From Concept to Market: Surgical Robot Development

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ABSTRACT
Surgical robotics and supporting technologies have really become a prime example of modern applied information technology infiltrating our everyday lives. The development of these systems spans across four decades, and only the last few years brought the market value and saw the rising customer base imagined already by the early developers. This chapter guides through the historical development of the most important systems, and provide references and lessons learnt for current engineers facing similar challenges. A special emphasis is put on system validation, assessment and clearance, as the most commonly cited barrier hindering the wider deployment of a system.

Key terms: surgical robot prototyping, assessment and validation, computer-integrated surgery, image-guided surgery, medical device clearance

INTRODUCTION
Traditionally, robotics is a combination of mechatronics, electronics and software. The recent development in robot structures and components gradually enabled the rise of smaller scale and fine mechatronic structures that can be used in various applications beyond the industry (Habib, 2006). These trends can also be tracked in standardization activities, the newly released ISO 13482:2014 is the first representative of a new family of standards aimed at service robotics. It applies to personal care robots designed to the quality of life of humans, excluding medical applications. Service robots are to support their users and humanity in various tasks, from elderly care to demining (Habib, 2007).

A rapidly growing field within service robotics is medical robotics, including rehabilitation robotics and surgical systems. In the past decades, numerous different robotic surgery devices have been created, and only a few reached the market. The Medical Robotic Database (Pott, 2014) lists over 450 international surgical robotic projects, of which several dozen are with the potential to become commercially available. Parallel, the number of surgical robotics related publications has been steadily rising in the past years (O'Toole et al., 2010), making *Computer-Integrated Surgery* (CIS) one of the leading areas within medical technology.

CIS refers to the entire field of technology-aided interventional medicine, from image processing and augmented reality applications to automated tissue ablation. CIS means the combination of innovative algorithms, robotic devices, imaging systems, sensors and human–machine interfaces. These systems should work cooperatively with physicians in the planning, execution and evaluation phases of surgical procedures (Taylor & Kazanzides, 2008). A subfield of CIS is called *Image-Guided Surgery* (IGS), where the digital system is not necessarily involved in the physical part of the operation, but improves the quality of surgery by better visualization or guidance. IGS means the accurate registration (correlation

and mapping) of the operative field to a pre-operative (typically *Magnetic Resonance Imaging*—MRI, or *Computer Tomography*—CT) imaging or intra-operative (*ultrasound*—US, fluoroscopy) data set of the patient, providing free-hand navigation, positioning accuracy of equipment, or guidance for a mechatronic system. IGS systems have been successfully prototyped and commercialized, and now being used in neurosurgery, radiotherapy, pediatrics, orthopedics and various other fields.

This chapter introduces the aims and means of surgical robot development, giving a better understanding of the difficulties the field is challenged with through examples taken from existing robots. Medical robots are mostly employed for the accuracy and reliability of their mechanics; however, it may still be hard to fully exploit their features, as surgical tasks are typically unique, involving the semi-autonomous manipulation of deformable objects in an organic, limited environment.

Medical imaging gives the capability to navigate and position a surgical tool at the target point. Furthermore, there is the option to introduce advanced digital signal processing to control or record the spatial point-of-interests and motions (Kazanzides et al., 2010). This can be useful for surgical simulation and risk-free training. Finally, robotized equipment can greatly add to the ergonomics of the procedures. The main advantages of robotic surgery systems—based on (Karas & Chiocca, 2007) and (Lirici et al., 1997)— are the following:

- superior 3D spatial accuracy provided by the robot,
- specific design for maximum performance (including miniature robots),
- stabilization of the instruments within the surgical field,
- advanced ergonomics supporting long procedures,
- stable performance,
- high fidelity information integration,
- invulnerability to environmental hazards,
- patient advantages (reduced blood loss, less trauma, shorter recovery time),
- decreased costs (per treatment) due to shorter hospitalization and recovery,
- possibility to provide better and more realistic training to physicians.

Further optional benefits:

- improvement of manual dexterity, motion scaling,
- physiological tremor filtering,
- integrated 3D vision system with high definition (HD) resolution.

