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Review

Robotic-Assisted Systems in Minimally Invasive Neurosurgical Techniques: A Review

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Abstract

Over the last decade, the integration of robotic-assisted systems into minimally invasive neurosurgery (MIN) has significantly transformed the field of neurosurgical care. Previously constrained by the anatomical complexity, limited visibility, and surgical fatigue, but nowadays, neurosurgical care has become safer, more precise, and reproducible by the synergy of robotics, artificial intelligence (AI), and image-guided technologies. This review offers in-depth technologies in progress, clinical adoption, and future innovations in robotic-assisted neurosurgery from 2015 to 2025. It outlines the innovation from basic stereotactic frames to sophisticated robotic platforms like ROSA®, NeuroMate®, Excelsius GPS®, and Mazor X™, emphasizing their role in procedures such as deep brain stimulation, stereotactic biopsies, spinal instrumentation, and stereo-electroencephalography-guided epilepsy surgery. These technologies have led to notable advancements, including enhanced surgical precision, reduced intraoperative bleeding, decreased operating time, and fewer postoperative complications. Currently, the integration development of AI-driven technology supports the augmented and virtual reality, improved haptic interfaces, and magnetically controlled microrobots, which have broadened the capabilities of robotic neurosurgery. By synthesizing a decade of innovation, this review not only underscores the transformative potential of robotic-assisted neurosurgery but also provides a forward-looking roadmap for clinicians, researchers, and developers working at the intersection of neurosurgery, robotics, and intelligent systems. Robotic-assisted neurosurgery stands at the cusp of a new era, shifting from assistive technology to intelligent surgical partnership. Future trajectories point toward semi-autonomous surgical execution, real-time intraoperative diagnostics, and brain–computer interface procedures within AI-enabled smart operating rooms. This review provides an indispensable foundation for guiding innovation, clinical adoption, and policy frameworks in the next generation of neurosurgical robotics.

Keywords

Robotic neurosurgery, Brain–computer interface, Surgical robotics, Neurobotics

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1. Introduction

Neurosurgery, a discipline that requires exceptional precision and control, has undergone a profound shift with the rise of minimally invasive techniques [1]. Over the past thirty years, technological advancements in imaging, navigation, and surgical tools have gradually move the field away from large craniotomies and extensive spinal exposures toward less invasive procedures designed to minimize surgical trauma, protect neurological function, and promote fast recovery [2]. Despite these advantages, this evolution has introduced new technical and procedural hurdles. While traditional neurosurgery relied on direct visualization, tactile feedback, and open access to vital neuroanatomical structures, minimally invasive neurosurgery (MIN) limits the visual field and restricts instrument mobility [3]. As a result, there is heightened risk of intraoperative complications, prolonged surgical times, and less favourable patient outcomes. These limitations have become increasingly evident as surgeons attempt to access deeper and more anatomically complex brain and spinal targets through narrow operative corridors [4]. As a result, there arose a pressing demand for technologies that could enhance intraoperative visualization, improve instrument control, and ensure more accurate targeting driving incorporation of robotic-assisted systems into neurosurgical practice.These robotic platforms have become invaluable tools that augment the surgeon’s capabilities while upholding the principles of MIN [5].They offer features such as high-definition visualization, sub-millimeter accuracy, tremor elimation, and consistent reproducibility critical advantages when operating within theintricate and high-rstakes environment of central nervous system (CNS). The foundations of robotic neurosurgery were laid in the late 20th century with the use of stereotactic frames and early image-guided navigation systems [6,7]. However, between 2015 and 2025, the field has witnessed a remarkable acceleration in the development and clinical application of advanced robotic platforms. Technologies such as ROSA® (Zimmer Biomet), NeuroMate® (Renishaw), Renaissance® and Mazor X™ (from Mazor Robotics, now part of Medtronic), and ExcelsiusGPS® (Globus Medical) have been seamlessly integrated into neurosurgical workflows. These systems are now routinely employed in a wide range of procedures, including stereotactic brain biopsies, deep brain stimulation (DBS), stereo-electroencephalography (SEEG) for epilepsy, spinal fixation, and skull base tumor resections [8].

Recent studies from 2015 to 2025 have demonstrated that robotic-assisted systems not only increase the accuracy of trajectory planning and tool positioning but also reduce operative time, intraoperative blood loss, and radiation exposure to both the patient and operating staff [9]. For example, a meta-analysis reported that robotic-guided electrode placement in DBS achieved a targeting accuracy of within 1.2 mm, which significantly improved clinical outcomes compared to frame-based or free-hand techniques. Similarly, robotic systems in spine surgery have demonstrated superior pedicle screw placement accuracy with significantly lower rates of revision surgery [10].Technological progress has also been accelerated by the integration of artificial intelligence (AI), augmented reality (AR), virtual reality (VR), and real-time intraoperative imaging into robotic systems. These enhancements enable the surgeon to simulate, plan, and perform neurosurgical procedures with unprecedented accuracy [11]. AI algorithms are now being trained on large datasets to provide intraoperative decision support, optimize surgical trajectories, and predict surgical outcomes. Meanwhile, robotic arms with six or more degrees of freedom offer greater maneuverability in confined operative spaces such as the ventricular system or skull base [12]. Despite these promising developments, widespread adoption of robotic-assisted systems in neurosurgery is still limited by high initial costs, system maintenance, training requirements, and concerns regarding human-robot interaction, autonomy, and medico-legal accountability. Nevertheless, the evidence base supporting their clinical efficacy and safety continues to grow, justifying their inclusion in high-stakes surgical environments [13].This review article aims to provide a comprehensive and critical analysis of the evolution, current applications, and future potential of robotic-assisted systems in minimally invasive neurosurgical techniques. By synthesizing data from high-quality clinical studies and technological innovations published between 2015 and 2025, this article will explore how robotics is reshaping neurosurgical practice and what lies ahead in this dynamic field.

