The SAGES Atlas of Robotic Surgery

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This book is dedicated to the memory of Jeffrey Ying (1954–2017).

I first met him on the Fourth of July 2014, at a picnic he and his wife Renee were throwing to celebrate the birth of our nation. My wife and I were new to Southern California and were invited because of who Jeffrey was: generous, welcoming of any new neighbor, and always sharing and celebrating life.

Jeffrey was an engineer and founder of the I/O Controls Corporation. In business he was known as an entrepreneur, an innovator, and a leader. He held more than 100 patents. He believed in science and engineering for the betterment of mankind. In his work and through his inventions, he has touched the lives of many.

For those who knew him, he was always the most interesting man in the room. He lived life to the fullest and was accomplished in so many areas outside of work. Whatever he did, he did the utmost. He was the first Chinese pilot from Taiwan to circumnavigate the globe in a single engine aircraft, when he and Renee performed the feat in 2010.

Jeffrey was also kind, loyal, compassionate, and generous. He and his wife Renee started the 12K Foundation to fund education for orphans in Tibet. They were also generous in support of medical research directed at engineering new cancer therapies.

We are happy to have known him and continue to be inspired by him.

"Always be curious and adventurous; keep the heart of a child inside and fill it up with joy and peace, and be the best you can be (Jeffrey Ying)."

Preface

Robotic Surgery as the Natural Evolution of Minimally Invasive Surgery

Minimally invasive surgery (MIS) was largely restricted to diagnostic procedures until the second half of the twentieth century. Improving instrumentation, particularly in energy devices for sealing and in stapling devices for anastomosis of luminal organs, prompted rapid development of laparoscopy in the end of the last century. The first laparoscopic cholecystectomy was performed in 1985 [1] and within a decade was the standard of care [2]. The first laparoscopic colectomies were performed in 1990 and now are accepted as standard [3]. Many operations, including complex esophageal, liver, lung, and endocrine procedures, are now routinely performed using laparoscopic approaches and to the benefit of many patients. Robotic surgery, introduced to surgeons at the beginning of the twenty-first century, is the natural evolution of this MIS revolution. Using computer control of the MIS instruments, robotic surgery offers many potential advantages including improved visibility, easily controlled articulated instruments, and superb ergonomics. Complex tasks such as suturing that have challenged the laparoscopic surgeon are now easily within reach of the robotic MIS surgeon. The surgical robot has evolved from a single-purpose robot to a true surgical instrument with many potential operations. Over three million operations of many types have been performed with the assistance of the surgical robot.

The evolution of robotic surgery is reminiscent of what transpired in the evolution of industrial robots in the mid-twentieth century. Industrial robots were born as necessary safety tools for nuclear engineering. In the 1940s, mechanical teleoperators were created for handling dangerous radioactive materials. In the 1950s, computer controllers were added to the tele-manipulators to improve reliability and ergonomics. In the 1960s, General Motors deployed the first Unimation® robots in their automotive factories. In the early days, these robots were put to work just stacking boxes and unloading trucks. This is reminiscent of the first robots that arrived in the operating room. In 1992, Computer Motion Inc. brought forth the operative robot "Automated Endoscopic System for Optimal Positioning (AESOP)," which did not drive any surgical interventional instrument. AESOP was a single-purpose camera holder that reliably held and moved the laparoscopic camera, improving visualization of the MIS operation.

Industrial robots are now well advanced. Robots are now used autonomously for many of the essential steps in welding and assembling the more than 70 million vehicles produced yearly. Robots are even used to autonomously drive cars here on Earth and on Mars [4]. Most importantly, there is now general public acceptance of robotics for manufacturing and transportation.

Surgical robots are now mainly used as mechanical teleoperators in the surgical suite, allowing rapid and precise movement of the laparoscope within and between multiple operating fields. The surgical robotic tele-manipulator is also used to drive an increasingly diverse number of instruments to facilitate accessibility and performance of increasingly complex MIS tasks. We are now at a pivotal point in the field when a technology is about to transform from a tool for innovators and experts to a tool for general practitioners. To facilitate general deployment, teaching tools are necessary including comprehensive atlases such as the current volume. This book is a step-by-step guide to document the current state of the field, to increase accessibility for those venturing in the field, and to improve the safety of procedures. Ultimately, the goal is to improve outcomes for patients undergoing such procedures by providing an easy to understand, illustrated atlas of robotic surgery.