Robots have been introduced to the operating room primarily to provide higher accuracy and dexterity. They can support surgeons with advanced targeting, steady positioning and task execution with a precision beyond human capabilities. Therefore, the treatment delivery accuracy and objective evaluation of interventional systems is crucial, especially when they are image-guided and operating semi-autonomously (Stiehl et al., 2007). Errors and imperfections may originate in:

- CT imaging errors,
- volume model generation errors,
- treatment planning errors,
- errors introduced by hardware fixturing,
- intra-operative data noise,
- registration errors,
- inherent inaccuracies of surgical tools and actions.

It is important to keep in mind from the first stage of development which errors will be critical regarding the final application of the system, and how to minimize their disturbing effect.

SYSTEM DEVELOPMENT STRATEGIES

CIS systems are strongly application-oriented (ideally driven by a strong clinical need), therefore their entire architecture may be defined by the targeted treatment. It may be extremely hard to switch from one concept to another during a latter development, therefore strategic planning is a must. Different categories of surgical robots have been built for various procedures. Hand-held and directly controlled devices may serve as an incremental upgrade for existing tools, while teleoperated systems represent a whole different field. The advantage of versatility comes with the emergence of issues with control, latency handling and emergency protocols.

Robots can be involved in medical procedures with various level of autonomy (Nathoo et al., 2005), and each type requires different approach during system development. Some of them serve as a robust tool holding equipment having been directed to the desired position. Systems that are able to perform fully automated procedures—such as CT-based biopsy or cutting—are called autonomous or supervisory controlled devices. On the other hand, if the robot is entirely teleoperated or remote-controlled (robotic telesurgery system) the surgeon is absolutely in charge of its motion. The latter consists of three parts:

- one or more slave manipulators,
- a master controller
- a vision system providing visual feedback to the user.

Based on the gathered visual (and sometimes haptic) information, the surgeon guides the arm by moving the controller and closely watching its effect. In most of the cases, the slave system and camera are acting as the remote hands and eyes of the surgeon, and therefore they are key elements of the operation.

Modifying the teleoperation control paradigm we can introduce *cooperative control* (also called shared control or hands-on surgery). It means that the surgeon is directly giving the control signals to the machine through e.g., a force sensor. It is possible to read and process these signals in real-time to create the robot's motion. The human is always in contact with the robot, as the master and the slave devices are physically identical. In this case, the robot is the extension of the doctor's hand, equipped with special features and effectors. This approach keeps the human in the loop, and still allows the surgeons to use all their senses. It is often used in the case of micro-manipulation operations, such as micro-vascular, urologic, eye or brain procedures. Cooperative control is a promising way to provide highly integrated robotic support for procedures while applying all the necessary safety standards.

It is commonly quoted that a medical product needs 10–15 years to grow from the conception of an idea to commercialization. This extremely long time-to-market period requires wise considerations from the developers to ensure the continuous funding of the project. Developing an engineering prototype is only the first step, success in business requires various skills and sometimes entirely different approach towards R&D. The history of the first generation of surgical robots summarized in the next session provides great examples and lessons on the critical aspects of the development process.

FIRST PROTOTYPES

Early concepts of surgical telerobots

Since the 1980s, hundreds of medical robotic research projects have been initiated, creating a set of instruments for remote and local robotic surgery. CIS and telemedicine have become widely used around the world, surgeons and engineers created systems and networks for advanced patient care, demonstrated over a hundred different procedures, transcontinental surgery and even performed procedures in weightlessness (Doarn et al., 1998).

The general idea of telerobotic health care in space was born in the early ’70s, proposed in a study for the *National Aeronautics and Space Administration* (NASA) to provide surgical care for astronauts with remote controlled robots (Alexander, 1972). The concept-system, presented in Fig. 1. shows very well the fundamental characteristics of a complete teleoperational system, although the first prototypes were only built almost 15 years later. In the late ’80s, the idea of commercial surgical robotics was born to extend the surgeons’ dexterity, multiple academic centers started to develop new prototypes.

