Review Article

Evolution of Robotics in Neurosurgery

Salman T. Shaikh[1] T.A. Dwarakanath[2] Aliasgar V. Moiyadi[3,4]

[1] Department of Neurosurgery, Salford Royal Hospital, Manchester Centre for Clinical Neurosciences, United Kingdom
[2] Section for Intelligent Machines and Robotics, Division of Remote Handling & Robotics, Bhabha Atomic Research Centre, Homi Bhabha National Institute, Mumbai, India
[3] Neurosurgical Oncology Services, Department of Surgical oncology, Tata Memorial Centre, Mumbai, India
[4] Homi Bhabha National Institute, Mumbai, India

Address for correspondence Aliasgar Moiyadi, MCh Neurosurgery, Neurosurgical Oncology, Tata Memorial Centre, Mumbai 400012, India (e-mail: aliasgar.moiyadi@gmail.com).

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Abstract

Technology and neurosurgery have gone hand in hand since a long time. Technological development of robotics in neurosurgery over the last couple of decades has been rapid, yet it still has a long way to go before it becomes a "routine" element of the standard neurosurgical procedure. Apart from the obvious advantages they have over humans, that is, precision, consistency, endurance, and reproducibility, robots also provide additional freedom of movement beyond what is anatomically feasible for humans. Since its first practical application in 1985, the promise of robotics has spurred development and design of numerous such devices for application in neurosurgery. In the current era, the role of robots in neurosurgery is limited to programming movements and planning trajectories for deep cranial targets, biopsies, spinal screw placements, deep brain stimulation, and stereotactic radiosurgery. This narrative, nonsystematic review discusses the evolution of various robotic systems, with a focus on their neurosurgical applications.

Keywords
- robotic neurosurgery
- computer-aided surgery
- image-guided surgery
- minimally invasive neurosurgery
- evolution

Introduction

The word robot was first used in 1920 in the play "Rossum's Universal Robots" by Karel Capek.[1] While initially the connotation of robotics in neurosurgery was akin to "forced labor," it has since evolved by leaps and bounds to grow beyond the confines of the "master–slave" concept. The first practical application of robotics in surgery was described in fact in the field of neurosurgery by Kwoh et al on April 11, 1985.[2] A computed tomography (CT) guided brain biopsy of a malignant tumor came positive in the first sample, and this set the stage for its use in various surgical specialties. Robotics-based neurosurgery is challenging because of anatomical constraints and the lack of a uniform subject-based education and training. The goal lies in seamlessly integrating robotics into the existing armamentarium of technological adjuncts. All stakeholders need to be on the same page from the early process of development in order to produce technologies with wider reach and applicability. This article documents the journey and reviews salient milestones and some important robotic solutions up to the present day.

Early Developments Leading up to the Deployment of Robotic Technology in Neurosurgery

The quest for precision and accuracy while working within complex and often invisible neural substrates resulted in the

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spawning of the field of image-guided surgery. This started as frame-based stereotaxy as early as 1908 when Victor Horsley and Henry Clarke invented the first stereotactic system and culminated in the development of a very advanced and accurate polar coordinate-centric frame-based stereotactic device by Prof. Lars Leksell in 1949.[3] Subsequent advances in imaging (CT, magnetic resonance imaging [MRI]) and evolution in technology in the latter half of the 20th century gave rise to frameless stereotaxy (neuronavigation). It was a matter of time before computer-aided surgery metamorphosed into computer-directed surgery. Simultaneously neurosurgeons started adopting less invasive approaches. The concept of minimally invasive neurosurgery stemmed from the series of stereotactic biopsies described by various neurosurgeons in the early 1990s[4] but was popularized after the introduction of "keyhole surgical approaches" by Axel Perneczky in 1998.[5] The next step in the evolution of minimally invasive neurosurgery was the wider integration of robotics. These parallel and complimentary developments provided an impetus to the nascent field of robotics as neurosurgery stepped into the new millennium.

Composition and Classification of Robotic Systems

The Robotic Institute of America formally defines the word robot as "a reprogrammable, multifunctional manipulator designed to move materials, parts, tools, or other specialized devices through various programmed motions for the performance of a variety of tasks."[6] The basic components of a robotic system in neurosurgery include sensors, which provide feedback (tactile, kinesthetic, and visual), a computing unit or data processing center, controllers providing instruction to the effector robot, actuators converting electrical energy into physical motion, and imaging input system.

Robotic systems in surgery were traditionally classified as per their underlying principles into the following:

- *Active system:* This type of robot has more autonomy than passive systems. The safe operation of the actively powered robotic arm is a difficult task, but it provides a much wider scope of joint mobility.
- *Intermediate system:* The functioning here is shared between the surgeon and the robot. With the surgeon operating and manipulating the instruments, the robot provides guidance and correction of movements.
- *Passive system:* Driven by the "master–slave" concept, the arm is locked in position during surgery and completely controlled by the surgeon at all times. Considered to be safer than the actively powered robots, they are limited by the range of motions the arm can provide.

A more intuitive and practically useful classification groups them as per their mode of functioning and the required level of neurosurgeons' participation:

- *Surgeon supervised and controlled* (►**Fig. 1**): It can be equated with a preplanned surgical procedure with the neurosurgeon plotting the movements of the robotic arm beforehand. This matrix is then downloaded onto the robotic system and the robot performs the planned movements with the neurosurgeon overseeing/supervising the same in person. This corresponds to the "active" system.
- *Telesurgical robots* (►**Fig. 2**): In this type, the neurosurgeon controls the surgical movements of the robot real time from a console (similar to the "passive" systems). The operating surgeon need not be in the same room and can control the maneuvers via an online network. There is provision for haptic feedback and live video transmission for the surgeon to simulate a life-like experience.
- *Shared controlled systems* (►**Fig. 3**): The robot and the neurosurgeon perform the task together with the surgeon in control of the movement and the robot providing concurrent stabilizing forces.