This book outlines the basics of successfully organizing, initiating, and running a robotic program. Details regarding technical, financial, and medico-legal aspects are presented, including room design and surgical team needs. This section is intended to help efficiently set up and start a robotic program. The economic cost of robot-assisted surgery is a major and consistent factor contributing to inertia against adoption [5]. Mitigating the higher cost is an essential component to the routine adoption of robotic surgery. We hope this section of the book will alert readers to the avoidable inefficiencies and wasted costs in the initial phase of launching a new program.

Safety is an important issue since extensive operations are being performed through 8 mm incisions. In cases where emergencies arise, it is critical to have meticulously rehearsed plans for urgent or emergent conversion to ensure life-saving interventions. These are described in chapters on workflow (Chap. 7) and emergencies (Chap. 9).

We then present technical steps and detailed pearls of 34 operations that are routinely performed, with room setup and instrument usage, as well as technical steps. The operations presented range from surgery in the oral pharynx to pelvic operations. Some of these, such as prostatectomy, colectomy, cholecystectomy, pulmonary resection, and gynecologic procedures, are well established and are the standard procedures for the organ involved. Some procedures described, such as radical gastrectomies, pancreatectomies, and trans-oral surgery, are emerging procedures that we anticipate will become important in the field. For some of the most complex operations, such as pancreaticoduodenectomy, we detail descriptions by more than one group to show variations in procedure.

The field of robotics is both dynamic and rapidly evolving. Many new operations are being invented and improvements in current operative technique will develop with wider deployment and increasing input from more robotic surgeons, as well as from improvements in robots and instrumentation. We hope that the reader will see our book as a living work that our robotic surgical community will shape together. If you have new variations of the current procedures or a new procedure that is becoming popularized, please let us know so we can plan to include it in the next edition.

The future for robotic MIS surgery is bright. However, for most of the operations performed by a robotic approach, there is a perception that it takes longer and costs more, especially at the initiation of a new program. Most cars in the world are created by robots because *quality is more consistent, production is faster, and it costs less*. Interventional radiologic procedures are rarely debated even when initial costs are steep because the procedures are clearly more efficient and significantly reduce morbidity. For common low-intensity robotic operations, we need to make them safer, faster, cheaper, or easier [6].

For high-end technical operations, technical enhancements including better instrumentation and workflows that enable improvements in accessibility or outcome are critical to growing this application. As physicians, we tirelessly aim to improve the learning curve for established and emerging techniques, improve outcomes for our patients, and most of all help our patients return to normal and productive lives. We hope this atlas will contribute to all of these goals.

This book is intended for anyone who plans to incorporate robotically assisted surgery into their portfolio of practice. We hope this will include surgeons, nurses, and other operating room personnel, as well as administrators and engineers. A work like this is only possible because of the contributions of many. The authorship of this work includes experienced surgical oncologists, general surgeons, thoracic surgeons, gynecologic oncologists, urologists, transplantation specialists, anesthesiologists, architects, and attorneys. We thank them for their contributions and efforts to collaborate in the creation of this comprehensive and special work.

We also thank our teachers, residents, clinical fellows, and colleagues who have shared their knowledge and experience with us. We thank our patients who inspire us to be superior clinicians, who inspire us to constantly strive to improve the field. We thank our editor at Springer Lee Klein. Finally, we thank our families, particularly Nicole, Christy, James, Jonathan, Jungwon, Boyun, and Seokwoo, for the patience and support they have given us daily for our clinical work, and then to complete a work such as this.