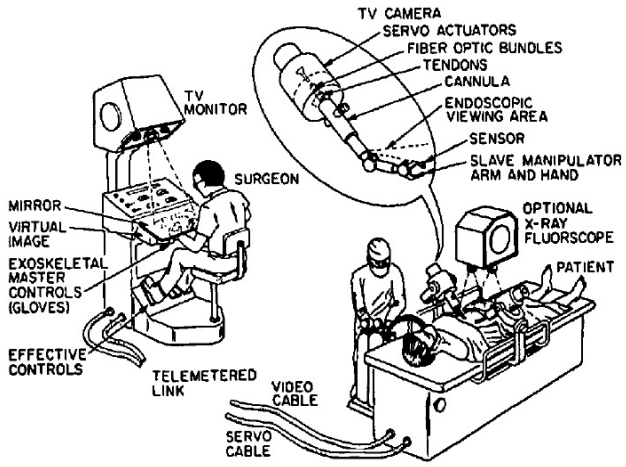

Figure 1. The very first design concept of a surgical robot system, aimed to support astronauts in space (Alexander, 1973).

It was first proven thirty years ago that robotics can extend human surgeons’ capabilities. The first robot used on a human patient was a Puma 200 (*Programmable Universal Machine for Assembly*), manipulating a biopsy cannulae using a *Brown–Roberts–Wells stereotactic frame* (mounted on the robot’s base). The operation took place in the Memorial Medical Center (Long Beach, CA) in 1985 (Kwoh et al., 1988). In later experiments, the Puma performed complete stereotactic neurosurgical operations based on CT scans, processing the scanned images, positioning the arm and manipulating different probes (Fig. 2).

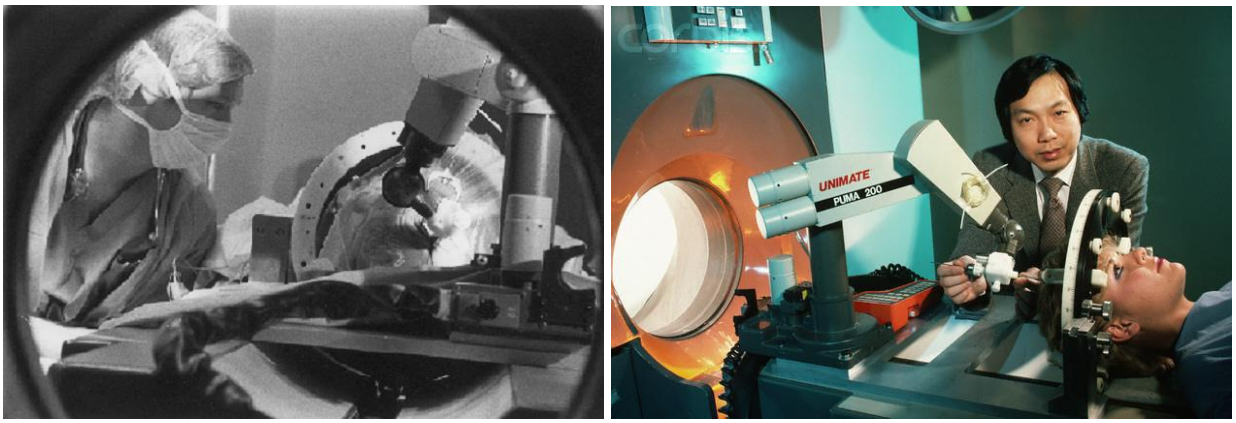

Figure 2. The first robot that performed (assisted with) human surgery in 1985 (Kwoh, 1988). Dr. Kwoh with the Unimate robot prepared for stereotactic neurosurgery. (Image credit: Corbis)

The U.S. Army has long been interested in robotic surgery for the battlefield, and currently, the *Telemedicine & Advanced Technology Research Center* (TATRC) supports the development of prototypes to test and extend the reach of remote health care. Physicians were first able to affect distant

patients with the Green telepresence system in 1991 (Bowersox et al., 1996), and the first long distance telerobotic experiment was in 1993 between NASA Jet Propulsion Laboratory (JPL) in Pasadena and Milan (Rovetta et al., 1996). The *U.S. Department of Defense* (DoD) aims to develop a system—*Trauma Pod*—by 2025 that allows combat surgeons to perform lifesaving operations from a safe distance (Satava, 1995) and (Garcia et al., 2009). Much of these projects created the basis of the most successful surgical robot, the da Vinci.