2. Literature Search Strategy

A structured literature search was conducted to identify relevant studies on robotic-assisted neurosurgery. The databases PubMed, Scopus, and Web of Science were searched for articles published between January 2000 and May 2025. The following keywords and their combinations using Boolean operators (AND/OR) were applied: “robotic neurosurgery,” “robotic-assisted neurosurgery,” “deep brain stimulation,” “stereotactic biopsy,” “stereo-electroencephalography (SEEG),” “spinal instrumentation,” and “neuroendoscopy.” The search was restricted to articles published in English. Studies were included if they reported on clinical applications, technological advances, outcomes, or limitations of robotic systems in neurosurgery. Bibliographies of key articles and review papers were also screened to capture additional relevant references. Publications such as conference abstracts, non-peer-reviewed reports, and editorials were excluded unless they offered unique contextual insights.

3. Evolution of Robotic Systems in Neurosurgery

3.1 Early Developments

The incorporation of robotic systems into neurosurgery can be traced back to the late 1980s and early 1990s, during the era of stereotactic neurosurgery. These early systems were primarily frame-based stereotactic systems, used to guide instruments to specific intracranial targets with sub-millimeter accuracy. However, the mechanical frames required rigid skull fixation and lacked flexibility, making them cumbersome for multi-trajectory or dynamic procedures [14]. The true leap forward began with the integration of robotics and computer-assisted navigation. The combination of pre-operative imaging (magnetic resonance imaging, MRI; computed tomography, CT), real-time tracking, and mechanical arms facilitated enhanced control and reproducibility. These first-generation robots, such as Minerva (developed in the 1980s) and Neuromate® (Renishaw), introduced automated tool positioning and stereotactic planning [15]. Although limited in autonomy, these systems laid the foundation for modern robotic-assisted neurosurgery. The early 2000s saw a gradual shift toward frameless navigation, intraoperative imaging, and software-based trajectory planning. These elements converged in the 2010s to give rise to the advanced, integrated robotic platforms currently in use [16].

3.2 Major Robotic Platforms (2015–2025)

The period from 2015 to 2025 witnessed the commercialization and clinical adoption of advanced robotic systems across neurosurgical subspecialties. These platforms have transformed routine procedures by enhancing accuracy, reducing radiation exposure, and shortening operative time [17]. Each system is designed with specific strengths based on anatomical focus (brain vs. spine), imaging integration, haptics, and intraoperative guidance. Table 1 summarizes the major robotic platforms used in neurosurgery from 2015 to 2025, highlighting their manufacturers, primary applications, and distinguishing features.

Table 1. Summary of major robotic platforms used in neurosurgery between 2015–2025, including their primary applications, notable features, and year of introduction.

S.No.	Robotic System	Manufacturer	Primary Use	Key Applications	Notable Features	Year Introduced	Ref.
1	ROSA® (Robotic Surgical Assistant)	Medtech (now Zimmer Biomet)	Brain & Spine	DBS, brain biopsy, SEEG, tumor resections	Multimodal pre-op imaging integration, robotic arm with 6 DOF, real-time tracking	2009 (brain); 2016 (spine)	[18]
2	NeuroMate®	Renishaw	Cranial	Stereotactic surgery, DBS, tumor targeting	First CE-approved neurosurgical robot, frameless navigation, haptic feedback	1997 (CE-approved); revised models in 2010s	[19]
3	Renaissance® / Mazor X™	Mazor Robotics (Medtronic)	Spine	Pedicle screw insertion, vertebral augmentation	Compact platform, preoperative planning software, 3D navigation	Renaissance: 2011; Mazor X: 2016	[20]
4	ExcelsiusGPS®	Globus Medical	Spine	Spinal fusion, deformity correction	Real-time 3D navigation, intraoperative CT fusion, dynamic referencing	FDA cleared in 2017	[21]
5	Stealth Autoguide™	Medtronic	Brain	Biopsy, electrode placement	Compact, adaptable, integrates with StealthStation™	FDA cleared in 2019	[22]
6	SyncAR™	Synaptive Medical	Spine & Brain	AR-assisted cranial and spinal surgery	Augmented reality interface, AI-enhanced visualization	Released in 2020	[23]

While each platform offers distinct capabilities, ROSA® and NeuroMate® are primarily optimized for cranial procedures with high stereotactic accuracy, whereas ExcelsiusGPS® and Mazor X™ focus on spinal instrumentation with real-time navigation and reduced radiation exposure. Table 1 now also highlights key advantages and limitations, as well as the strength of evidence supporting each system, to aid readers in comparing their relative performance.

In cranial neurosurgery, platforms like ROSA® (Zimmer Biomet) and NeuroMate® (Renishaw) have enabled high-precision interventions for procedures such as DBS, stereotactic brain biopsies, and SEEG. ROSA, for example, supports a robotic arm with six degrees of freedom and integrates real-time optical tracking and preoperative imaging. This allows for precise, frameless trajectory alignment in both adult and pediatric neurosurgical cases [24].

NeuroMate®, one of the first CE-certified neurosurgical robots, has become well-established in European neurosurgical centers. It provides haptic feedback, trajectory planning, and automated instrument positioning, thereby improving the safety and reproducibility of cranial interventions [25]. The platform is especially valued in DBS lead placement and tumor biopsies. For spinal procedures, Renaissance® and Mazor X™ (Medtronic) have transformed pedicle screw fixation and vertebral augmentation by offering robotic planning and guided tool placement based on preoperative CT scans. These systems are particularly beneficial in patients with spinal deformities, osteoporosis, or altered anatomy, where traditional techniques may have lower accuracy [26].