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Part I

History and Basics of Robotic Surgery

History of Robots and Robotic Surgery

1

Paolo Fiorini

Introduction

This chapter presents a brief history of robotics and one of its most successful applications, surgical robotics. The first section describes the beginning of this technology, from 1950 to 1980, when the basic concepts and technologies were developed. The second section addresses the development of robotic surgery, which has established itself as a necessary complement to standard surgical practice. The third section briefly summarizes some of the current research efforts in robotic surgery, and the fourth section introduces the main commercial surgical robots available on the market. The final section describes the most important robotic concepts that are necessary to understand the main features of any surgical robot.

The Beginnings

Robots are among the good byproducts of the Second World War. Their technology derived from the early teleoperation systems developed in 1948 by Raymond Goertz at the Argonne National Laboratory in the United States, to handle radioactive material [1]. The word "robot" and the concept of a mechanical entity able to carry out tasks that a person cannot do or does not want to do pre-date this technology development. The word "robot" started to be used in the 1920s following a play by the Czech author Karel Capek, called R.U.R. (Rossum's Universal Robots), in which artificial biological organisms in human form obey their master's orders [2]. These organisms were called "robots," a word derived from the Czech "robota," meaning "forced labor." They were more similar to androids than to current humanoid robots, as they could also think for themselves, which eventually led to a rebellion that destroyed the human race. The word "robot" then came to identify all devices developed to display an animate behavior.

In ancient times, many mythological figures and brilliant devices have been described that mimic human or animal functions. It is worth remembering the clay golems of Jewish legend [3], the clay giants of Norse legend, and the Greek myth of Talos [4], in which a bronze warrior guarded the island of Crete in 400 BC. The quest to develop mechanical humans is present in most cultures. In early China, about 900 BC, the inventor Yan Shi developed for King Mu of Zhou a life-sized, human-shaped figure made of leather and wood [5]. In 1066, the Chinese inventor Su Song built a water clock shaped as a tower with mechanical figures indicating the hours [6]. About 1495 in Italy, Leonardo da Vinci drew in his notebooks the plans for a mechanical knight able to sit up, wave its arms, and move its head and jaw [7]. In Japan, complex animal and human automata were built in the seventeenth to nineteenth centuries [8], such as the "karakuri ningyō," a type of mechanical device used to recreate different events, such as the tea ceremony. In France, between 1738 and 1739, Jacques de Vaucanson developed several life-sized automatons, including his famous mechanical duck, which could flap its wings, move its neck, swallow food, and give the illusion of digesting it by excreting matter stored in its body [9]. To impress the Empress Maria Theresa of Austria, in 1770 the Hungarian inventor Kempelen Farkas developed a mechanism that was unbeatable at chess. The machine was called the "Mechanical Turk"; only in 1820 was it exposed as a hoax, with a person hidden inside the structure [10].

The word "robotics" has also a nontechnical origin. It was created in the 1940s by the Russian writer Isaac Asimov to represent the study of mechanical robots of human appearance. The robots' behavior was programmed in a "positronic" brain and satisfied certain rules of ethical conduct, which came to be known as the Three Laws of Robotics [11].

The first teleoperation system credited to Raymond Goertz consisted of a master device, held by the operator,

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and by a slave mechanical arm, in contact with the environment, in the so-called master-slave configuration. The slave was coupled to the master through a series of mechanical linkages, and it duplicated the motions of the operator's hands and fingers. These linkages were eventually replaced by electric or hydraulic coupling; the operator could then control the position of the slave arms but lost the perception of contacts provided by the mechanical linkages. Force feedback was then added to the teleoperation system to prevent crushing glass containers, and the operator could again feel the interaction forces of the slave with the environment. This solution was called "teleoperator" to represent a teleoperation system that was not mechanically linked with the operator. The term "telepresence" was also introduced to describe the added sensory feedback, from the remote environment to the operator, who thus has increased sensory and decision-making abilities.