The da Vinci Surgical System

The market leader *da Vinci* robot from Intuitive Surgical Inc. (Sunnyvale, CA), is a complete teleoperated system created with roughly $500M investment. The company was founded in 1995, licensing many promising technologies, and by 1997 the first functional surgical robot (*Lenny*) was ready for animal trials. Concepts from around the world and various engineering prototypes were integrated into the project (DiMaio et al., 2011):

- the *Black Falcon* teleoperated surgical robot from MIT (Madhani et al., 1998),
- the *Robot Assisted Microsurgery* (RAMS) workstation from NASA JPL,
- *PROBOT* prostate surgery device from Imperial College,
- teleoperation control techniques from *University of Washington* (UW),
- *Green telepresence surgery system* developed at *Stanford Research International* (SRI).

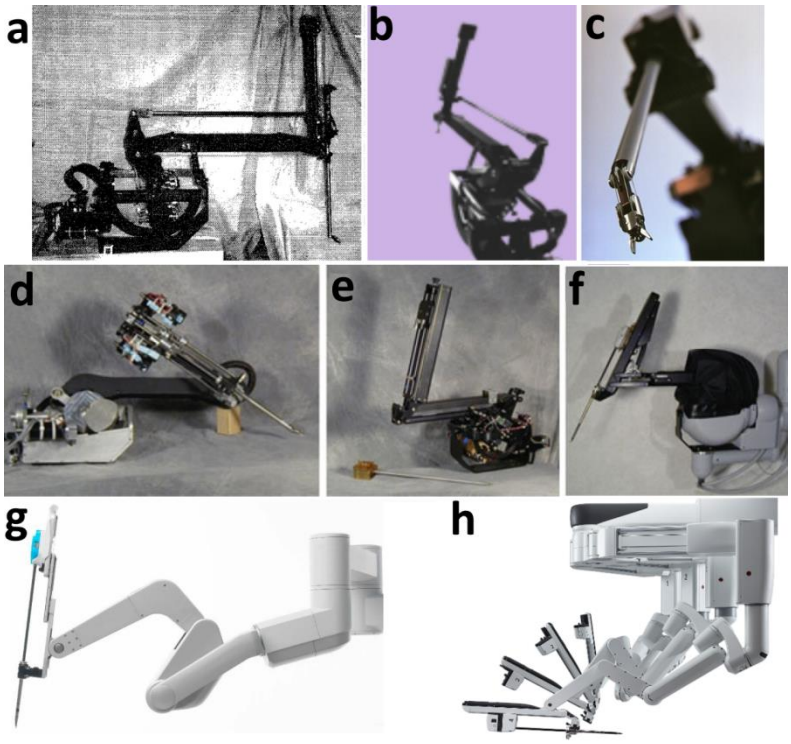

Figure 3. The evolution of the da Vinci robot's slave manipulators. a–c)The original Black falcon prototype, developed at MIT. (Courtesy of Science Photo Library.) d–f) The slave mechanisms of Leny, Mona and first da Vinci, respectively. (Courtesy of Intuitive Surgical Inc.) g) The da Vinci Si version of the slave arms. (Courtesy of Intuitive Surgical Inc.) h) The newest da Vinci Xi's Patient Side Manipulators. (Courtesy of Intuitive Surgical Inc.)

The next prototype—*Mona*—performed the first human trials in Belgium in 1997, and the first da Vinci unit was created within a year (Guthart & Salisbury, 2000). The *U.S. Food and Drug Administration* (FDA) cleared the system for general laparoscopic surgery (August 2000), thorascopic surgery (March

2001) and laparoscopic radical prostatectomy (May 2001), followed by many other approvals. Most recently, it was approved for transoral otolaryngologic procedures and adjunctive mediastinotomy to perform coronary anastomosis during cardiac revascularization.