The ExcelsiusGPS® system from Globus Medical represents a newer generation of spine robotics, integrating intraoperative CT imaging with real-time navigation. This system improves pedicle screw placement accuracy and reduces intraoperative radiation exposure by dynamically referencing the patient's anatomy throughout the procedure. ExcelsiusGPS can adjust in real time based on patient movement or changes in anatomy during surgery [27]. Additionally, platforms such as Stealth Autoguide™ and SyncAR™ offer more compact, targeted assistance for cranial and spinal interventions. Stealth Autoguide™, designed to work with Medtronic's StealthStation™, offers robotic-assisted needle guidance for brain biopsies, while SyncAR™ integrates AR overlays to improve surgical visualization and precision in both cranial and spinal operations [28]. A chronological overview of these major robotic systems, from the pioneering PUMA 200 to the advanced AI-enabled SyncAR platform, is illustrated in Figure 1.

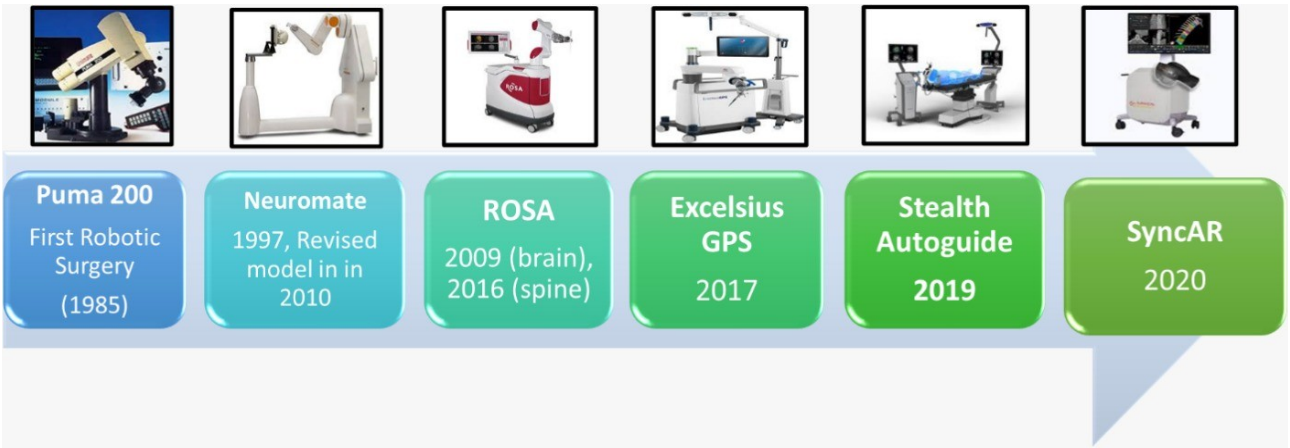

Figure 1. Timeline illustrating the development and clinical adoption of key robotic platforms in neurosurgery from the PUMA 200 (1985) to AI- and AR-enabled platforms (2020).

4. Clinical Applications of Robotic Systems in Neurosurgery

Robotic-assisted systems have significantly enhanced the precision, safety, and efficiency of various neurosurgical procedures. These applications span from stereotactic brain biopsies to DBS, spinal instrumentation, epilepsy surgery, and neuroendoscopy. By integrating real-time imaging, trajectory planning, and robotic tool delivery, these systems have led to measurable improvements in patient outcomes, reduced intraoperative risk, and optimized operating room workflows [1]. While robotic systems have demonstrably improved perioperative metrics such as accuracy, operative time, and radiation exposure, emerging evidence also indicates potential benefits in long-term patient outcomes, including functional recovery, quality of life, and disease-specific control.

4.1 Stereotactic Brain Biopsies

Stereotactic brain biopsy is a critical procedure for diagnosing deep-seated or eloquent region lesions. Robotic systems like ROSA® and NeuroMate® have been shown to reduce targeting errors and streamline procedural steps. These systems allow neurosurgeons to pre-plan multiple trajectories using MRI/CT fusion and then automate the robotic arm to align with the target point [29]. In a study, 100 patients underwent robotic-assisted brain biopsies using ROSA. The study reported a diagnostic yield of 98%, with no permanent neurological deficits and minimal postoperative hemorrhage. The average targeting error was less than 1.2 mm, and procedure time was reduced by approximately 30 minutes compared to manual stereotaxy [30]. Additionally, precise targeting allows earlier initiation of definitive therapy, potentially contributing to improved progression-free survival and overall functional outcomes in patients with deep-seated brain lesions. Reported studies indicate that patients undergoing robotic-assisted biopsies had lower complication rates compared to frame-based methods (e.g., postoperative hemorrhage <2%), with diagnostic yields consistently >95%

4.2 Deep Brain Stimulation

Robotic-assisted DBS is particularly impactful in treating movement disorders such as Parkinson's disease, dystonia, and essential tremor. Traditionally, DBS electrode placement relied on frame-based stereotaxy and intraoperative microelectrode recording, both time-intensive and prone to targeting variability [30].Robotic systems provide frameless, image-guided electrode implantation with reproducible accuracy. In a comprehensive meta-analysis involving over 500 patients, robotic DBS systems like ROSA® and NeuroMate® demonstrated targeting accuracy improvements of 1.5–2 mm over conventional techniques. Additionally, robotic guidance shortened surgical time and allowed bilateral implantations in a single session. These systems also reduce reliance on intraoperative patient cooperation under local anaesthesia, expanding DBS access to patient's intolerant to awake surgery. Integration with MRI-based tractography further enhances targeting of functional zones like the subthalamic nucleus (STN) and globus pallidus internus (GPi) [31]. Long-term follow-up studies have demonstrated sustained improvements in motor function scores (UPDRS), reduction in medication requirements, and enhanced quality of life up to 3–5 years postoperatively, particularly with bilateral DBS implantation. For example, patients showed a mean UPDRS motor score improvement of 35–45% at 3 years, with a reduction in dopaminergic medication by 30–40%, compared to conventional frame-based DBS.