In 1949, the US Air Force sponsored the development of numerically controlled milling machines [12] that combined servo systems with the newly developed numerical computers. In 1953, the MIT Radiation Laboratory demonstrated the prototype of a computer numerically controlled (CNC) machine. In 1954, George Devol replaced the master device of the teleoperator with the computer control of a CNC machine and called this device a "programmed articulated transfer device" for which he filed a patent [13]. The patent rights were bought by a Columbia University student, Joseph Engelberger, who founded a company called Unimation in 1956. In 1960, the first Unimation robot was demonstrated, and the first installation was done the following year at a General Motors plant. This industrial robot could be reprogrammed to perform different pick-and-place tasks, but all parts needed to be accurately positioned in the working cell, as the robot could not adapt to any position error [14]. The first applications were for material handling in steel plants. To overcome the need for precise part positioning, in 1961 a robot with force sensing was developed at MIT [15], which enabled the robot to stack blocks in an unstructured environment without explicitly programming the robot motions. Other sensors were added to robots to increase the perception of their environment. In the 1960s, binary and halftone vision systems were also developed for obstacle detection [16], followed later by a camera vision system [17]. One of the most influential early designs was the Stanford arm designed in 1969 by Victor Scheinman at the Stanford Artificial Intelligence Lab (SAIL) (Fig. 1.1). It was a six-joint, all-electric mechanical manipulator designed exclusively for computer control [18].

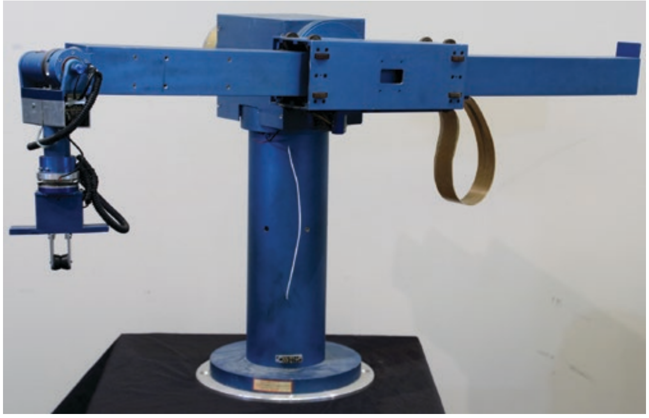

Fig. 1.1 The Stanford Arm (courtesy of Prof. Oussama Khatib, Stanford University)

This robot was enhanced with artificial intelligence algorithms that enabled it to solve puzzles [19]. These sensor-equipped robots were able to perform tasks requiring the control of the interaction forces with the environment. Japanese researchers developed the automatic selection of force and position control, and this led to the development of a mechanical manipulator with compliance control [20]. Roughly at the same time, in 1973, Stanford researchers developed the first language for programming a robot [21]. The first anthropomorphic industrial robot was developed in 1976 by Cincinnati Milacron Inc. The Tomorrow Tool (T3) could lift 50 kg and track objects on a moving conveyor belt [22]. In 1973, Victor Scheinman developed the Vicarm, which was sold in 1977 to Unimation. Figure 1.2 shows the brochure of the robots produced by Scheinman company. The following year, with support from General Motors,

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Fig. 1.2 Brochure of Vicarm, the first manufacturer of commercial robots (courtesy of Prof. Paolo Fiorini, University of Verona)

Unimation developed the Vicarm into the PUMA (Programmable Universal Machine for Assembly) family of robots, which would become the workhorse of robotics research (Figs. 1.3 and 1.4). In the mid-1970s, Antal Bejczy at Caltech NASA-Jet Propulsion Laboratory (JPL) developed the first dynamic model of a robotic arm and later began the teleoperation program for space-based manipulators, which led to robotic surgery. In 1979, the SCARA (Selective Compliant Articulated Robot for Assembly) was developed. Based on these results, the group of Antal Bejczy developed the Advanced Teleoperation Laboratory to demonstrate the feasibility of space repair from Earth and developed some of the technologies for bilateral teleoperation used in later telesurgical systems (Figs. 1.5 and 1.6).