Methods

Robotic systems specific to neurosurgical maneuvers can be grossly considered to be of three major types, with each distinct from another:

- Cranial robotic system.
- Spinal robotic system.
- Microscope integrated robotic system.

There are various articles in the literature discussing about the robotic research programs in neurosurgery encompassing those that could not be executed as well as programs that are commercially available worldwide.[7,8] A nonsystematic literature search using the keywords "robotic," "minimally invasive," and "neurosurgery" was performed in PubMed. The major robotic systems described in neurosurgery were then reviewed looking at the year it was described and their original application in neurosurgery. A chronological description of the promising robotic systems introduced in neurosurgery is discussed further in a narrative fashion.

Neurosurgical Robots

- **PUMA-200** (Programmable Universal Manipulation Arm or Programmable Universal Machine Assembly). This active robotic system was conceptualized by Kwoh et al in 1988.[2] The motions it provided via its six revolute joints were waist, shoulder, elbow, wrist, and flange rotation, and wrist bend, which was quite comparable to human motions. Once the target was locked by the robotic arm, the surgeon could choose the safest trajectory without worrying about a change in the position of the target. Buoyed by its initial success, the PUMA 200 was also used for holding and manipulating surgical retractors while achieving radical excision of thalamic astrocytomas in six children in 1991.[9] This system was the pioneer in practical surgical application of robotics.
- **Neuromate:** This was the first robotic system to achieve Food and Drug Administration (FDA) approval in 1997 in the United States and to achieve Conformité Européenne (CE) certification in Europe. First described in 1987 in Grenoble University by Benabid et al,[10–12] this passive

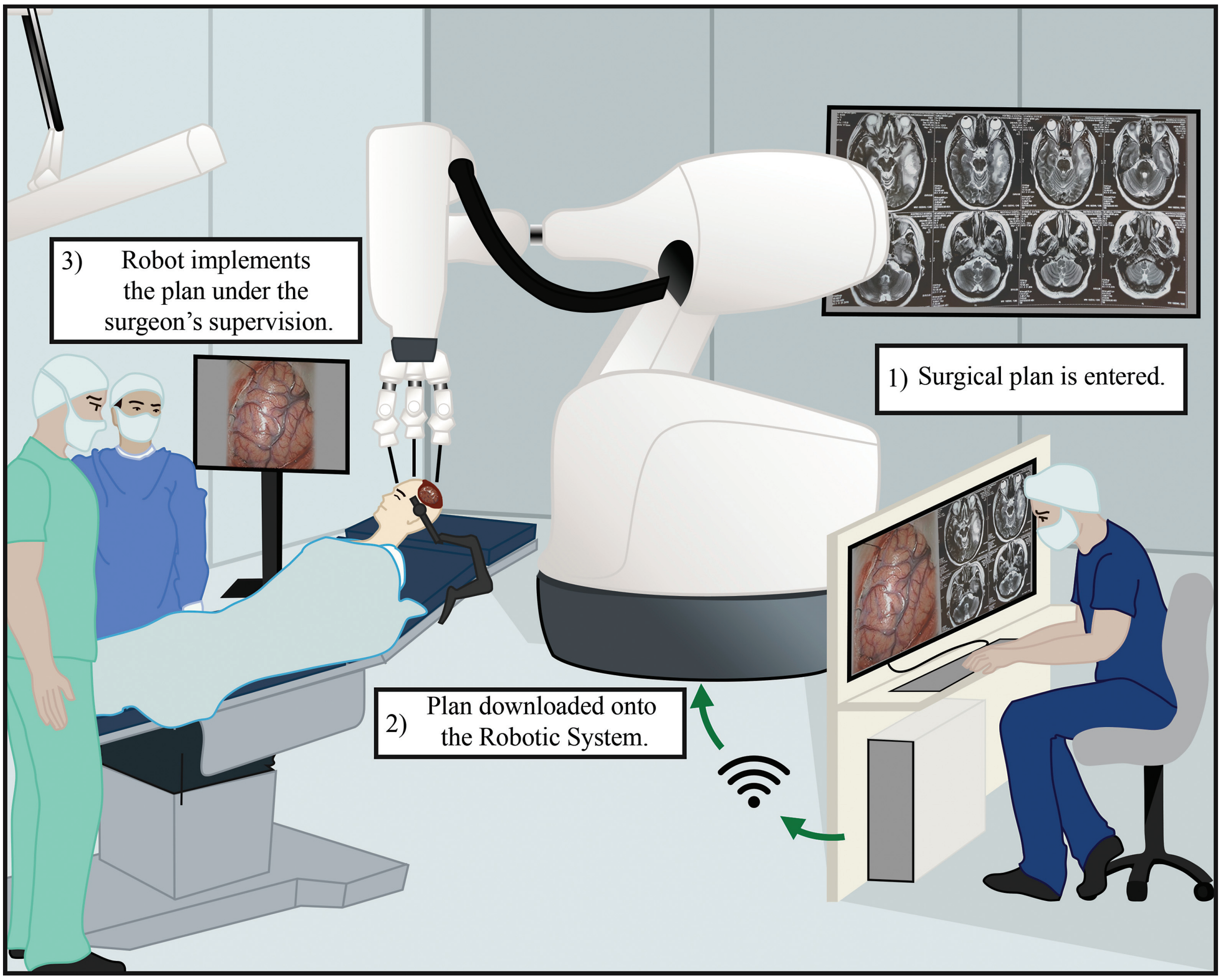

Fig. 1 Supervisory-controlled robot system. The surgeon enters the plan in a computer using the patient's data before the actual surgery. The plan then gets downloaded to the robotic system, which then implements the plan under supervision and close observation of the surgical team.

system consisted of a single arm and was widely used for stereotactic biopsies (frame based or frameless) along with deep brain stimulation (DBS) for movement disorder surgery.[13] A frameless fiducial registration system (Neurolocate) compatible with this system has been described in 2017, which led to a quicker, more accurate and touch-free registration process.[14]