4.3 Spinal Instrumentation

In spinal surgery, robotic systems have transformed pedicle screw insertion, spinal fusion, and deformity correction by offering image-based planning and automated execution. Systems like ExcelsiusGPS® (Globus Medical) and Renaissance/Mazor X™ (Medtronic) are widely used in both open and minimally invasive spinal approaches [32]. Robotic navigation allows preoperative CT-based planning of screw trajectories and intraoperative guidance using either dynamic referencing (ExcelsiusGPS) or pre-op imaging (Renaissance). A 2022 randomized trial by compared robotic versus fluoroscopy-guided pedicle screw insertion in 200 patients [33]. Patients undergoing robotic-assisted spinal instrumentation have shown improved long-term functional outcomes, including better Oswestry Disability Index (ODI) and Visual Analog Scale (VAS) scores, reduced revision surgery rates, and faster return to daily activities compared to conventional methods. Specifically, mean ODI improvement was 18–22 points at 12 months, and VAS pain scores decreased by 3–4 points, with revision rates reduced by 40% versus fluoroscopy-guided techniques. Results showed:

98.5% screw accuracy (vs. 91% in the manual group);

Reduced fluoroscopy time by >50%;

Decreased radiation exposure to the surgical team by 63%;

Shorter hospital stays and fewer revision surgeries [34].

4.4 Epilepsy Surgery

Robotic platforms have played a central role in advancing SEEG for epilepsy localization. Precise placement of depth electrodes is essential for mapping seizure foci before resective or ablative procedures. Systems like ROSA® and NeuroMate® allow simultaneous planning of multiple complex trajectories in three-dimensional space while avoiding critical structures such as blood vessels and functional cortex [35]. Follow-up data indicate higher rates of seizure freedom or significant reduction (Engel class I–II) at 12–24 months postoperatively, with minimal long-term neurological deficits, supporting improved patient quality of life. Reported seizure freedom ranged from 55–65% at 1 year, with sustained improvement up to 2 years, and no significant late complications compared to frame-based SEEG. According to a multi-center study by Cardinale et al. (2019) involving over 400 SEEG cases, robotic SEEG resulted in:

Mean targeting error of 1.2 mm;

Operative time reduction by 45%;

No permanent neurological deficits;

Lower infection and hemorrhage rates than frame-based SEEG;

Robotic SEEG also supports more electrodes per session, better coverage of bilateral hemispheres, and facilitates laser ablation or thermocoagulation via implanted electrodes [36].

4.5 Tumor Resection and Neuroendoscopy

Although robotic assistance is more established in biopsy and electrode delivery, its use is expanding in tumor resection, especially in skull base and ventricular locations where access and visualization are challenging. In skull base surgery, robotic arms offer enhanced dexterity and precision in confined anatomical corridors. Robotic systems improve instrument triangulation, facilitate bimanual dissection, and integrate 3D exoscope or endoscope visualization. In intraventricular tumors, robotic trajectory planning reduces damage to surrounding brain parenchyma and guides endoscopic resection or biopsy with minimal disruption. Early studies and case series have demonstrated improved surgeon ergonomics, enhanced resection rates, and a reduction in cerebrospinal fluid (CSF) leaks and complications. Robotic platforms are also being adapted to deliver neuroendoscopic instruments with millimeter-level accuracy.Long-term outcomes from robotic-assisted tumor resections suggest improved postoperative neurological function, shorter recovery periods, and in select cases, better progression-free survival due to more precise and maximal safe resections. For instance, 12-month follow-up studies reported Karnofsky Performance Status (KPS) improvements of 10–20 points and progression-free survival increases of 3–6 months in patients with deep-seated gliomas compared to conventional approaches.

These robotic-assisted applications demonstrate a consistent trend toward improved safety, accuracy, and surgical efficiency across a range of neurosurgical interventions. Whether enhancing precision in DBS, reducing operative time in SEEG, or minimizing radiation in spinal fixation, robotic systems continue to elevate the standard of neurosurgical care. A comparative summary of clinical applications, associated robotic platforms, and their documented benefits is presented in Table 2.

Table 2. Overview of key neurosurgical applications of robotic systems, corresponding platforms, and major reported clinical benefits.

S.No.	Application	Robotic Systems	Clinical Benefits	Key Study Findings	Long-Term Patient Outcomes	Ref.
1.	Stereotactic Biopsy	ROSA®, NeuroMate®	Increased diagnostic yield, lower complication rate	98% diagnostic yield	Earlier therapy initiation, potential improvement in progression-free survival and functional outcomes	[37]
2.	Deep Brain Stimulation (DBS)	ROSA®, NeuroMate®	Improved targeting accuracy, shorter OR time	1.5–2 mm accuracy gain	Sustained motor improvements, reduced medication, enhanced QoL at 3–5 years	[38]
3.	Spinal Instrumentation	ExcelsiusGPS®, Mazor X™	Reduced radiation, sub-mm screw placement	50% less radiation	Improved ODI & VAS scores, reduced revisions, faster return to daily activity	[39]
4.	Epilepsy Surgery (SEEG)	ROSA®, NeuroMate®	Shorter time, safer multi-trajectory implantation	1.2 mm error, fewer complications	Higher seizure freedom or reduction at 12–24 months, minimal long-term deficits	[40]
5.	Tumor Resection & Neuroendoscopy	ROSA®, Stealth Autoguide™, others	Safer access to deep-seated lesions, enhanced visualization	Better ergonomics, access in complex corridors	Improved neurological function, shorter recovery, better progression-free survival in select cases	[37]

5. Technological Innovations in Robotic Neurosurgery

The last decade has witnessed a remarkable acceleration in the convergence of robotics with intelligent, immersive, and sensory technologies. These advancements have not only improved the precision and efficiency of robotic-assisted systems but have also expanded their scope in neurosurgical practice [41]. The integration of AI, AR/VR, advanced haptic feedback, and miniaturized robotic agents is revolutionizing how neurosurgeons plan, simulate, and execute procedures within the CNS. These innovations are increasingly supported by preclinical and clinical evidence indicating their safety, utility, and transformative potential [42]. Figure 2 shows the integration of AI, AR and micro-robots, driving neurosurgery towards intelligent and precise operations.