Fig. 1.3 The Puma 500 robotic arm (courtesy of Prof. Paolo Fiorini, University of Verona)

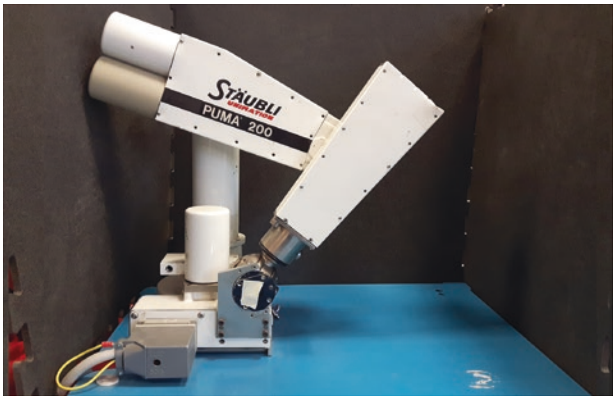

Fig. 1.4 The Puma 200 robotic arm (courtesy of Prof. Paolo Fiorini, University of Verona)

Fig. 1.5 The master station of the Advanced Teleoperation Laboratory at NASA-JPL (courtesy of NASA/JPL-Caltech)

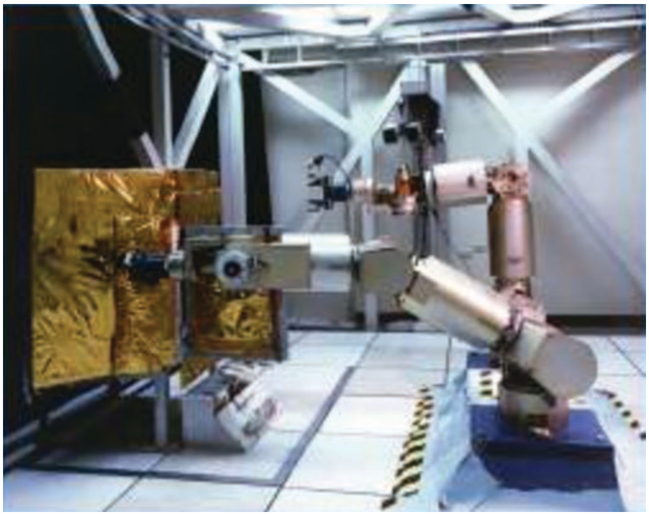

Fig. 1.6 The slave station of the Advanced Teleoperation Laboratory at NASA-JPL (courtesy of NASA/JPL-Caltech)

The introduction of force and touch sensing raised the attention of the medical community, and in 1963 researchers at the Institute Mihajlo Pupin in Belgrade developed the first robotic prosthetic device capable of programmed grasping patterns, later known as the Belgrade hand [23]. Shortly afterward, in 1972, the same Institute developed a powered exoskeleton, one of the first assistive devices for walking disabilities. Papers on robotic research carried out by scientists at the Institute Mihajlo Pupin started to appear in the western press in 1973 [24], together with the results of Russian scientists [25]. English editions of books summarizing the results achieved by the Russian robotics community [26] and books reporting on the activities of the Pupin Institute [27] were published shortly afterward.

The other important player in the early days of robotics and teleoperation research was the Paris laboratory of CEA (the French "Commissariat à l'énergie atomique et aux énergies alternatives"), where Jean Vertut established his laboratory in 1962. The other leading French laboratory in robotics was the Laboratory for Automation and Microprocessing, Monipellier (LAMM), led by Philippe Coiffet. Both laboratories are still very active in teleoperation and robotic research. These early developments and the results achieved by the French robotics community are well documented in several books [28].

In the 1920s, robots began appearing in department stores in Japan under the shape of a humanoid robot named Gakutensoku. Later, the robotic idea was carried on by the cartoon character Astro Boy, a manga series running from 1952 to 1968 [29]. Industrial robots made their appearance in Japan through Kawasaki's acquisition of a license from Unimation in 1968. In 1972, researchers were able to program a robot to build a block structure after examining the drawings of a final configuration [30]. The following year, researchers at the Waseda University in Tokyo developed the "WABOT-1," a full-scale humanoid robot with two arms, capable of walking on two legs and seeing with stereo cameras [31]. The introduction of new force sensors prompted the development of efficient algorithms for the control of dynamic interactions between the robot and its environment, such as the automatic turning of a crank [32].

