer Handbook of Robotics, B. Siciliano and O. Khatib, Eds., Berlin, Germany: Springer International Publishing, 2016, pp. 1087–1108. https://doi.org/10.1007/978-3-319-32552-1_43
[55] A. Mohan, U. U. Wara, M. T. A. Shaikh, R. M. Rahman, and Z. A. Zaidi, "Telesurgery and Robotics: An Improved and Efficient Era," *Cureus*, vol. 13, no. 3, Mar. 2021, Art. no. e14124, https://doi.org/10.7759/cureus.14124
[56] P. B. Panfilov, F. M. Cardullo, and H. W. Lewis III, "Building Tele-Presence Framework for Performing Robotic Surgical Procedures," in *Proceedings of PRESENCE 2006*, 2006.
[57] L. Ai, P. Kazanzides, dan E. Azimi, "Mixed reality based teleoperation and visualization of surgical robotics," *IET Healthcare Technology Letters*, vol. 11, no. 2–3, pp. 179–188, Apr. 2024. https://doi.org/10.1049/htl2.12079
[58] V. Kumar, "Telerobotic Surgery: Advancing Modern Healthcare Services," *Analytics Insight*, Nov. 13, 2020.
[59] K. Cleary and C. Nguyen, "State of the Art in Surgical Robotics: Clinical Applications and Technology Challenges," *Comput. Aided Surg*., vol. 6, no. 6, pp. 312–328, 2001. https://doi.org/10.1002/igs.10019
[60] J. Klodmann, C. Schlenk, A. Heillings-Kuß, T. Bahls, R. Unterhinninghofen, A. Albu-Schaffer, G. Hirzinger, (April 2021), "An Introduction to Robotically Assisted Surgical Systems: Current Developments and Focus Areas of Research," *Curr. Robot. Rep.*, vol. 2, pp. 321–332, Apr. 2021. https://doi.org/10.1007/s43154-021-00064-3
[61] N. Simaan, R. H. Taylor, and H. Choset, "Intelligent surgical robots with situational awareness: From good to great surgeons," *Mechanical Engineering*, vol. 137, no. 9, pp. 3–6, Sep. 2015.

[62] Y. Li, S. Wu, J. Fan, T. Jiang, and G. Shi, "Design and Analysis of a Spatial 2R1T Remote Center of Motion Mechanism for a Subretinal Surgical Robot," *Actuators*, vol. 13, p. 124, Mar. 2024. https://doi.org/10.3390/act1304012

[63] A. Ogihara, M. Omata, H. Shidei, S. Mitsuboshi, H. Aoshima, T. Isaka, T. Matsumoto, and M. Kanzaki, "Intraoperative Robotic Surgical System-Related Problems in Robot-Assisted Thoracoscopic Surgery," *General Thoracic and Cardiovascular Surgery*, Jan. 2024. https://doi.org/10.1007/s11748-024-02013-1

[64] B. Szabó, B. Őrsi, and C. Csukonyi, "Robots for Surgeons? Surgeons for Robots? Exploring the Acceptance of Robotic Surgery in the Light of Attitudes and Trust in Robots," *BMC Psychology*, vol. 12, art. 74, 2024. https://doi.org/10.1186/s40359-024-01529-8

[65] E. Holland, "The Extent to Which Surgical Robots Will Be Used in the Next 20 Years," 2021.

[66] Cleveland Clinic, "Robotic Surgery: Robot-Assisted Surgery, Advantages, Disadvantages," Cleveland Clinic, Apr. 30, 2024. [Online]. Available: https://my.clevelandclinic.org/health/treatments/22178-robotic-surgery

[67] "Challenges in Robotic-Assisted Surgery," Kontron Blog., Jun. 12, 2024. [Online] Available: https://www.kontron.com/en/blog/embedded/Challenges-in-Robotic-Assisted-Surgery

[68] P. Fuller, A. Smith, M. Johnson, and L. Thompson, "Understanding the Challenges of Robotic-Assisted Surgery Adoption: Perspectives from Stakeholders and the General Population on Human-Interaction, Built Environment, and Training," *Applied Ergonomics*, vol. 122, p. 104403, Oct. 2024. https://doi.org/10.1016/j.apergo.2024.104403