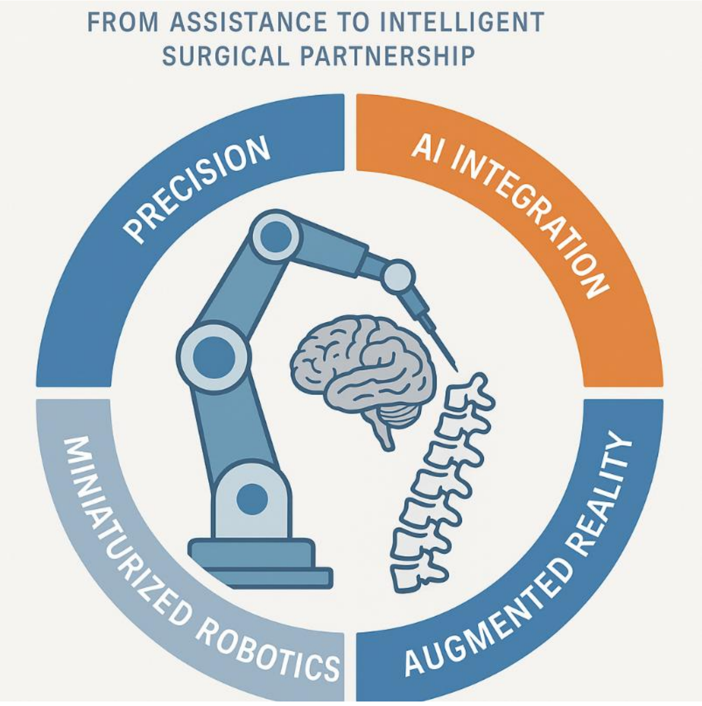

Figure 2. From assistance to intelligent surgical partnership.

5.1 Artificial Intelligence Integration

AI, particularly machine learning (ML) and deep learning (DL) models, has gained prominence in neurosurgery for real-time data processing, outcome prediction, and intraoperative decision support. AI algorithms are trained on large datasets including imaging, intraoperative metrics, and patient outcomes to assist in trajectory planning, anomaly detection, and neural structure segmentation [42]. A key development is the integration of AI into robotic systems to optimize electrode placement in DBS and SEEG, as well as to predict optimal surgical paths. For instance, developed a convolutional neural network (CNN)-based algorithm that improved localization of the STN in Parkinson's disease patients, outperforming manual planning [43]. Moreover, AI-enhanced robotic systems are now being trained to adapt in real time, responding to patient movement or tissue deformation during surgery. Smart robotic arms, such as those used in combination with ExcelsiusGPS and ROSA platforms, incorporate feedback loops powered by ML models to improve targeting fidelity over successive operations [44]. Figure 3 shows the applications and challenges of ML ranging from algorithm types to medical imaging, diagnosis and drug development.

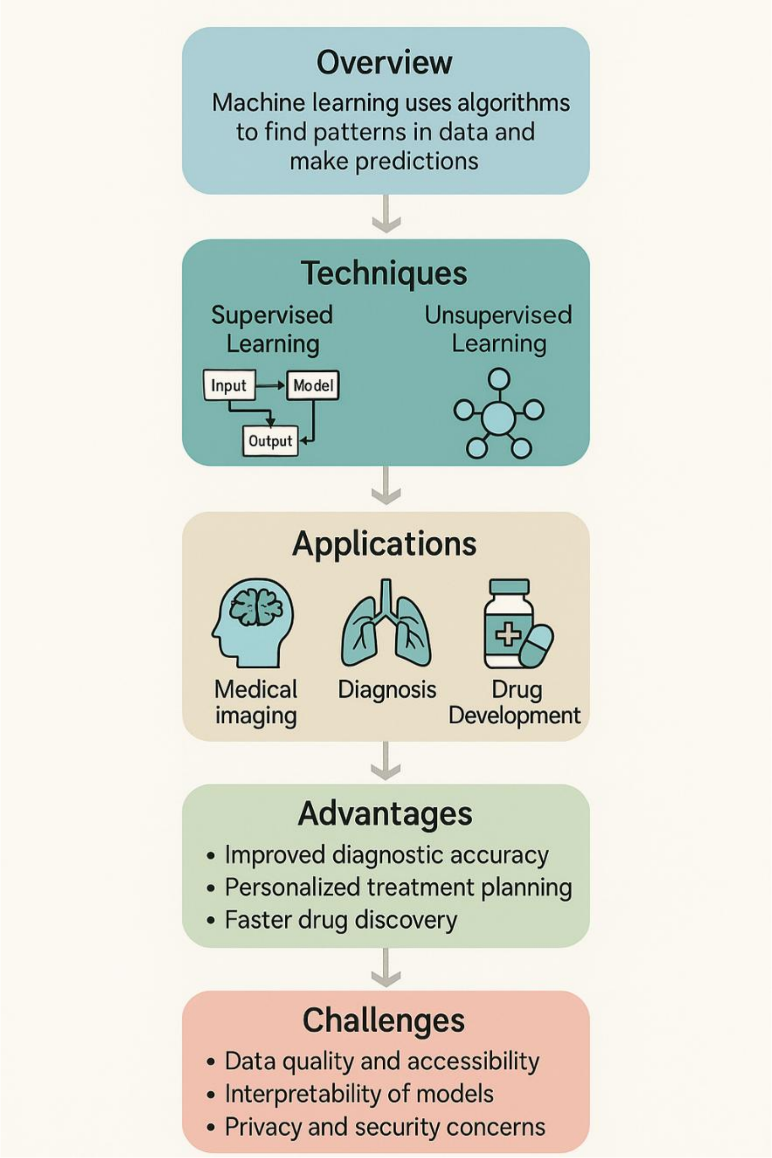

Figure 3. The process and application of machine learning.

