LITERATURE SURVEY OPEN ACCESS

Robotic surgery with the help of AI

Suraj Mule *, Aditi Jagtap**, Yashovardhan Sangle***, LeenaMehta****
*(Department of Electronics and Telecommunication, CWIT, Pune411001)
** (Department ofElectronics and Telecommunication, CWIT, Pune 411001)
*** (Department ofElectronics and Telecommunication, CWIT, Pune411001)
**** (Department ofElectronics and Telecommunication, CWIT, Pune411001)

ABSTRACT
The integration of artificial intelligence (AI) into surgical practices is rapidly transforming the landscape of modern surgery. This paper focuses the integration of artificial intelligence (AI) in modern surgical practices, focusing on its applications in surgical robotics, intraoperative guidance, and preoperative planning. Drawing from findings in various surgical specialties, including spine surgery, regional anesthesia, rectal cancer treatment, endoscopic surgery, thoracic surgery, and brain surgery, the study reveals AI's potential to significantly enhance surgical precision and patient outcomes. Challenges such as limited generalization and explainability are being addressed through collaborative efforts between surgeons and AI researchers. The future of AI in surgery holds promise for the development of versatile, cost-effective robotic systems and enhanced training methodologies. Overall, the integration of AI promises to revolutionize surgical practices and improve patient care globally, as evidenced by the remarkable advancements observed in recent studies and clinical applications.

Keywords–artificial intelligence, Machine learning, preoperative planning,Surgical robots

Date of Submission: 03-02-2024 Date of acceptance: 14-02-2024

I. INTRODUCTION

Surgical operations have seen considerable changes due to technology, which has created new challenges for those in the technical, legal, and bioethical domains in determining how well they were conducted.[10]In a short amount of time, robotic surgery with the fewest incisions has improved, which is advantageous to both the patient and the surgeon.[10]This indicates that general surgery increasingly uses and improves robotic platforms and instruments.[10]Future advancements in robotics will mostly concentrate on miniaturization and micro-robotics, autonomous robots, more resolution detail and magnification in visual feedback, and more resilient haptic systems that offer tactile and kinesthetic input.[10] The days of industrial automation and medicine—especially surgery—not working together have passed. Robots for surgery have proliferated in the profession.[11] Endoscopic cameras are regularly maneuvered by voice-activated robotic arms, and sophisticated master-slave robotic systems are currently FDA-certified, marketed, and utilized for a range of operations.[11]The roots ofsurgical robots can be found in the advantages and disadvantages of minimally invasive surgery, its forerunner. The benefits of minimally invasive surgery are well-liked by patients, physicians, and insurance providers. There are fewer incisions, a lower chance of infection, shorter hospital stays—if any—and a far faster convalescence.[11] The purpose of this study is to examine current and developing surgical robotic technology in the rapidly expanding and dynamic field of research and development.[10]

II. LITERATURE SURVEY

1. APPLICATIONS

AI systems appear to have countless uses in medicine today, from selecting the best course of treatment and predicting patient outcomes to developing diagnoses and predicting patient risks. These methods are intended to help clinical decision-making by extracting pertinent information from vast amounts of healthcare data. By doing so, they hope to lower medical errors and improve the effectiveness and quality of care.[16]

i. Artificial Intelligence in Spine Surgery.

The potential benefits of AI for systems and how it might be used in spine surgery are gaining more and more attention and interest.It has the ability to completely transform the accepted practice in spine surgery, cut expenses, and waste, and enhance patient care and efficiency if well executed. AI may also improve patient-specific care and lessen clinical practice and research heterogeneity.[12]

ii. Use of Artificial Intelligence and Robotics in Regional Anaesthesia.

There is a huge opportunity for artificial intelligence in regional anesthesia. Applications encompass the development of sophisticated clinical decision support systems, performance metrics analysis during simulation training, and, in the end, the production of robots that optimize local anesthetic administration and needle tip accuracy.[13]

iii. Robotic Surgery in Rectal Cancer.