[69] R. M. Higgins, M. J. Frelich, M. E. Bosler, and J. C. Gould, "Cost Analysis of Robotic Assisted Surgery vs Laparoscopy in General Surgery," SAGES Annual Meeting Abstracts Archive, 2019. [Online]. Available: https://www.sages.org/meetings/annual-meeting/abstracts-archive/cost-analysis-of-robotic-assisted-surgery-vs-laparoscopy-in-general-surgery/

[70] B. Crew, "Worth the Cost? A Closer Look at the da Vinci Robot's Impact on Prostate Cancer Surgery," *Nature*, vol. 580, no. 7804, pp. S5–S7, Apr. 2020. https://doi.org/10.1038/d41586-020-01037-w

[71] K. McBride et al., "Detailed cost of robotic-assisted surgery in the Australian public health sector: from implementation to a multi-specialty caseload," *BMC Health Services Research*, vol. 21, no. 1, p. 44, Feb. 2021. https://doi.org/10.1186/s12913-021-06105-z

[72] T. Bonaci, J. Herron, T. Kohno, and K. J. Chizeck, "To make a robot secure: An experimental analysis of cyber security threats against teleoperated surgical robotics," *Proc. IEEE*, vol. 103, no. 5, pp. 647–661, May 2015. https://doi.org/10.1109/JPROC.2015.2404212

[73] W. J. Gordon, N. Ikoma, H. Lyu, G. P. Jackson, and A. Landman, "Protecting procedural care—cybersecurity considerations for robotic surgery," *npj Digital Medicine*, vol. 5, no. 1, pp. 1–3, Sep. 2022. https://doi.org/10.1038/s41746-022-00693-8

[74] H. Alemzadeh, J. Raman, N. Leveson, Z. Kalbarczyk, and R. K. Iyer, "Adverse Events in Robotic Surgery: A Retrospective Study of 14 Years of FDA Data," *PLOS ONE*, vol. 11, no. 4, e0151470, Apr. 2016. https://doi.org/10.1371/journal.pone.0151470

[75] M. B. Schäfer, K. W. Stewart, and P. Pott, "Industrial Robots for Teleoperated Surgery – A Systematic Review of Existing Approaches," in *Curr. Dir. Biomed. Eng.*, vol. 5, no. 1, pp. 305–308, Sep. 2019. https://doi.org/10.1515/cdbme-2019-0039

[76] H. Pelikan, A. Cheatle, M. F. Jung, and S. J. Jackson, "Operating at a Distance: How a Teleoperated Surgical Robot Reconfigures Teamwork in the Operating Room," *Proc. ACM Hum.-Comput. Interact.*, vol. 2, no. CSCW, pp. 1–26, Nov. 2018. https://doi.org/10.1145/3274325

[77] P. Varley, "Techniques for development of safety-related software for surgical robots," *IEEE Trans. Inf. Technol. Biomed.*, vol. 3, no. 4, pp. 261–267, Dec. 1999. https://doi.org/10.1109/4233.809170

[78] "Technique finds software bugs in surgical robots and helps developers fix flaws, ensure safety," ScienceDaily, Apr. 8, 2013. [Online]. Available: https://www.sciencedaily.com/releases/2013/04/130408103334.htm

[79] M. Yang Jung, R. H. Taylor, and P. Kazanzides, "Software System Safety for Medical and Surgical Robotics – SMARTS," Johns Hopkins University, 2014. [Online]. Available: https://smarts.lcsr.jhu.edu/research/software-system-safety/

[80] F. Despinoy, N. Zemiti, G. Forestier, A. Sánchez, P. Jannin, and P. Poignet, "Evaluation of contactless human–machine interface for robotic surgical training," *Int. J. Comput. Assist. Radiol. Surg.*, vol. 13, no. 1, pp. 13–24, Sep. 2017. https://doi.org/10.1007/s11548-017-1666-6

[81] J. Y. Chew, M. Kawamoto, T. Okuma, E. Yoshida, and N. Kato, "Adaptive attention-based human machine interface system for teleoperation of industrial vehicle," *Scientific Reports*, vol. 11, no. 1, p. 17284, Aug. 2021. https://doi.org/10.1038/s41598-021-96682-0