- **Minerva:** Developed in 1995 by Glauser et al,[15] this was the first real-time image guidance robotic system for complex stereotactic biopsy procedures. Being linked to the CT gantry, the overall procedural time was reduced since the CT scan could be taken in real time while performing a biopsy. However, the marked radiation exposure, nonusability of the CT gantry for other patients during the procedure, and the bulky stereotactic frame led to a fall in its acceptance.
- **CyberKnife:** This system, although conceptualized much earlier by Prof. John Adler from the United States, was described in the literature in 1997.[16,17] This was the first system to provide conformal radiosurgery dosages in a frameless manner along with real-time imaging guidance.
- **Robot-Assisted Microsurgery System (RAMS):** In 1999, the existing robotic technology of National Aeronautics and Space Administration (NASA)[18] was utilized to create a master–slave type of robot with the slave robotic arm having 10 joints and the master arm having 8 joints. The prototype offered to scale down the tremors and provide precision to the tune of 10 microns (cf. 70 microns for the most accurate of human surgical hands). When this prototype was tested on 10 rats for endarterectomies, it was found to increase the duration of procedure with no obvious advantage over the human techniques.[19]
- **Leksell Gamma Knife Model C:** Lars Leksell is a name synonymous with the field of gamma knife radiosurgery. His first system was described in 1967; thereafter, this version was set up in 1999 and included an automatic patient positioning system (APS). This robotic function drastically cut down on the procedural time obviating the need for manually changing coordinates with every change of plan.[20,21] The subsequent version known as Leksell Gamma Knife Perfexion introduced in 2006 involves fully automated patient position system (PPS) rather than only the head as in the previous system.
- **da Vinci:** This is the most commonly used master-controlled console-based robotic system today after being introduced in 2000. As compared to other surgical branches (laparoscopic and other minimally invasive procedures), its application in neurosurgery is yet to

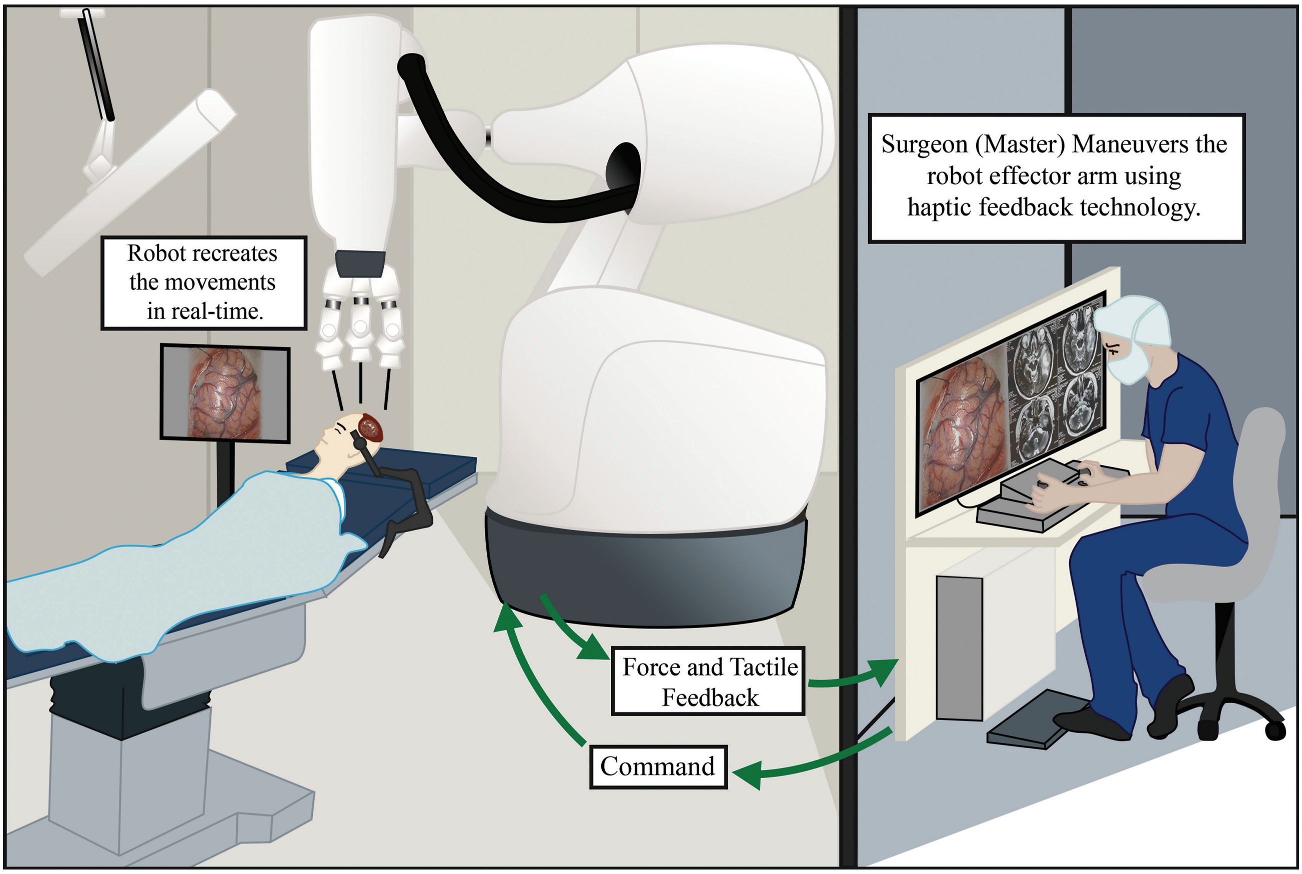

Fig. 2 Telesurgical robot system. The surgeon (master) maneuvers the robotic arms (slave) from the computer console room under guidance of real-time imaging and the tactile feedback elicited via haptic technology.