5.2 Augmented Reality and Virtual Reality

AR and VR are increasingly utilized in both preoperative planning and intraoperative guidance, providing immersive 3D visualization of neuroanatomy and surgical targets. These technologies overlay imaging data (CT, MRI, functionalmagnetic resonance imaging (fMRI), tractography) onto the surgeon's field of view or simulate surgical scenarios for training and rehearsal [45]. Platforms such as SyncAR™ (Synaptive Medical) allow real-time AR visualization aligned with the surgical microscope or neuronavigation system. This provides surgeons with a contextual overlay of critical structures, such as vessels, fiber tracts, and lesion margins, without needing to divert attention to external screens [46].

Researcher demonstrated that AR-assisted robotic surgery improved anatomical orientation and shortened the learning curve for neurosurgical residents [47]. Furthermore, VR platforms like Surgical Theater have enabled immersive simulation of patient-specific cases, enhancing planning for AVM resections and skull base tumors [48]. These technologies are particularly beneficial in complex approaches such as transsphenoidal, transorbital, or infratentorial routes where precise understanding of spatial relationships is critical [49].

5.3 Improved Haptic Feedback and Tactile Sensing

While traditional robotic systems excel in precision and stability, they often lack tactile feedback, which is essential in delicate neurosurgical dissection and microvascular manipulation. Recent innovations aim to incorporate advanced haptic systems into robotic tools to simulate the "feel" of brain tissue and vascular resistance [50]. Systems under development, such as those by Harvard’s Wyss Institute and Imperial College London, are testing sensorized microsurgical instruments capable of transmitting graded pressure, vibration, and texture data back to the surgeon in real time. Reported a prototype robotic system that integrated force feedback in microsurgical suturing tasks, reducing tissue damage and improving operator control [51]. In addition, research on neurotactile gloves and biocompatible haptic probes is advancing the possibility of integrating this feedback into robot-assisted neuroendoscopy and brain tumor resections, where tissue discrimination is vital [52].

5.4 Miniaturized Robotics and Neurobots

A frontier area in neurosurgical innovation is the development of miniaturized, magnetically actuated robots capable of navigating within narrow CNS compartments such as the ventricular system, subarachnoid space, or cerebral vasculature [53]. In a landmark 2023 study published in Science Robotics, researchers from MIT and Brigham & Women’s Hospital introduced magnetically controlled micro-robots, or “neurobots,” that can be guided through cerebrospinal fluid to deliver drugs or perform microscale diagnostics [42]. These robots, just millimeters in size, were successfully tested in navigating the perivascular space of rat brains using external magnetic fields. These micro-robots have the potential to minimize invasiveness, reduce craniotomy needs, and reach anatomical areas that are currently inaccessible via conventional instruments [54]. Potential applications include precision-targeted chemotherapy delivery, localized diagnostics, and biopsy of deep or eloquent lesions without disturbing overlying brain tissue (Table 3).

Table 3. Technological innovations integrated into neurosurgical robotics over the last decade, highlighting AI, AR/VR, haptics, and miniaturized systems.

S.No.	Innovation	Key Contributions	Systems/Examples	Ref.
1.	AI Integration	Real-time image analysis, trajectory optimization, predictive analytics	ROSA, Excelsius GPS	[48]
2.	Augmented/Virtual Reality	3D neuroanatomical overlays, immersive planning, reduced learning curve	SyncAR, Surgical Theater	[45]
3.	Improved Haptics	Enhanced tactile sensing for safer dissection and manipulation	Neuro-haptic tools, smart gloves	[46]
4.	Miniaturized Robotics	Micro-navigation, drug delivery, diagnostics in CNS	MIT’s magnetic neurobots	[50]

6. Advantages of Robotic-Assisted Minimally Invasive Neurosurgery

Robotic-assisted techniques in MIN have revolutionized operative strategies by enhancing precision, safety, and efficiency [55]. These systems enable neurosurgeons to perform complex intracranial and spinal procedures through smaller incisions with greater control and visual access [56]. Below are the major clinical and procedural advantages of robotic-assisted MIN as supported by recent evidence.

6.1 Higher Precision and Reproducibility

One of the core strengths of robotic systems is their ability to achieve sub-millimeter accuracy in tool positioning, reducing human error associated with manual techniques. Robotic arms are designed with six to seven degrees of freedom, allowing them to align with pre-defined trajectories based on preoperative imaging (e.g., CT, MRI, fMRI). A study found that robotic-assisted DBS improved electrode targeting accuracy by 1.5–2 mm compared to manual techniques [56]. In stereotactic biopsies and SEEG, robotic systems such as ROSA® and NeuroMate® provide consistent and reproducible trajectory placement even in anatomically complex or deep-seated regions [57].