Rectal cancer treatment has entered a new age of advanced minimally invasive surgery with the help of robotic colorectal surgery. Up to 1,037,000 procedures have been carried out in 67 countries since the first successful surgery utilizing the da Vinci Surgical System (Intuitive Surgical Inc., Sunnyvale, CA, USA) was carried out in 2000. As of right now, the da Vinci System is the robotic surgical system that is most frequently utilized worldwide.[14]

iv. Application of AI in Endoscopic Surgical Operations

Artificial intelligence models have advanced to surpass human decision-making in medical specialties that primarily depend on pattern recognition, such as radiography and endoscopy. According to reports from numerous institutions, artificial intelligence can be effective in the endoscopic diagnosis of gastrointestinal lesions. The use of graphical processing units (GPUs) for parallel processing, the availability of many movie data formats, and the renewed interest in neural networks and other machine learning techniques have all contributed to technological advancements in computing, which have resulted in recent advancements in the application of AI in endoscopic surgery.[15]

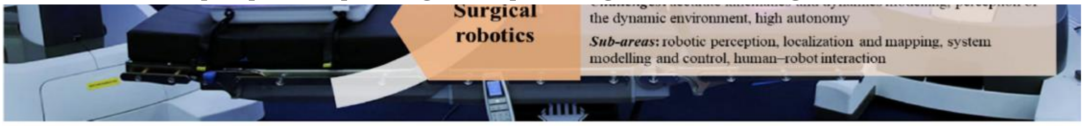
v. Artificial intelligence in thoracic surgery

The utilization of artificial intelligence in healthcare environments is expanding quickly, despite its limited application in clinical practice. Machine learning algorithms are used extensively in thoracic surgery, including every stage of the clinical workflow. Machine learning techniques are showing interesting outcomes in the areas of clinical, organizational, and instructional thoracic surgery. Artificial intelligence-based solutions demonstrated exceptional effectiveness in enhancing the patient's perioperative assessment, supporting decision-making, improving surgical performance, and optimizing operating room scheduling.[16]

vi. Artificial Intelligence in Robotically Assisted Brain Surgery

Around the world, several operating rooms have already been outfitted with the initial iterations of surgical robots. In contrast to conventional surgery, robotically assisted brain surgery is highly beneficial. Another name for robotically aided surgery is computer-assisted surgery. One could refer to this procedure as technological development. It is able to identify the tumor cells by using the sensors.[17]

Fig. 1 An overview of popular AI techniques, as well as the key requirements, challenges, and sub-areas of AI used in preoperative planning, intraoperative guidance, and surgicalrobotics.[1]



III. METHODOLOGY

1. Preoperative planning

The use of AI (Artificial Intelligence) for preoperative planning refers to the application of advanced computational algorithms and machine learning techniques to assist healthcare professionals in preparing for surgical procedures is known as preoperative planning.

Preoperative planning is where the surgeon plan's the surgical procedure on the basis of existing medical records andimaging is essential for the success of a surgery. X-ray, CT,ultrasound, and MRI are the most common imagingmodalities used in clinical practice. Routine tasks based onmedical imaging include anatomical classification, detection,segmentation, and registration.[1]

i. Anatomical classification

Anatomical classification serves as a foundational element for leveraging artificial intelligence. AI algorithms utilize anatomical classification to accurately identify structures in medical imaging data, detect and localize abnormalities, segment specific regions of interest, and align images from various modalities. Thisenhances surgical precision, allows for comprehensive planning by integrating diverse imaging sources, and optimizes surgical pathways based on patient-specific data. Additionally, AI-driven decision support, incorporating the latest medical literature and case studies, empowers surgeons to make informed, data-driven decisions during the planning phase. Overall, the integration of anatomical classification with AI in preoperative planning contributes to more accurate, personalized, and successful surgical interventions.