gain a foothold due to reasons such as large size of the system and limited number of instruments.[22]

- **Evolution-1:** Described in 2002 by Zimmermann et al.,[23] this was the first to cater specifically to navigated neuroendoscopy to hold and maneuver the endoscopic instruments with precision. The solitary robotic arm can be steered with a remotely controlled joystick. In 2004, it was successfully used for endoscopic third ventriculostomies (ETV) in six patients by the same group.[24]
- **NeuRobot:** Till 2002, none of the robotic systems had multiple arms. Neither were they capable of microsurgical application nor were they telesurgically controllable. NeuRobot designed by Goto et al[25–27] as a master–slave system incorporated all these features. Introduced as a telecontrolled micromanipulator system for minimally invasive microneurosurgery, it consisted of four main parts: an input device, a manipulator, a supporting device, and a three-dimensional (3D) display system. The manipulator device (slave) included three 1-mm dissecting forceps and a 3D endoscope. Clinically, it was first attempted for partial meningioma excision, ETV, and sylvian fissure dissection apart from remote controlled surgical stimulation of a rat's brain.[28]
- **Georgetown Needle Driver Robot:** This was the first system specific for spinal surgeries developed by Cleary et al in 2002.[29] The robotic arm (mounted on the operating table and controlled via a joystick) was used for percutaneous nerve blocks and facet joint blocks under fluorescence guidance and was later expanded for CT-guided lung biopsies.[30]
- **SOCRATES:** This was the first telementoring (robotic arm being controlled by a mentor from another institute) system in neurosurgery and another telerobotic system after NeuRobot. Experience with six cases consisting of craniotomies, endarterectomy, and laminectomy operated using the SOCRATES system was published by Mendez et al in 2005.[31] The audio and video feedback was real time without any lag between the mentor and operating surgeon.
- **SpineAssist Miniature Robotic System:** The most popular and advanced of spinal robotic systems, this was introduced in 2006 by Barzilay et al (Mazor Robotics, Israel).[32] A multicenter study from 14 institutions verified that this system improved the placement accuracy of screws and reduced the neurological complications.[33] The system provides 6 degrees of freedom (DOF) and is made up of a miniature hexapod (2.5 cm, 250 g) fixed on bony spinous process. The Mazor workstation is used for planning the screw placement on 3D models.
- **Pathfinder:** This robot was first validated by Eljamel in 2007.[34] It consists of a single arm on a stable base. Pathfinder differed from the others introduced till then in having an inbuilt camera sensor system for tracking position. It fixed onto the Mayfield clamp and the image

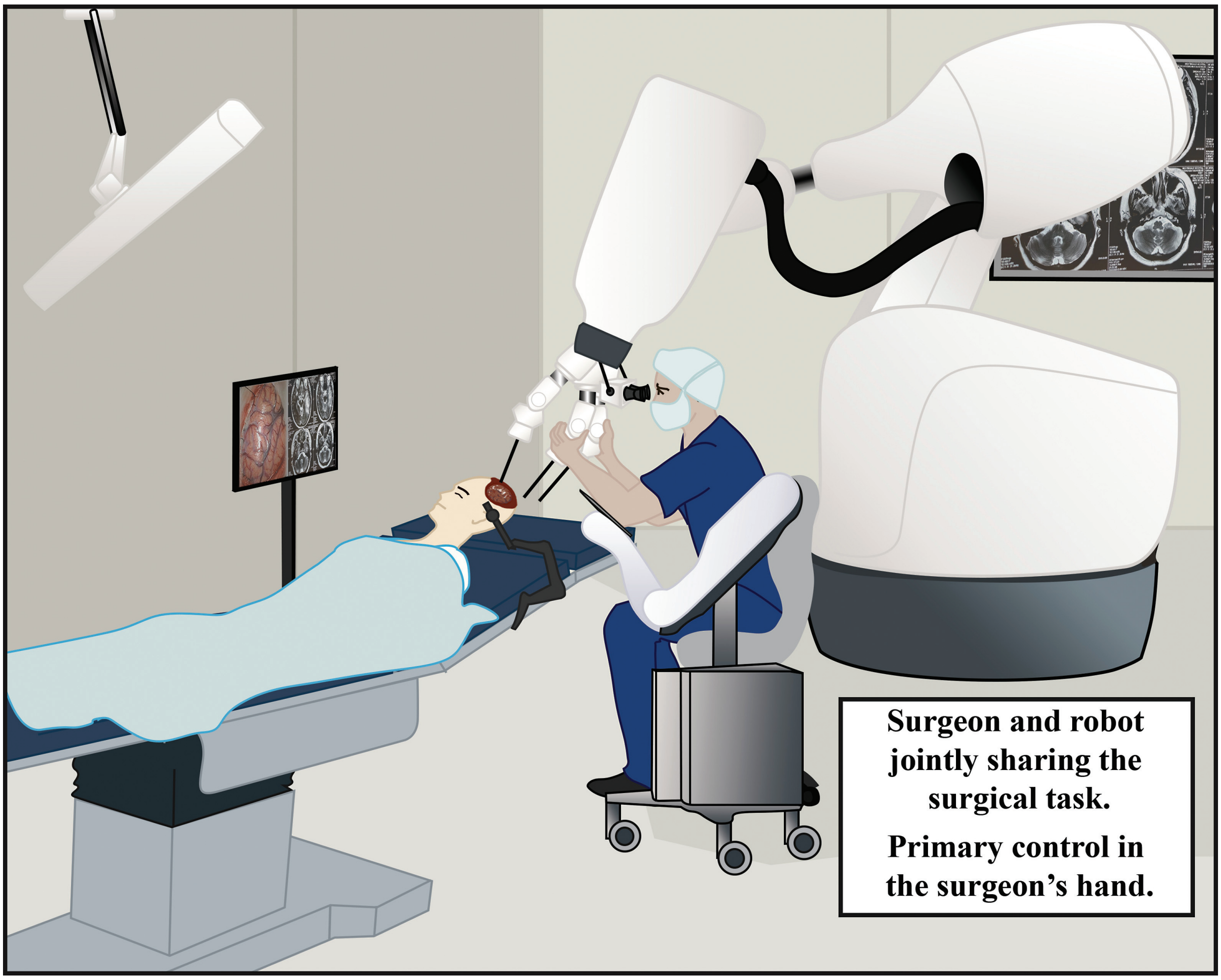

Fig. 3 Shared-control robot system. The surgeon and the robot jointly sharing the surgical task. Primary control remains with the surgeon, while the robot provides assistance in the form of armrest, steadying the hand movements, etc.