The 1980s saw the development of many robotic products for industrial automation, and of new algorithms to improve robot speed and position accuracy, leading to an in-depth understanding of the capabilities and limitations of robotic systems, identifying promising applications. During this period, robotics became a recognized field of research with regular conferences and scientific publications. Research results were initially reported by two international organizations, the American Nuclear Society and the International Federation for Theory of Machines and Mechanisms (IFToMM), which started organizing at the Centre International des Sciences Mecaniques (CISM, Udine, Italy) the Robot and Manipulator Symposiums (RO.MAN.SY), still an important forum for today's robotics community. Later, also other major robotics conferences began to be organized: the International Conference on Advanced Robotics (ICAR), the IEEE International Conference on Automation and Robotics (ICRA), and the International Conference on Intelligent Robotic Systems (IROS).

The Development of Surgical Robotics

Together with the development of basic robotic technologies, researchers started considering the use of robots in areas in which human performance could be improved [33, 34]. The idea of robotic surgery was probably born in the early 1970s, proposed in a study for the National Aeronautics and Space Administration (NASA) to provide surgical care for astronauts with remote-controlled robots [35].

The first robot that was designed for patient treatment was the Arthrobot in 1983, for arthroscopic procedures. The development was led by J. McEwen, G. Auchinlec, and B. Day at the University of British Columbia, Canada [36]; the first procedures were carried out in 1984. At the same time, experiments were carried out in California of robot-assisted stereotaxic brain surgery. A joint team from Memorial Medical Center in Long Beach and NASA-JPL led by Y. S. Kwoh and Samad Hayati used a Puma 200 to hold and manipulate a biopsy cannula, navigated by a stereotactic frame mounted on the base of the robot [37]. In the same period, similar interventions were also performed in China.

In the late 1980s, the idea of robot-assisted minimally invasive telesurgery was primarily developed under the leadership of Richard Satava within the US Army, which funded SRI International's development of a prototype telesurgical system [38]. The prototype was demonstrated in animal experiments, described by Bowersox et al. [39]. Contemporary to the US development, at the University of Karlsruhe (Germany), the team led by Gerhard Buess, already a pioneer of endoscopic surgery, developed (together with the Nuclear Research Center in Karlsruhe) the surgical robot prototype ARTEMIS, with seven degrees of freedom (DoF) [40, 41], shown in Fig. 1.7.

In the mid-1980s, Brian Davies and his team at Imperial College (London, UK) started to work on prostate surgery and developed the system called PROBOT for transurethral resection of the prostate (TURP) procedures in 1991 [42]. In Milano, the team lead by Alberto Rovetta also developed a robot for TURP, which was used in a clinical trial [43].

The first robotic system for orthopedic surgery was developed in 1986 by a team formed by two surgeons, Dr. Howard Paul and Dr. William Bargar, and researchers at IBM Watson Research Center (Yorktown Heights, NY) led by Russell Taylor. This system was further developed by Integrated Surgical Systems (ISS, Santa Monica, CA), which in 1992 created the first orthopedic surgical system, in collaboration with the University of California–Davis. This system was called ROBODOC and was used for robot-assisted human hip replacement [44]. The team at Imperial College also addressed orthopedic surgery and developed the Acrobot® system for total knee replacement procedures [45]. Other robots developed for orthopedic surgery were CRIGOS [46] and Orto Maquet CASPAR [47].

In 1989, Yulan Wang founded Computer Motion Inc. (Goleta, CA), and, with a NASA-JPL grant, in 1992 he developed a robotic system able to move an endoscope during laparoscopic surgeries. He then commercialized this device as the Automated Endoscopic System for Optimal Positioning (AESOP), the first commercial robot to be routinely used in the operating room [48]. The AESOP system was later extended with the addition of more arms and different surgical instruments, and it became the Zeus Robotic Surgical System (Fig. 1.8), which included three arms [49].