[82] Y. Chae, S. Gupta, and Y. Ham, "Effects of visual prompts in human-machine interface for construction teleoperation system," in *Proc. Int. Symp. Automation and Robotics in Construction* (*IAARC*), Jun. 2024. https://doi.org/10.22260/isarc2024/0011

[83] W. B. Stetson, S. Polinsky, S. Dilbeck, and B. C. Chung, "The use of telesurgery mentoring and augmented reality to teach arthroscopy," *Arthroscopy Techniques*, vol. 11, no. 2, pp. e203–e207, Feb. 2022. https://doi.org/10.1016/j.eats.2021.10.008

[84] J. Luck et al., "Augmented reality in undergraduate surgical training: The PROXIMIE pilot," *International Journal of Surgery*, vol. 47, p. S1, Nov. 2017. https://doi.org/10.1016/j.ijsu.2017.08.029

[85] "Technology provides ability to save lives through telesurgery," U.S. Army, Jun. 9, 2017. [Online]. Available: https://www.army.mil/article/189087/technology_provides_ability_to_save_lives_through_telesurgery

[86] M. C. Davis, D. D. Can, J. Pindrik, B. G. Rocque, and J. M. Johnston, "Virtual interactive presence in global surgical education: International collaboration through augmented reality," *World Neurosurgery*, vol. 86, pp. 103–111, Feb. 2016. https://doi.org/10.1016/j.wneu.2015.08.053

[87] D. L. Stymiest, "Predictive maintenance for hospital equipment," *Health Facilities Management*, 15 August 2022. [Online]. Available: https://www.hfmmagazine.com/articles/4533-predictive-maintenance-for-hospital-equipment?utm_source=chatgpt.com

[88] L. Akintola and K. Potter, "Predictive maintenance for medical robots: Leveraging AI to analyze data from robotic surgical systems to predict and prevent equipment failures," *Journal of Robotic Surgery*, Apr. 2024.

[89] H. Zhou et al., "Healthcare facilities management: A novel data-driven model for predictive maintenance of computed tomography equipment," *Artificial Intelligence in Medicine*, vol. 149, p. 102807, Mar. 2024. https://doi.org/10.1016/j.artmed.2024.102807

[90] Hitachi, "Predictive maintenance of medical devices based on years of experience and advanced analytics," *Social Innovation*, Mar. 28, 2017. [Online]. Available: https://social-innovation.hitachi/en-eu/case_studies/mri_predictive_maintenance/

[91] Simbo AI, "Utilizing AI for Predictive Maintenance of Medical Equipment: Strategies for Minimizing Downtime and Optimizing Patient Care," *Simbo AI Blogs*, Oct. 5, 2024. [Online]. Available: https://www.simbo.ai/blog/utilizing-ai-for-predictive-maintenance-of-medical-equipment-strategies-for-minimizing-downtime-and-optimizing-patient-care-3332577/ (accessed Nov. 24, 2024).

[92] Samariya, J. Ma, S. Aryal, and X. Zhao, "Detection and explanation of anomalies in healthcare data," *Health Technol. Lett.*, vol. 11, no. 1, Apr. 2023, https://doi.org/10.1007/s13755-023-00221-2

[93] E. Šabić, D. Keeley, B. Henderson, and S. Nannemann, "Healthcare and anomaly detection: using machine learning to predict anomalies in heart rate data," *AI & SOCIETY*, May 2020, https://doi.org/10.1007/s00146-020-00985-1

[94] D. Antonelli, G. Bruno, and S. Chiusano, "Anomaly detection in medical treatment to discover unusual patient management," *IIE Trans. Healthc. Syst. Eng.*, vol. 3, no. 2, pp. 69–77, Apr. 2013, https://doi.org/10.1080/19488300.2013.787564

[95] J. Lopes, T. Guimarães, and M. F. Santos, "Predictive and prescriptive analytics in healthcare: A survey," *Procedia Comput. Sci.*, vol. 170, pp. 1029–1034, 2020, https://doi.org/10.1016/j.procs.2020.03.078

[96] J. Kaur and K. S. Mann, "AI based healthcare platform for real time, predictive and prescriptive analytics using reactive programming," *J. Phys.: Conf. Ser.*, vol. 933, p. 012010, Jan. 2018, https://doi.org/10.1088/1742-6596/933/1/012010