registration relied on fiducials and surface targets on the patient's skull rather than any form of imaging. The initial study was conducted on phantoms and it was found to be more accurate than the frameless navigation machines as well as the frame-based stereotactic devices.

- **NeuroArm:** Launched in 2008,[35] this is widely considered the most advanced robotic system. NeuroArm was the first neurosurgical system to incorporate and allow MRI within it. To enable MRI compatibility, the arms are made up of titanium and polyether ether ketone (PEEK) material. The arms rest on a mobile supporting base and the end effector arm can hold a variety of instruments needed for microneurosurgery. The first clinical series using this system in 35 cases was published in 2013 with 1 adverse event reported.[36]
- **Neurosurgical robot with offset forceps:** School of Engineering Department, University of Tokyo, in 2008, described a robot for deep surgical fields using offset variants of forceps of 2.5 mm diameter that do not interfere with the microscope's vision.[37]
- **Renaissance Robotic System:** This was the second-generation version of the SpineAssist system produced by the same parent company in 2011.[38] This version is faster, ergonomically better, smaller in size, and more accurate than the SpineAssist robot. Apart from the fixation techniques, biopsy of spinal tumors can also be done via this system. It is presently the most widely used spinal robotic system.
- **Spine Bull's-Eye Robot:** This is another spinal robotic system designed by Zhang et al in 2012. A 97.1% accuracy was reported by their group for thoracic pedicle guidewire insertion.[39]
- **EXPERT:** This passively controlled arm holder was first described by Goto et al in 2013.[40] The inbuilt position modes were transfer, arm hold, and arm free. A second-generation version was described (iARMS) in 2017 by Ogiwara et al[41] (►**Fig. 4**). With a heavy base, to prevent tilting over, the system supports and follows the surgeon's arm to reduce fatigability. The initial experience in 43 cases of endoscopic endonasal surgery showed that the surgeon did not feel any heavy handedness during surgical movements, nor was there any need to toggle switches in between major movements. It was subsequently validated by 14 neurosurgeons in the coming year and the results have been very positive.[42]
- **Robotic Stereotactic Assistance (ROSA):** This single-arm robot provides very good dexterity and accuracy and shortens the operative time in procedures, namely, DBS,

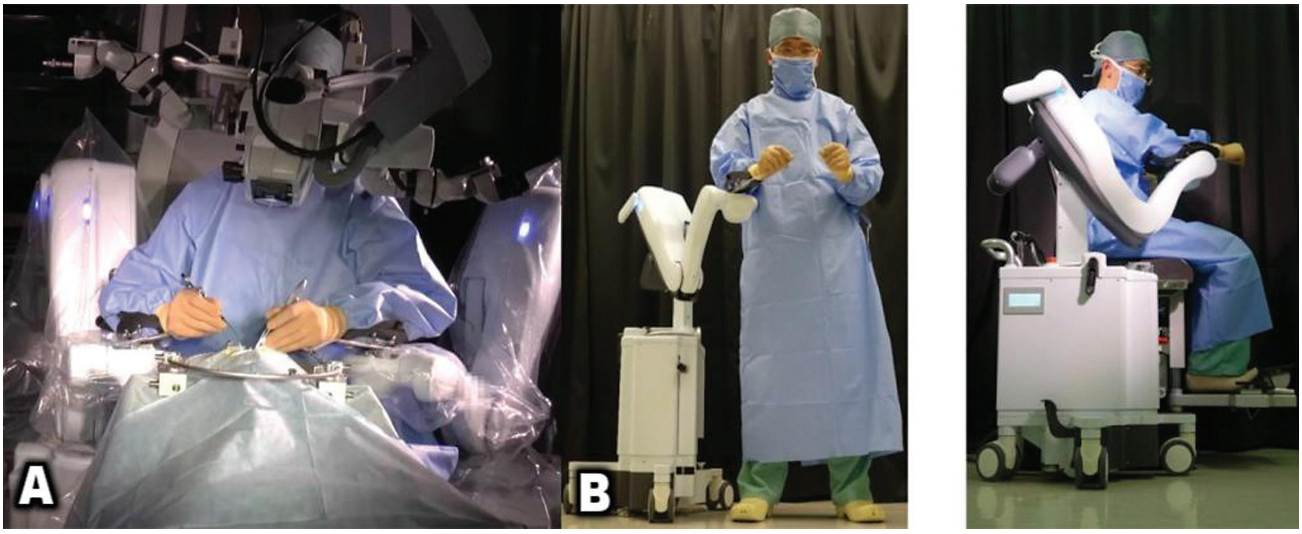

Fig. 4 (**A**) Use of iArmS in microneurosurgery in the locked position. (**B**) Demonstration of its adaptability in various positions taken by the surgeon. (These images are provided courtesy of Dr. Tetsuya Goto from Shinshu University.)

stereoelectroencephalography (SEEG), repetitive nerve stimulation (RNS), etc.[43] It is one of the few systems featuring an integrated haptic technology to create a more life-like interface for surgeons and the only system that can be used for cranial as well as spinal surgeries. Preliminary results of electrode placement for thermocoagulation of hypothalamic hamartomas using ROSA have been satisfactory.[44] The largest reported series utilizing this system is of 116 pediatric cases, which demonstrated reduced postoperative morbidity and improved surgical outcomes.[45]