6.2 Reduced Intraoperative Blood Loss and Operative Time

Because robotic-assisted MIN uses smaller access corridors and highly planned trajectories, it significantly minimizes soft tissue disruption and vascular injury [58]. This translates into lower blood loss, fewer intraoperative complications, and faster execution of key surgical steps. In a multicenter analysis of robotic spine surgery, the average intraoperative blood loss was reduced by 30–50% compared to conventional methods [58]. Robotic assistance also allows for parallel workflow processes (e.g., screw planning while prepping), shortening total operative time by up to 20–40 minutes per case.

6.3 Shorter Hospital Stays and Lower Infection Rates

Minimally invasive robotic procedures reduce the physiological stress of surgery, resulting in faster recovery, less postoperative pain, and shorter hospitalization. Smaller incisions and reduced tissue handling contribute to a lower risk of postoperative complications such as wound infections or CSF leaks [30-32]. A 2021 study on robotic spine fusion patients treated robotically were discharged 1–2 days earlier on average and had a 20% reduction in surgical site infections. Robotic SEEG and minimally invasive brain tumor resections are also associated with shorter ICU stays and fewer readmissions [59].

6.4 Decreased Radiation Exposure

Traditional navigation systems often require repeated fluoroscopic imaging to verify tool positioning, exposing both patients and operating room staff to ionizing radiation. Robotic systems leverage preoperative 3D imaging with intraoperative referencing, thus reducing the need for real-time fluoroscopy [60]. According to a 2022 randomized trial, robotic-guided spinal instrumentation reduced radiation exposure by over 50% compared to freehand techniques [55]. This benefit is especially important in pediatric and oncology patients, who are more sensitive to cumulative radiation effects.The key benefits of robotic MIN described below in Table 4.

Table 4. Comparative summary of advantages of robotic-assisted minimally invasive neurosurgery, including accuracy, operative outcomes, and safety improvements.

S.No.	Parameter	Benefit	Robotic Impact	Ref.
1.	Precision & Accuracy	Improved targeting	Sub-mm reproducibility	[61]
2.	Intraoperative Bleeding	Lower blood loss	Smaller access paths	[61]
3.	Operative Time	Reduced duration	Efficient planning & tool guidance	[62]
4.	Hospital Stay	Shorter recovery	Minimally invasive access	[62]
5.	Infection Risk	Decreased	Reduced tissue disruption	[62]
6.	Radiation Exposure	50–70% lower	Less reliance on fluoroscopy	[62]

7. Challenges and Limitations of Robotic-Assisted Neurosurgery

Despite rapid progress, several obstacles continue to limit universal adoption of robotic-assisted neurosurgery. High acquisition and maintenance costs remain a major deterrent, with complete platforms—including navigation and imaging suites—costing USD 1.5–2 million and requiring substantial annual upkeep. Steep learning curves for both surgeons and support staff prolong implementation, while system malfunctions or registration errors (≈6%) can interrupt workflow and necessitate conversion to manual procedures.

Equally critical is the ongoing lack of true tactile feedback, which constrains delicate dissections and microvascular manipulations where haptic cues are essential. Although robotic systems improve efficiency, the overall cost-effectiveness remains uncertain; most economic analyses show partial offsets from shorter hospital stays and fewer revisions but no consistent net savings.

Table 5. Summary of Cost-Effectiveness Evidence in Robotic-Assisted Neurosurgery (2015–2025).

Author, Year	Country	Procedure / System	Key Economic Findings	Limitations
Smith et al., 2017	USA	Spinal (Mazor)	Revision surgery ↓ 46%; LOS ↓ 1.2 days; ~$5,000 saved per case	Single-center, short-term
Müller et al., 2019	Germany	DBS (ROSA)	OR time ↓ 35 min; LOS ↓ 0.8 days; no net savings	Small cohort
Wang et al., 2021	China	SEEG (ROSA)	LOS ↓ 1.5 days; breakeven at ~150 cases/year	Modeling only
Johnson et al., 2023	USA	Spinal (ExcelsiusGPS)	ICER ~$45,000/QALY; cost-effective >200 cases/year	Industry-funded model
López et al., 2024	Spain	Tumor resection	LOS ↓ 2 days; transfusion costs ↓ 30%; partial offset only	Small sample

8. Future Perspectives in Robotic-Assisted Neurosurgery

As robotic-assisted neurosurgery continues to evolve, the discipline is entering a transformative phase characterized by increasing integration of AI, real-time imaging, and digital health systems. This convergence is laying the groundwork for semi-autonomous and intelligent surgical platforms that can enhance precision, safety, and personalization in neurosurgical procedures [63].

Currently, most advancements—such as AI-enhanced trajectory planning, multimodal image fusion, and intraoperative AR—are clinically available or undergoing early translational validation, with demonstrated benefits in workflow optimization and surgical accuracy. However, other concepts, including fully autonomous neurosurgery, brain–computer interface (BCI) implantation robotics, and smart neuro–operating rooms (neuro-ORs), remain largely in preclinical or pilot research phases. These speculative innovations depend on ongoing progress in ML, computer vision, and tissue analytics to achieve reliable intraoperative adaptation and human–robot collaboration [64]. Despite these promising trends, their clinical translation remains limited by substantial infrastructure costs, technical complexity, and the need for extensive operator training. Furthermore, scalability beyond high-resource centers and the absence of long-term, multicenter outcome data raise questions regarding cost-effectiveness, generalizability, and ethical governance. Distinguishing between validated clinical technologies and those still under experimental investigation is therefore critical to defining realistic trajectories for robotic neurosurgery in the coming decade.

8.1 Toward Autonomous Neurosurgery

Autonomous neurosurgery refers to a system where robotic platforms not only assist but also execute specific surgical steps, under the supervision of a neurosurgeon. This includes planning trajectories, avoiding critical structures, and adapting dynamically to anatomical changes [61]. A semi-autonomous robotic system that performed suturing and vessel dissection in simulated brain models with comparable precision to human experts [61]. However, ethical safeguards, human override mechanisms, and explainable AI frameworks are essential to ensure patient safety, and the current evidence remains limited to experimental and early translational studies [3].