Fig. 1.7 The master station of the ARTEMIS surgical robot (courtesy of Prof. Alberto Arezzo, University of Torino)

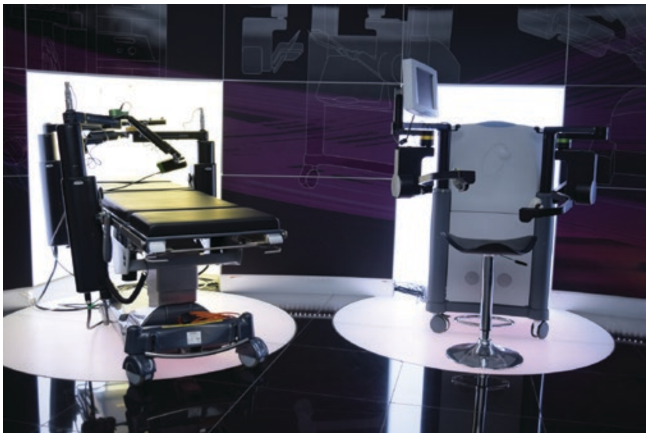

Fig. 1.8 The Zeus surgical robotic system (courtesy of Prof. Guang-Zhong Yang, The Hamlyn Center, Imperial College)

A collaboration between the ophthalmic surgeon Steve Charles and the NASA-JPL team of Antal Bejczy led to the development by Hari Nayar of the Advanced Teleoperation (ATOP) Lab of the robot-assisted microsurgery (RAMS) system in 1994, a robotic system for microsurgery with force feedback (Fig. 1.9) [50]. The RAMS capabilities were later demonstrated in coronary artery anastomoses on animals [51].

Intuitive Surgical Inc. (Mountain View, CA) was founded in 1995 by Frederic Moll. After acquiring some of the patents of SRI for their surgical robotic system, Intuitive Surgical created a first prototype of the da Vinci surgical system in 1997 to carry out clinical trials, which led to the first closed-chest, multivessel cardiac bypass procedure in 1999. The da Vinci system was cleared by the US Food and Drug Administration (FDA) for human use in 2000 and commercialized as shown in Fig. 1.10. After several attempts to create a market for beating-heart procedures, the da Vinci system found its niche in urology and gynecology, where it is now the gold standard for intervention. After a long patent dispute, Intuitive Surgical acquired Computer Motion, its only competitor, in 2003, and shortly afterward it discontinued the production of the Zeus system [52].

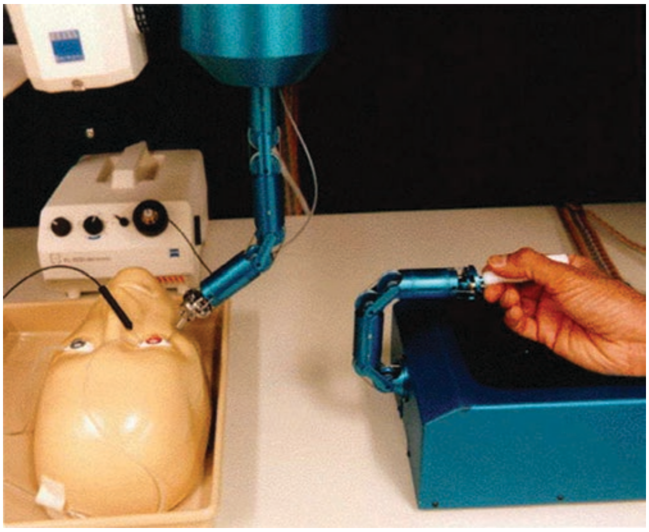

Fig. 1.9 The robot-assisted microsurgery system (courtesy of NASA/JPL-Caltech)