- **Robotically Operated Video Optical Telescopic-Microscope (ROVOT-M):** Described in 2017,[46] ROVOT-M provides an intuitive and more effective optical visualization system that can be utilized in a wide spectrum of complex cranial neurosurgical procedures.[47]
- **ExcelsiusGPS:** This spinal robotic system, marketed by Globus Medical since 2017, provides navigated guidance for accurate pedicle screw placement validated clinically.[48]
- **RoBoSculpt:** Developed in Eindhoven University of Technology in 2018, this robotic arm can provide precision-based drilling of the skull base and cut down on the duration of neurosurgical/ear, nose, and throat (ENT) procedures. It is yet to be clinically validated.[49]
- **REMEBOT:** This latest passive robotic system has been described by Wang et al[50] in 2019 for optimal stereotactic localization and evacuation of intracranial hemorrhage.
- **MYTHRI:** National Institute of Mental Health and Neurosciences (NIMHANS) and Indian Institute of Information Technology (IIIT) in Bangalore, India, have described a neurosurgical robotic system in 2020. This robot is unique in having two independent systems, that is, a functioning multi-arm base with 3 DOF and a distal hyperflexible end that adds further 2 DOF.[51]
- **Robot-Assisted Neurosurgical Suite:** This is a joint initiative led by Bhabha Atomic Research Centre (BARC), Mumbai, India, in collaboration with the Advanced Centre for Treatment Research and Education in Cancer (ACTREC), Tata Memorial Centre, Mumbai, India, to extend indigenous and affordable high-quality neurosurgical robotic technology in resource-constrained setups. The system incorporates inbuilt image guidance technology and is designed to execute all the presurgical planning procedures and certain aspects of high-precision robot-assisted neurosurgery (►**Fig. 5**). The Robot-Assisted Neurosurgical Suite is made up of the following important subunits:
    - Image registration and patient-specific 3D model algorithms for surgical planning.
    - Surgical coordinate measuring mechanism (SCMM).
    - High-definition visualization and integration of virtual SCMM and surgical tool for image-guided surgery.
    - High-precision, 6 DOF robot.
    - Algorithms for conducting the robot-based autonomous neurosurgical procedures including autonomous patient registration, neuronavigation, and robot-based neuroprocedure.[52]

The technology supports high-precision and accuracy in performing intricate targeted surgery. A 6 DOF parallel kinematic mechanism (6D-PKM) robot is used for neurosurgery. The robot is a compact portable system weighing 150 N, and it can support and manipulate a payload of 200 N. The repeatability of the robot is 10 µm, and absolute accuracy is 60 µm. It is dexterous to approach a point from multiple directions or, in other words, the end tool of the robot can be positioned and oriented at any desired posture in the workspace.

The visualization includes multisectional views and transparent 3D view to provide real-time feedback on the progress of the tool insertion. The image segmentation, enhancement of regions of interest, dynamic linking of 3D image and cross-sectional images, sections normal to the tool axis and passing through the tooltip, digitization of the image, etc., are obtained for accurate patient assessment and