Chilamkurthy et al. demonstrate that "deep learning can recognize intracranial hemorrhage, calvarial fracture, midline shift and mass effect through testing a set of deep learning algorithms on head CT scans" [4]

ii. Detection

Detection provides the spatial localization of regions ofinterest, often in the form of bounding boxes or landmarks,and may also include image- or region-levelclassification.Similarly, deep learning-based approacheshave shownpromise in detecting variousanomalies or medicalconditions.[1] preoperative planning with AI involves using advanced algorithms to automatically identify, highlight, and localize relevant features or abnormalities within medical images. This capability assists surgeons in understanding the patient's anatomy, locating areas of concern, and optimizing their preoperative plans.

iii. Segmentation

Segmentation in the context of medical imaging and preoperative planning refers to the process of dividing or partitioning an image into distinct and meaningful regions. In other words, it involves identifying and delineating different structures or areas within a medical image. This segmentation process is often performed using artificial intelligence (AI) algorithms to enhance precision and efficiency.

Artificial intelligence, particularly deep learning algorithms, plays a significant role in automated image segmentation. These algorithms can be trained to recognize patterns and boundaries within medical images, making the segmentation process more accurate and efficient.[1]

iv. Registration

Medical image registration plays a crucial role in aligning and integrating information from different imaging modalities, volumes, or time points, and it is essential for various medical applications, including preoperative and intraoperative planning. Traditionally, registration has relied on iterative algorithms that calculate parametric transformations to minimize metrics such as mean square error, normalized cross-correlation, or mutual information between medical images. However, recent advancements have witnessed a shift toward deep learning-based registration methods, offering faster and more efficient alternatives.

One notable example is VoxelMorph, which employs a convolutional neural network (CNN) structure and auxiliary segmentation to map input image pairs to a deformation field, thereby maximizing standard image-matching objective functions [5]. This approach showcases the integration of deep learning principles to enhance traditional image registration techniques.

2. AI for intraoperative guidance

AI for intraoperative guidance refers to the application of artificial intelligence (AI) techniques and technologies to assist and guide surgeons during surgical procedures. This field leverages advanced computational methods to enhance decision-making, precision, and overall surgical outcomes in real time. In functional neurosurgery, like deep brain stimulation, intra-operative planning enhances the targeting of specific brain areas. Beyond its clinical impact, intra-operative planning serves as an invaluable tool for training surgeons, enabling them to observe and learn from real-time decision-making by experienced practitioners.

The AI-based solution uses an algorithmemploying over 60,000 cervical images from the National Cancer Institute to identifyprecancerous signs. Researchers reported that the algorithm functions at a much higheraccuracy rate (91%) than a trained human expert (69%)[6]

Intra-operative planning in robotic surgery plays a crucial role in improving precision, adaptability, and patient outcomes. It enables surgeons to navigate complex procedures more effectively and tailor their approach based on real-time information, ultimately contributing to the advancement of minimally invasive and personalized surgical interventions.
Recent works can be divided into four main aspects: shape instantiation, endoscopic navigation, tissue tracking, and augmented reality[1]

3. AI for surgical robotics

Artificial Intelligence (AI) in surgical robotics refers to the integration of advanced computational algorithms and machine learning techniques into robotic systems used in various surgical procedures. The goal is to enhance the capabilities of surgical robots, allowing for more precise, efficient, and adaptable interventions.

CommonAI techniques used for Robotic and Autonomous Systems (RAS) can besummarized in the following four aspects: 1) perception, 2) localization andmapping, 3) system modelling and control, and 4) human-robot interaction.[1]