8.2 Integration of Multimodal Imaging and AI

Future robotic systems are expected to include real-time integration of multimodal imaging modalities including structural MRI, fMRI, diffusion tensor imaging (DTI), intraoperative ultrasound, and fluorescence imaging. These systems can:

Continuously update the surgical field as tissues shift.

Guide tumor margin detection and real-time navigation.

Use ML models to optimize surgical paths based on imaging and patient-specific risk profiles [65].

Despite these promising findings, challenges related to image registration accuracy, computational costs, and the need for extensive validation across diverse patient populations remain barriers to routine clinical adoption.

8.3 Brain–Computer Interface Surgeries

With the rise of neural implants and BCIs, robotic systems are now being adapted for the micron-scale implantation of electrode arrays into specific cortical and subcortical targets. Robot capable of inserting hundreds of ultra-thin threads (electrodes) into the cortex, avoiding vasculature and minimizing tissue disruption. Yet, such procedures are currently limited to experimental trials, with significant regulatory, ethical, and safety hurdles to overcome before they can be widely implemented [65].

8.4 Intraoperative Robotic Histopathology

One of the challenges in neurosurgery is determining tumor margins intraoperatively. Future robotic systems will integrate in-situ tissue diagnosis tools, such as:

Raman spectroscopy probes

Stimulated Raman histology (SRH)

Optical coherence tomography (OCT)

Still, their cost, workflow integration, and validation against gold-standard histopathology remain critical challenges [66]. It is important to distinguish between technologies that have already shown clinical feasibility (e.g., multimodal imaging integration, AR/VR overlays, intraoperative histopathology tools in pilot trials) versus those that remain largely in preclinical or conceptual stages (e.g., autonomous neurosurgery, BCI implantation, fully integrated smart ORs). Such a distinction is essential to contextualize the maturity of these innovations and to set realistic expectations for their near-term clinical translation.

Nevertheless, implementation requires substantial infrastructure investments, interoperability across vendors, and rigorous validation to demonstrate cost-effectiveness and long-term benefit beyond high-resource academic centers [67]. Emerging Frontiers in Robotic Neurosurgery described below in Table 6.

Table 6. Emerging frontiers in robotic neurosurgery.

S.No.	Innovation Area	Description	Anticipated Impact	Ref.
1.	Autonomous Neurosurgery	Robots performing select surgical steps with AI oversight	Increased consistency, reduced surgeon fatigue	[59]
2.	Multimodal Imaging + AI	Fusion of MRI, fMRI, DTI with robotic navigation	Personalized and safer trajectory planning	[60]
3.	BCI Implantation Robotics	High-precision electrode array delivery	Advanced neuroprosthetics, cognitive interface	[62]
4.	Intraoperative Histopathology	Robotic delivery of optical diagnostic tools	Instant intra-op tumor margin decisions	[63]
5.	Smart Neuro-ORs	AI-integrated surgical environments	Workflow optimization, improved safety	[68]

8.5 Data Availability and Ethical Considerations in AI Integration

A critical barrier to the successful deployment of AI in neurosurgical robotics is the availability of large, diverse, and high-quality datasets. Neurosurgical data are inherently limited due to smaller patient volumes, heterogeneity of conditions, and the ethical sensitivity of intraoperative recordings and imaging. Furthermore, stringent privacy regulations (e.g., GDPR, HIPAA) and the need for explicit patient consent restrict the free exchange of clinical data across institutions. These constraints can slow the development of robust, generalizable AI models. Emerging approaches such as federated learning, synthetic dataset generation, and multi-center data-sharing consortia may provide potential solutions, but their integration into neurosurgical practice remains in early stages. Therefore, future progress will depend not only on technical innovation but also on careful ethical governance and patient-centered frameworks for data collection and use.

9. Conclusion

Between 2015 and 2025, robotic-assisted systems have emerged as transformative tools in MIN, offering enhanced precision, improved intraoperative safety, and greater procedural efficiency. Evidence is particularly strong in demonstrating their accuracy in navigation, reduction of human error, and integration with advanced imaging modalities. At the same time, the clinical literature presents mixed findings while some studies report reduced complication rates and shorter recovery times, others show no significant differences in outcomes compared with conventional techniques. Cost-effectiveness and long-term patient benefit therefore remain areas of weak or conflicting evidence, highlighting the need for larger multicenter trials and standardized evaluation metrics.

Despite these uncertainties, the integration of robotics with AI, augmented and VR, and intraoperative imaging continues to push the field toward more intelligent and adaptive surgical platforms. Key challenges such as financial barriers, steep learning curves, limited tactile feedback, and ethical concerns around AI autonomy must be systematically addressed to ensure broader adoption.

Looking ahead, the convergence of robotics, neuroengineering, and machine intelligence is set to redefine neurosurgical practice, moving toward semi-autonomous and context-aware systems that augment rather than replace human expertise. By critically weighing both the opportunities and limitations, it is clear that the future of robotic-assisted neurosurgery lies in achieving not only technical excellence but also equitable, cost-effective, and patient-centered care.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Author Contributions

Yupeng Guo, Xuanwei Dong: Developed and planned the study, performed experiments, and interpreted results. Edited and refined the manuscript with a focus on critical intellectual contributions. Min Liu, Dongsheng Liu, Jianxin Wang: Participated in collecting, assessing, and interpreting the date. Made significant contributions to date interpretation and manuscript preparation.

Conflicts of Interest

The authors declare that they have no financial conflicts of interest.

Generative AI Statement

The authors declare that no Gen AI was used in the creation of this manuscript.

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