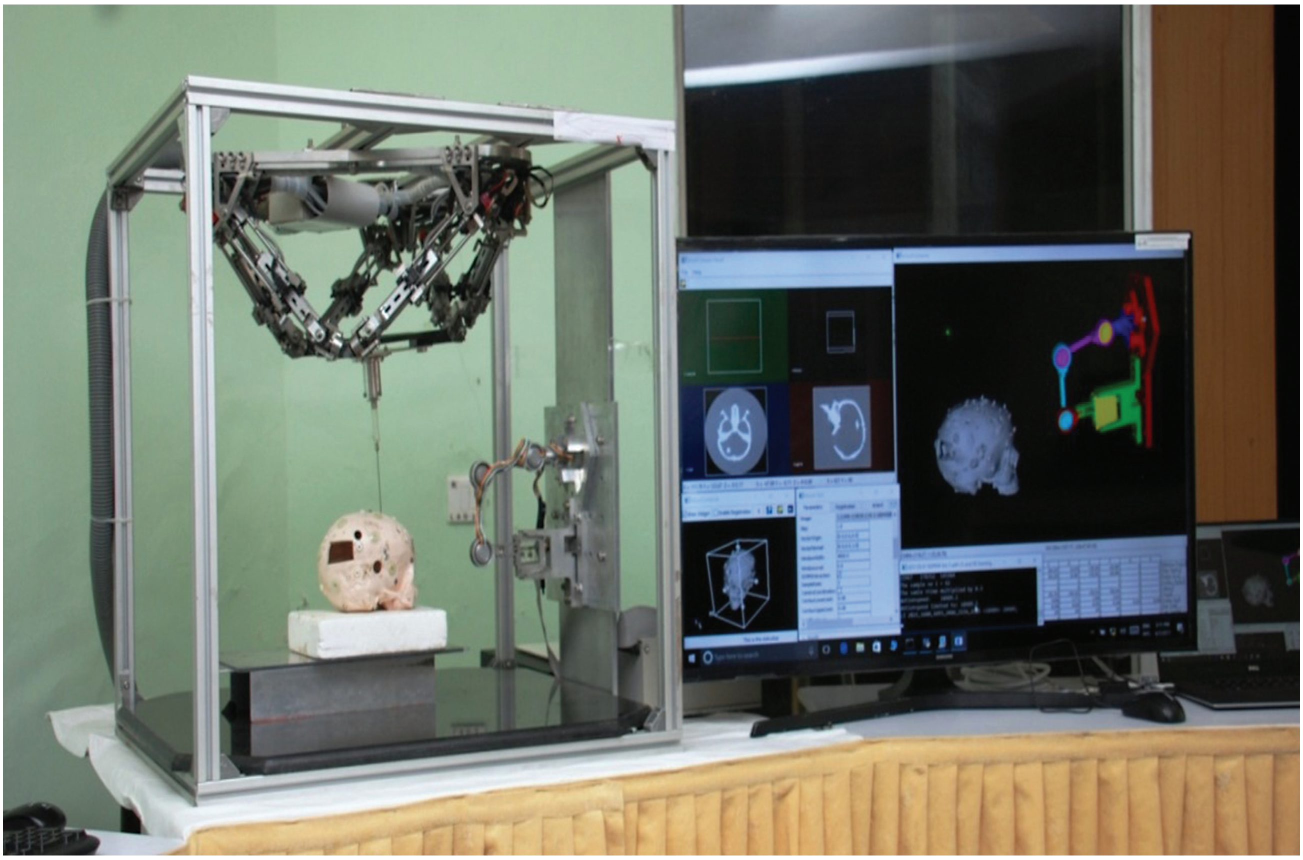

Fig. 5 Robot-assisted neurosurgical suite comprising the neurosurgical robot (Bhabha Atomic Research Centre, Mumbai and Tata Memorial Centre, Mumbai), surgical coordinate measuring mechanism, and visualization.

surgical planning. The important aspect is that the virtual surgical tool is integrated and the movement of real surgical tool is shown in all the cross-sections and in the patient-specific 3D model in real time.

The neuro-suite is equipped with a robust real-time algorithm to measure the coordinates of the point on the marker for robot-based autonomous registration and surgery. The algorithm is built in two parts. The first part deals with the detection of markers. The second part autonomously measures the coordinates of the reference point on the marker. Multiple studies have been conducted where the algorithm was tested for extreme conditions of uneven lighting, distorted color, surface distortions, and significant random orientation of the marker.

The average time of the manual patient registration process has been observed to be about 15 minutes. In all the experiments, the time taken for the autonomous phantom registration was found to be within 5 minutes. The phantom was registered within 1-mm accuracy in all the cases for all the poses. High-precision navigation to the target in all the poses was demonstrated. The detailed results of various case studies have been reported in the literature.[53,54] The localization module has no line-of-sight problem and thus has a minimum footprint in the operating room in contrast to the existing camera-based navigation systems.

The structure of this suite is based on parallel architecture, while most of the existing robots are based on serial structures. Parallel architectures inherently are compact, possess high rigidity, and result in high accuracy. They can support high payload for a given self-weight. However, their reachable workspace is small compared to the serial counterpart. The phantom-based trials have been conducted at the laboratory and subsequently validated in a simulated trial operation theater.[53,54] Presently, the neuro-suite is under advanced clinical trials at NIMHANS, Bangalore, and ACTREC, Navi Mumbai, with clinical validation on humans and animals pending.

►**Table 1** summarizes the major cranial robotic systems and ►**Fig. 6** gives a timeline of major events in their development.

Benefits and Challenges in Implementing Robotics in Neurosurgery

Apart from the generalized benefits of robots such as negation of tremor, improved dexterity, and 3D visualization, advantages specific to neurosurgery are its potential to provide increased micromanipulation, reproducibility, and telesurgery. Coupled with instantaneous and rapidly adapting biosensing technology (haptics and optics), it can enhance surgical precision, especially within constrained spaces. At the same time, safety checks can be incorporated preventing inadvertent potentially harmful maneuvers. Although there exists the possibility of better outcomes in handling monotonous surgical tissue in a consistent manner, these outcomes still need to be validated on a larger scale to enable wide applicability. The existing procedural standards,

Table 1 Summary of the major cranial robotic systems

Year	Name	Company/university	Type	Functionality	Highlights
1985	PUMA 200	UNIMATION, subsidiary company of Westington Electric, Pittsburgh, United States	Telesurgical	Effector	First surgically applied robotic system. 3 degrees of freedom (DOF). 0.05-mm precision
1987	Neuromate	Integrated Surgical Systems, Renishaw Mayfield, Lyon, France	Telesurgical	Effector	First neurosurgical robot to receive FDA and CE approval. 5 DOF. Incorporates preoperative imaging
1995	Minerva	Swiss Federal Institute of Technology, Lausanne, Switzerland	Supervised and controlled	Effector	First to provide real-time image guidance. 5 DOF
1997	CyberKnife	Accuray Inc., United States	Supervised and controlled	Effector	First robotic system to provide conformal radiosurgery in a frameless manner. 6 DOF
1999	RAMS	National Aeronautics and Space Administration's (NASA) Jet Propulsion Laboratory and Microdexterity System Inc., United States	Telesurgical	Effector	First to provide robotic surgical suites system. 6 DOF
1999	Leksell Gamma Knife Model C	Elekta, Stockholm, Sweden	Telesurgical	Effector	First robotic system to provide conformal radiosurgery in the frame-based technique
2002	Evolution 1	Universal Robot Systems, Schwerin, Germany	Shared Control	Holder	First to incorporate neuroendoscopy. 6 DOF for pedicle screw and 4 DOF for neuroendoscopy
2002	NeuRobot	Shinshu University, Japan	Telesurgical	Effector	Consists of 3D rigid endoscope and 3 arms of 1 cm diameter. 3 DOF
2007	Pathfinder	Prosurgics Ltd., High Wycombe, UK	Supervised and controlled	Effector	Inbuilt camera sensor for tracking. 6 DOF
2008	NeuroArm	University of Calgary, Canada	Supervised and controlled	Effector	First to integrate robot with intraoperative MRI. 2 arms with each having 7 DOF
2013	Expert	Shinshu University, Japan	Telesurgical	Holder	First of its kind robotic arm holder proven to reduce tremors. 5 DOF
2014	ROSA	Zimmer Biomet/Medtech Innovative Surgical Technology	Shared control	Effector	Used for multiple indications (cranial and spinal). 6 DOF
2017	ROVOT-M		Shared control	Visualization	