The original da Vinci system is basically a smart tool and interface between the hands of the surgeon and the laparoscopic instruments in use. The patient side consists of two/three tendon-driven, 6+1 *Degrees of Freedom* (DOF) slave manipulators (Fig. 3). These are designed with a *Remote Center of Motion* (RCM) kinematics, resulting in an inherent safety regarding the spatial stability of the entry port. This means that the gross positioning (passive) arms can move the base point of the actuated arms, and therefore define the RCM as the fixed entry point through their semi-parallel kinematics. The camera holder arm navigates in 3 DOF, controlled with the same master console. The system provides high quality 3D vision with stereo-endoscopes, adjustable tremor filtering (6 Hz) and motion scaling (1:1–1:5). The total weight of the system is 850 kg, and the setup takes up significant floor space in the *Operating Room* (OR). The intrinsic accuracy of the robot was measured to be 1.35 mm (Target Registration Error—TRE (see next section) with the points not used in registration), with 1.02 ± 0.58 mm (mean ± standard deviation—STD) Fiducial Localization Error (FLE) (Kwartowitz et al., 2006). The newer version had similar FLE, 1.05 ± 0.24 mm (Kwartowitz et al., 2007). To compensate for any application errors (and to avoid safety hazards), the robot only follows the movements of the surgeon. The arm configuration of the latest da Vinci Xi has been changed to improve dexterity and the range of motion.

Manipulation precision comes at a price, the da Vinci S version consisted of 10,000 individual parts, and the operating code stretches beyond 1.4 million lines. There are 39 backdriveable *Maxon motors* (maxon motor ag, Sachseln, CH) in each robot, most of them equipped with magnetic encoders. Communications in the da Vinci is acquired via Transmission Control Protocol over Internet Protocol (TCP/IP) using NI USB-6009 data acquisition boards (National Instrument, Austin, TX). The controller computer deals with the 48 DOF at an update rate of 1.5 kHz. There are 48 encoders and 96 analog input channels supported by parallel floating point DSP architecture with a peak computational power of 384 Mflops and a sustained processing power of between 128–256 Mflops. The robot has a network of 24 micro-controllers and integer DSPs performing data transfer and health watchdog functions. Velocity control algorithms are employed mostly with 2–3 filters, the one in the forward link is used to attenuate master input commands that could cause instrument tip vibrations otherwise. Redundant sensors, hardware watchdogs and real-time error detection protocols ensure fail-safe operation of the robot. The da Vinci uses an *Insite Vision and Navigator Camera Control* with two 3-chip cameras and two separate optical channels generating two images delivered separately to each eye of the surgeon. It gives 1000 frames of the instrument position per second and filters each image through a video processor that eliminates background noise (Haidegger, 2010).

Intuitive continued perfecting the system, and the second generation—da Vinci S—was released in 2005. The setup and docking procedures were streamlined, the 4th arm became more versatile, the slave arms were redesigned and arranged in a way to avoid collision and the console was enhanced with streaming images. The next version—da Vinci Si—became available in 2009 with improved full HD camera system, advanced ergonomic features and most importantly, the possibility to use two consoles for assisted surgery (Fig. 4). The da Vinci Xi was introduced in April 2014 featuring a brand new slave-side arm structure. The da Vinci Xi's features include a new overhead arm architecture designed to facilitate anatomical access from multiple directions, a new endoscope architecture that can fit to any of the slave arms, smaller, thinner arms with newly designed joints, offering greater range of motion. The slave cart positioning has been streamlined as well, and enabled with a laser-targeting system.

More recently, Intuitive received FDA clearance for its new da Vinci Sp single port robot system that we have already seen 5 years ago as a prototype. The system is designed for urologic minimally-invasive procedures that are already performed via a single incision, however it may only be commercially available from the end of 2015. According to the company, the Sp patient-side cart is designed to expand single-incision product range. It integrates an articulated 3D HD camera, along with three agile

instruments—which have two more degrees of freedom than the single-site instruments. All these are fitted through a 25 mm diameter cannula.

Having realized the potential in robotic surgery training, Intuitive has released its portable *da Vinci Skills Simulator*, which can be attached to a da Vinci Si and Xi systems. It allows users to practice unassisted or with supervision through a set of exercises ranging from camera handling to electric coagulation. The open architecture of the software allows for the future incorporation of additional modules. The simulator is continuously upgraded by the independent company called MIMIC (*http://mimicsimulation.wordpress.com/*).