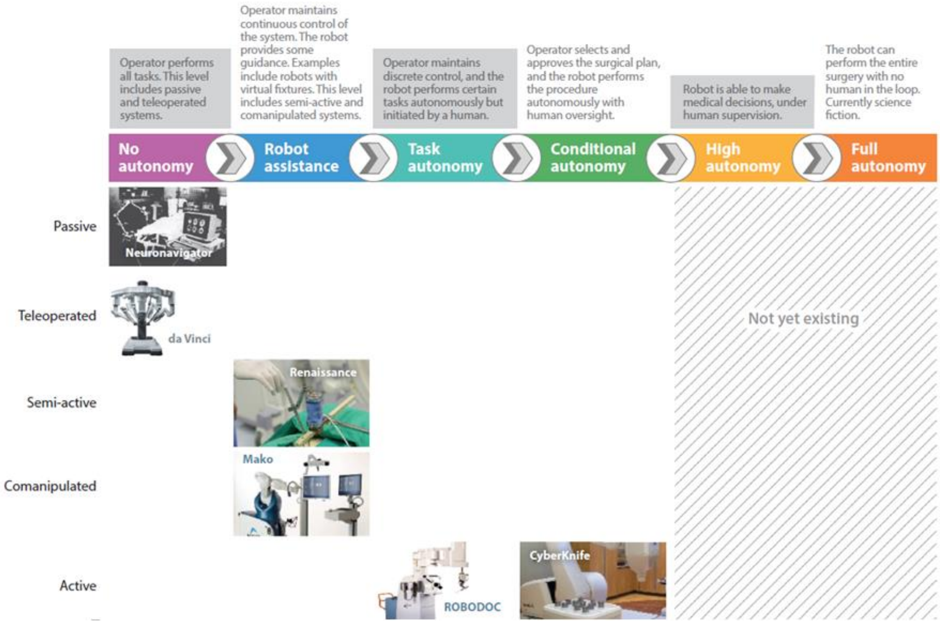


Fig. 2 Different levels of human–robot interaction and autonomy mapped to medical robots.[7]

Perception:
The incorporation of perception technologies into robotic surgery has revolutionized the field, enhancing the robot's ability to interpret and respond to its surgical environment. This section delves into key aspects of perception in robotic surgery, drawing insights from various studies.

Computer vision is a fundamental component of perception in robotic surgery. Studies have demonstrated the application of advanced computer vision techniques for real-time image processing during surgery. These technologies enable robots to recognize and track surgical instruments, interpret tissue characteristics, and provide the surgeon with enhanced visual information.[9]

Localization and mapping:

Simultaneous localization and mapping (SLAM) is the process by which a mobile robot can construct a map of an unknown environment and simultaneously compute its location using the map[2].These technologies enable surgeons to perform minimally invasive procedures with enhanced precision, reducing trauma to the patient and promoting faster recovery

While much-existing research in the area of Simultaneous Localization and Mapping (SLAM) focuses on issues related to uncertainty in sensor data, our work focuses on the problem of planning optimal exploration strategies. We develop a utility function that measures the quality of proposed sensing locations, give a randomized algorithm for selecting an optimal next sensing location, and provide methods for extracting features from sensor data and merging these into an incrementally constructed map.[18]

System modelling and control:

In recent years, the integration of Artificial Intelligence (AI) has emerged as a transformative force in enhancing system modeling and control in robotic surgery. AI techniques contribute to the adaptability, autonomy, and overall performance of robotic systems, providing unprecedented capabilities for surgeons.

Here's an exploration of how AI is incorporated into the system modeling and control aspects of robotic surgery:

1. AI-Enhanced System Modeling:
2. AI-Infused Control Strategies:
3. AI-Driven Adaptation and Decision Making:
4. Advancements and Challenges in AI Integration:

Human-robot interaction:

Human–robot interaction (HRI) is a field thatintegratesknowledge and techniques from multiple disciplines tobuild effective communication between humans androbots.[1]

In robotic surgery, AI plays a pivotal role in touchless control through surgical task-oriented Human-Robot Interaction (HRI). Surgeons can cooperate with surgical robotic systems using gaze, head movement, speech, and gestures.

Gaze-Based Interaction:

Eye-gaze tracking aids in surgical control and navigation, enhancing instrument precision.

Gaze-contingent paradigms enable accurate image transmission and instrument navigation.

Gaze-contingent perceptual docking allows robots to learn operator behaviour through eye movements.[1]

Head Movement Recognition:

Recognition of surgeons' head movement is utilized for remote control of laparoscopes or endoscopes, providing additional input for robotic systems.[1]

Voice Commands and Speech Recognition:

Despite challenges in noisy environments, AI-driven speech recognition improves precision, enabling reliable voice-command control of surgical robots.[1]