Table 1 (*Continued*)

Year	Name	Company/university	Type	Functionality	Highlights
		Aurora Institute Group, Milwaukee, United States			First navigated exoscope with a dynamic robotic arm not requiring to be manually repositioned
2019	REMEBOT	Remebot, China	Telesurgical	Holder and visualization	Provides 3D visualization and multimodal image fusion for planning ideal puncture trajectory for hematoma evacuation
2020	Robot Assisted Neurosurgical Suite	Bhabha Atomic Research Centre (BARC), Mumbai, India, with Advanced Centre for Training Research and Education in Cancer (ACTREC), Tata Memorial Centre, Mumbai, India	Supervised and controlled	Effector	First indigenous Indian robotic system in neurosurgery with inbuilt image guidance. 6 DOF (under clinical development)

Abbreviations: CE, Conformité Européenne; FDA, Food and Drug Administration; MRI, magnetic resonance imaging; 3D, three dimensional.

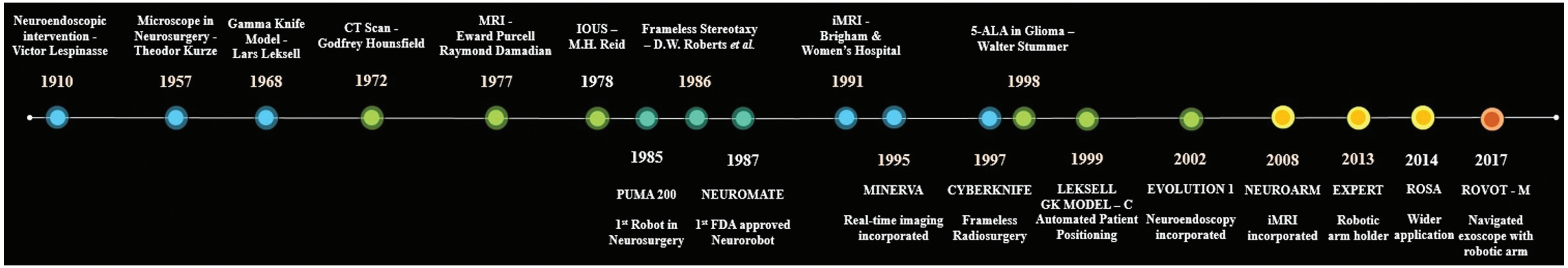

Fig. 6 Timeline of significant technological development and evolution of robotic systems in neurosurgery.

infrastructure, education, and training are conventionally in accordance with human-based surgery. It is a complex and challenging process to extrapolate this into robotic-based neurosurgery. The Digital Imaging and Communications in Medicine (DICOM) standards, which facilitate and guide human image-based surgical procedures, do not yet contain information required for robot-based neurosurgery. Furthermore, the conventional assessment of the surgical performance and outcome is highly qualitative in nature. Surgeons are intuitively nurtured because of their training and subjective experience, whereas robotic surgery is based entirely on objectivity. Accurate correlation and reconciliation of the qualitative feel and cognitive judgment of surgeons with objective and quantitative numbers for robot-based surgery are highly challenging. The skill set and training required for each make of robot are different, and the stakeholders may not like to invest in a specific and limited scope of training. Additionally, there are logistical issues, which may not seem obvious, namely, providing larger operating room setups, trained surgeons and support staff, increase in the operating time, etc. These limitations, coupled with the significantly high costs of devices, make the proposition less attractive as of today. In spite of the technological developments since its first description, application of robotics in neurosurgery remains limited due to the intricate anatomy, difficulty in differentiating normal from neoplastic brain tissue, achieving satisfactory hemostasis, and possibility of mechanical failure in autonomous robots

Future Perspectives

The science of learning from experience and high-precision evaluation is being pursued using artificial intelligence (AI) and deep learning. AI integration of sensory perception, neural networks, and thought processing superceding mathematical algorithms coupled with nanotechnology represents the horizon where we can expect the next major advancements to occur with respect to robotic technology.[55] With time, smartphones may play an important role in augmenting surgical techniques coupled with robotics. Telerobotic technology for long-distance surgeries such as in warzones is also under development by Verb Surgical in collaboration with technology from SRI International.[56] A finger attachment device has been recently described, which illustrates an example where robotics can effectively alter the decision-making process independently.[57] This gives us a glimpse of the future where such robotic attachments may discriminate tumor tissue from normal brain not just via their feel but with rapid pathological assessment as well. Above all, health economics is likely to govern many of the implementable developments in robotics, and cost-effectiveness studies (besides principle and efficacy studies) are the need of the hour.

Although we have alluded to a few of the possibilities, the potential remains limitless. Presently, robotic systems provide enhanced visualization and positioning of payloads along with controlled deployment of predetermined payloads. At present, robotics plays a role in accessing deep-rooted points with high accuracy for biopsy, DBS, positioning neural implants, neurosurgical assistance in ultrasound navigation, etc. In the future, it is anticipated that these functions will be integrated into commonly used neurosurgical platforms along with intuitive performance of complex neurosurgical maneuvers with real-time feedback.

Conclusion

Neurosurgical practice involves complex surgeries that are being attempted through narrower corridors, partly due to advances in the tools and approaches and partly due to the nonfeasibility of extended corridors. Robotics can provide an advantage in this aspect where it seems that the limits of human surgical expertise have been reached. In developing countries like India, a unified intent needs to be exhibited by all the collaborators including designers, manufacturers, policy makers, and neurosurgeons to push forward the realm of robotics into neurosurgical practice with a focus on the operational feasibility and cost-effectiveness.

Authors' Contributions

S.T.S. contributed to literature review, journal formatting, and figure and table formatting. T.A.D. contributed to the review of article. A.V.M. conceptualized the article and contributed to the review and final proofreading of the manuscript.

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Conflict of Interest

None declared.

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