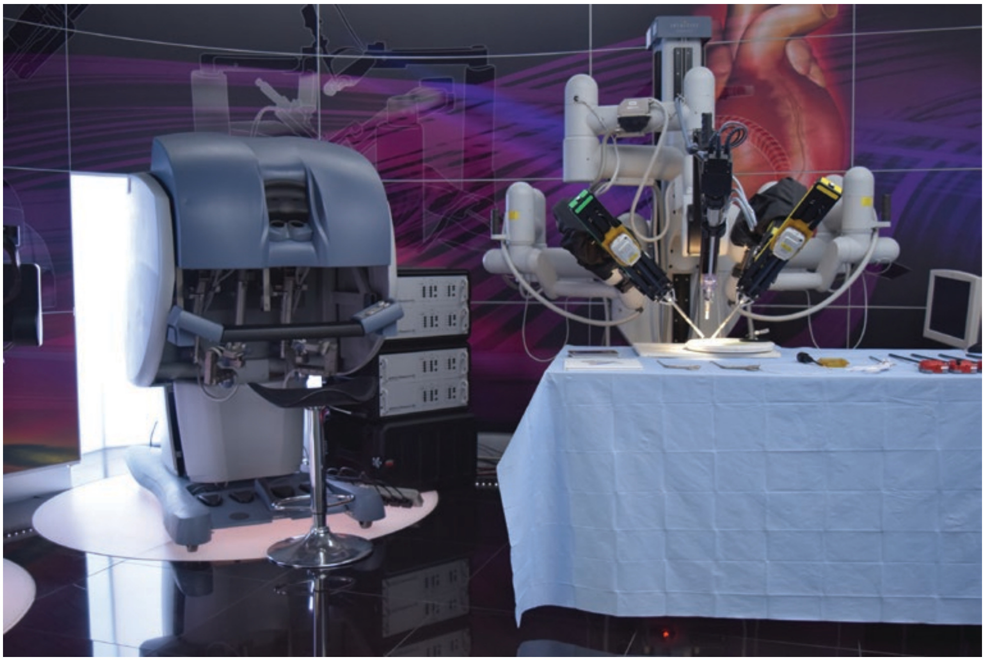

Fig. 1.10 The first generation of the da Vinci Surgical System (courtesy of Prof. Guang-Zhong Yang, The Hamlyn Center, Imperial College)

There have also been a few attempts at long-distance telesurgery. The first experiment was performed in 1993 between NASA-JPL (Pasadena, CA) and Milan, Italy, by the teams of Antal Bejczy and Alberto Rovetta [53]. A few years later, Jacques Marescaux performed a cholecystectomy on a patient in Strasbourg (France) from New York, controlling a Zeus robot in France [54]. The Zeus robot was also involved in the 2004 NEEMO experiments of undersea simulated surgery controlled remotely from the Centre for Minimal Access Surgery, London, UK. In 2005, the US Department of Defense launched its long-distance medical assistance project, the Trauma Pod [55], to demonstrate the feasibility of the original idea of Richard Satava, an emergency surgical unit in combat areas [56]. Although all these experiments were successful, long-distance telesurgery has not yet entered clinical practice because of safety and certification issues.

Several robots were also developed for neurosurgery. In 1997, the team of Alim Louis Benabid in Grenoble developed the NeuroMate system [57], a stereotaxic targeting device for neurosurgery, which was the first neurosurgical robot to receive FDA clearance. This robot was initially marketed by Innovative Medical Machines International (Lyon, France) and now is a Renishaw product [58]. Minerva [59] was designed for stereotactic brain biopsy to meet specifications incorporating safety and geometry, to perform single-dimensional incursions into the brain while the patient is within a CT system that continuously provides real-time imaging data to the robot. The PathFinder was an image-guided, frameless, six-axes robot to accurately position a tool for neurosurgery [60].

Development Directions in Surgical Robotics

Robotic surgery is a very active area of research, and it is worth mentioning some of the most successful prototypes. The German Space Agency DLR has developed the MIRO surgical system [61], whose fast dynamics could allow beating-heart interventions. It has been designed to achieve the requirements of a broad range of surgical applications in endoscopic and open surgery. Integrated multimodal sensors and different control modes allow system configurations for telepresence (Fig. 1.11).

Fig. 1.11 The MIRO surgical system (courtesy of Deutschen Zentrums für Luft- und Raumfahrt [*DLR*])