IV. RESULT AND DISCUSSION

1. Pre-operative planning: While deep learning methods often outperform conventional approaches, they face challenges such as limited generalizability, explainability, and high data requirements. The proposed solutions include fostering collaborations between surgeons and AI researchers to generate large annotated datasets and exploring techniques like meta-learning for improved generalizability and explainability. Recognizing the significant differences between medical and natural images, transfer learning is suggested to bridge the gap, and the need for interpretable AI algorithms in surgery is emphasized. Additionally, leveraging personalized multimodal patient information, including omics-data and lifestyle details, is highlighted for enhancing early detection, diagnosis, and personalized treatment with minimal trauma and shorter recovery time [1]. In registration, due to general learning nature, VoxelMorph can be applied to a variety of medical image registration applications, including cardiac MR scans and lung CT images. It is not restricted to any specific picture type or architecture.[5]

2. Intra-operative planning: AI has significantly enhanced intraoperative guidance for minimally invasive surgeries (MIS), addressing challenges like 3D shape instantiation, camera pose

estimation, and dynamic environment tracking. Key focuses for computer-assisted guidance include improving localization on texture-less surfaces, handling variations in illumination, and addressing organ/tissue deformation during surgery. While AI excels in detection, segmentation, and tracking, extending to more sophisticated 3D applications is necessary. Real-time efficiency is crucial for assisting surgeons, especially in augmented reality (AR) or virtual reality (VR) development. Future AI technologies should integrate multimodal data from various sensors for precise perception of complex surgical environments, and the rise of micro- and nano-robotics introduces new guidance challenges [7].

3. Robotic surgery: AI integration enhances surgical robotics by enabling perception, understanding, real-time decision-making, and precise task execution. Current robots can autonomously perform simple surgical tasks like suturing and knot tying [8]. Advanced Learning from Demonstration (LfD) and Reinforcement Learning (RL) algorithms are crucial for increasing robotic autonomy in complex tasks, especially in dynamic environments. Generalized learning is essential for accurate modeling and control due to the diversity of surgical robotic platforms. Current surgical robots are costly, large, and often limited to master-slave operations, highlighting the need for more versatile, lighter, and cost-effective systems for minimally invasive surgeries (MIS) [7]. Such robotic systems should seamlessly integrate into well-established surgical workflows for collaborative operation with human operators. Achieving full autonomy in robotic-assisted surgery (RAS) remains a challenge, necessitating ongoing human supervision for safety and high-level decision-making. Future advancements may lead to intelligent micro- and nano-robots for non-invasive surgeries and drug delivery. Robotics could utilize pre-operative examination data to assist in manufacturing personalized 3D bio-printed tissues and organs for transplant surgery. Overall, the potential for AI-driven surgical robotics lies in increasing versatility, reducing costs, and advancing towards more autonomous and integrated systems [1].

V. CONCLUSION& FUTURE SCOPE

Modern surgery is moving toward more accurate and independent intervention for the treatment of both acute and chronic problems because of advancements in AI. Through the use of these methods, significant advancements in surgical robotics, intraoperative guidance, and preoperative planning have been made. AI in surgery has the potential to improve surgical results, save time, and reduce medical errors. But because surgery involves making morally and critically important decisions, multi-directional algorithms which are still lacking are required to create robots that can perform all of the duties performed by a surgeon. The methods in which technology will improve surgical training are still unknown. AI technology integration is here to stay and has an endless number of potential applications in the future. AI can help surgeons at all levels have more individualized and flexible surgical learning experiences. Not only may machine learning algorithms be used to benefit the individual but also the surgical community by analyzing performance data and identifying strengths and places for growth. AI can also be utilized to create more lifelike simulation environments, making it possible to train in controlled, realistic, immersive settings.