In recent years, Intuitive has been focusing on enlarging the tool inventory, developing useful and specific end effectors for various procedures (e.g., US probe, FireFly—fluoroscopic imaging, etc.). Also, they put an effort to provide a generic research interface to help institutes developing compatible tools and techniques. In a joint venture with the CISST ERC they are about to release the SAW architecture (Surgical Assistant Workstation) that would further integrate the robot into any surgical information system. Current extensions allow visual overlay and augmented reality features in a prototype version (Kazanzides et al., 2010).

As of today, there are around 3100 da Vincis around the world, 3/4 of them in the U.S. The number of successful procedures performed is close to a million; the most successful applications being prostatectomy and hysterectomy. According to Intuitive, over 80% of all radical prostate removal procedures were performed robotically in the U.S. in 2013. One of the key elements in the success of the system is the universality of the platform. Despite the fact that originally it was planned to be used for beating heart surgery, it was versatile enough to shift the focus to urologic and gynecological procedures that became the most lucrative business for the company. Their extensive patenting strategy allowed them a freedom to operate in the market over the past 20 years.

Figure 4. The da Vinci Xi system, debuted in 2014. (Courtesy of Intuitive Surgical Inc.)

The NeuroMate neurosurgical robot

Although the *NeuroMate* was the first robot to gain CE mark (*Conformité Européenne—European Conformity*) in Europe and then the FDA approval in 1997 for stereotactic neurosurgical procedures, it could not achieve any similar success to the da Vinci. Originally designed based on an industrial robot at the Grenoble University and developed market-ready by *Innovative Medical Machines International* (IMMI—Lyon, France), the 5 DOF NeuroMate provides accurate and trusted assistance for supervised needle positioning for brain biopsy (Fig. 5). Combined with pre-operative images, it offers real-time

visualization to give the surgeon precise location of a tumor. It has an approval for neuro-endoscopic applications and for frameless stereotactic surgery (Li et al., 2002).

The robot consists of 5 revolute joints, each mobilized by a separate, high precision servo. The joint values are read by encoders with a resolution of 1/26825 degree due to the high gearing. The Neuromate contains embedded joint controller boards that are integrated into the links of the robot, significantly reducing the required cabling. Each joint controller board contains a microprocessor and is responsible for controlling up to two axes of the robot, including the power amplification. The power supplies are placed in the triangle shaped base, eliminating the need for a separate controller rack. The ISS version of the system communicates with the main PC through a *Controller Area Network* (CAN) bus with a 18.2 ms communication cycle. On the lowest level, the joints are given position commands. The highest linear velocity of the robot is approximately 50 mm /sec.

The NeuroMate's reported intrinsic accuracy (i.e., the precision of the individual hardware and software components) is 0.75 mm, with a repeatability of 0.15 mm (Varma & Eldridge, 2006). In a human stereotactic surgical experiment conducted in 2002, the application accuracy (the overall precision in performing the desired task, as discussed below) was measured to be 0.86 ± 0.32 mm in frame-based configuration and 1.95 ± 0.44 mm in frameless model (Li et al., 2002). The average application accuracy of 10 different robots was measured to be 0.6 mm. In a more recent experiment, the intrinsic accuracy of the robot was 0.36 mm FRE and 0.36 ± 0.17 mm TRE (Haidegger et al., 2008).

The technology was bought by *Integrated Surgical Systems Inc.* (ISS—Sacramento, CA) in 1997. In the first couple of years of operation, the company installed around 20 NeuroMate systems in the United States, Europe and Japan. However, due to the lack of sustainable market and investment for further innovation, the company ceased operations in the early 2000s. The NeuroMate technology was acquired first by *Siemens Finance and Leasing* (Munich, Germany), then by *Schaerer Mayfield NeuroMate AG* (Lyon, France) in 2007, and reappeared on the market in *Renishaw plc*'s (Wotton-under-Edge, UK) product line. It received a facelift, and runnning under the trademark neuro|mate (Fig. 5). More recently, the robot has been used for thousands of electrode implantation procedures for *Deep Brain Stimulation* (DBS), *Stereotactic Electroencephalography* (SEEG) and *Transcranial Magnetic Stimulation* (TMS). This also supports the importance of the ability to deploy a robotic system in various clinical fields.