REFERENCES

[1]. Zhou, Xiao-Yun and Guo, Yao and Shen, Mali and Yang, Guang-Zhong,"Application of artificial intelligence in surgery," Frontiers of medicine,vol.14,pp.417-430,2020
[2]. Scaradozzi, David and Zingaretti, Silvia and Ferrari, Arianna,"Simultaneous localization and mapping (SLAM) robotics techniques: a possible application in surgery," Shanghai Chest, vol.2, no.1, 2018
[3]. Li, Xiangchun and Zhang, Sheng and Zhang, Qiang and Wei, Xi and Pan, Yi and Zhao, Jing and Xin, Xiaojie and Qin, Chunxin and Wang, Xiaoqing and Li, Jianxin,"Diagnosis of thyroid cancer using deep convolutional neural network models applied to sonographic images: a retrospective, multicohort, diagnostic study," The Lancet Oncology, vol.20, no.2, pp.193-201
[4]. Chilamkurthy, Sasank and Ghosh, Rohit and Tanamala, Swetha and Biviji, Mustafa and Campeau, Norbert G and Venugopal, Vasantha Kumar and Mahajan, Vidur and Rao, Pooja and Warier, Prashant,"Deep learning algorithms for detection of critical findings in head CT scans: a retrospective study," The Lancet, vol.392, no.10162, pp.2388-2396, 2018

[5]. Balakrishnan, Guha and Zhao, Amy and Sabuncu, Mert R and Guttag, John and Dalca, Adrian V,"VoxelMorph: a learning framework for deformable medical image registration," IEEE transactions on medical imaging, vol.38, no.8, pp.1788-1800, 2019

[6]. Lee, DonHee and Yoon, Seong No,"Application of artificial intelligence-based technologies in the healthcare industry: Opportunities and challenges," International Journal of Environmental Research and Public Health, vol.18, no.1, pp.271, 2021

[7]. Troccaz, Jocelyne and Dagnino, Giulio and Yang, Guang-Zhong, "Frontiers of medical robotics: from concept to systems to clinical translation," Annual review of biomedical engineering, vol.21, pp.193-218, 2019

[8]. Y. Hu, L. Zhang, W. Li, and G.-Z. Yang, "Robotic sewing and knot tying for personalized stent graft manufacturing," in Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, 2018, pp. 754–760.

[9]. Lanfranco, Anthony R and Castellanos, Andres E and Desai, Jaydev P and Meyers, William C, "Robotic surgery: a current perspective," Annals of surgery, vol.239, no.1, pp.14, 2004

[10]. Bramhe, Sakshi and Pathak, Swanand S,"Robotic surgery: A narrative review," cureus, vol.14, no.9, 2022

[11]. Lanfranco, Anthony R and Castellanos, Andres E and Desai, Jaydev P and Meyers, William C,"Robotic surgery: a current perspective," Annals of surgery, vol.239, no.1, pp.14, 2014

[12]. Rasouli, Jonathan J and Shao, Jianning and Neifert, Sean and Gibbs, Wende N and Habboub, Ghaith and Steinmetz, Michael P and Benzel, Edward and Mroz, Thomas E,"Artificial intelligence and robotics in spine surgery," Global spine journal, vol.11, no.4, pp.556-564, 2021

[13]. McKendrick, M and Yang, S and McLeod, GA,"The use of artificial intelligence and robotics in regional anaesthesia," Anaesthesia, vol.776, pp.171-181, 2021

[14]. Liu, Ge and Zhang, Shoujia and Zhang, Yan and Fu, Xiaoqing and Liu, Xinlu,"Robotic surgery in rectal cancer: potential, challenges, and opportunities," Current Treatment Options in Oncology, vol.23, no.7, pp.961-979, 2022

[15]. Wada, Norihito and Kitagawa, Yuko,"Application of AI in Endoscopic Surgical Operations," Surgery and Operating Room Innovation, pp.71-77, 2021

[16]. Bellini, Valentina and Valente, Marina and Del Rio, Paolo and Bignami, Elena, "Artificial intelligence in thoracic surgery: a narrative review," Journal of Thoracic Disease, vol.13, no.12, pp.6963, 2021

[17]. Prabu, A Jerwin and Narmadha, J and Jeyaprakash, K,"Artificial intelligence robotically assisted brain surgery," Artificial Intelligence, vol.4, no.05, 2014

[18]. Tovar, Benjam{\'\i}n and Munoz-G{\'o}mez, Lourdes and Murrieta-Cid, Rafael and Alencastre-Miranda, Mois{\'e}s and Monroy, Ra{\'u}l and Hutchinson, Seth,"Planning exploration strategies for simultaneous localization and mapping," Robotics and Autonomous Systems, vol.54, no.4, pp.314-331, 2006