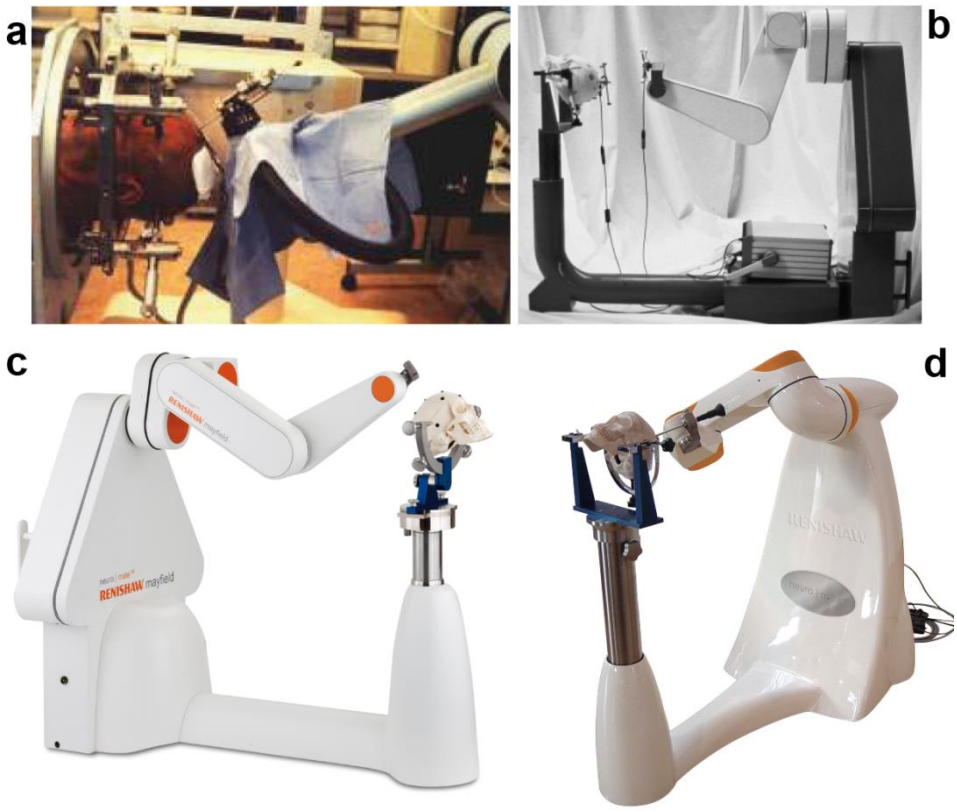

Figure 5. a) IGOR, the original industrial robot-based prototype for neurosurgery (Benabid et al., 1987). b) IMMI's NeuroMate (Li et al., 2002). c–d) Current and next version of the system with newly designed interior controllers. (Courtesy of Renishaw plc.)

ROBODOC for orthopaedics

ROBODOC Surgical Assistant System shares a similar story to NeuroMate, it was the first robot of ISS, when the company was founded in 1990. Development began in 1986 at *IBM T. J. Watson Center* and *U.C. Davis*, aiming to create a bone milling robot (Pransky, 1997) and (Bargar, 2007). A 5 DOF IBM SCARA robot was custom designed for Total Hip Arthroplasty (THA—surgical shaping or alteration of the joint). The 3D planning station (called *Orthodoc*) together with the ROBODOC use pre-surgical images and software to first design the surgical procedure (Fig. 6). Surgeon can precisely define the desired cavity in the bone, size and position the prosthesis before the real surgery. In fact, the robot was originally aimed at canine surgery, and later changed the focus to human operations. The first-ever robotic human trial was performed in 1992 (Kazanzides, 2009), and later extended to being *Total Knee Artroplasty* (TKA) procedures as well. The company invested over $80M into system development.

ROBODOC drills the bone without direct human control of the tool during the procedure; therefore the application accuracy of the system is critical. The robot has a 0.5 mm intrinsic accuracy, while the application accuracy was 1.2 mm in average, ranging from 1.0 to 3.5 mm in cadaver trials (Paul et al., 1994). The later version of the device had around 0.1 mm dimensional error and 1.0 mm placement error, providing over 95% implant-bone contact (Taylor, 2001). Since 1994, ISS has sold around 80 systems across Europe and Asia, and in 2008, it became the first FDA approved automated bone milling robot, under *Curexo Technology Corporation*.

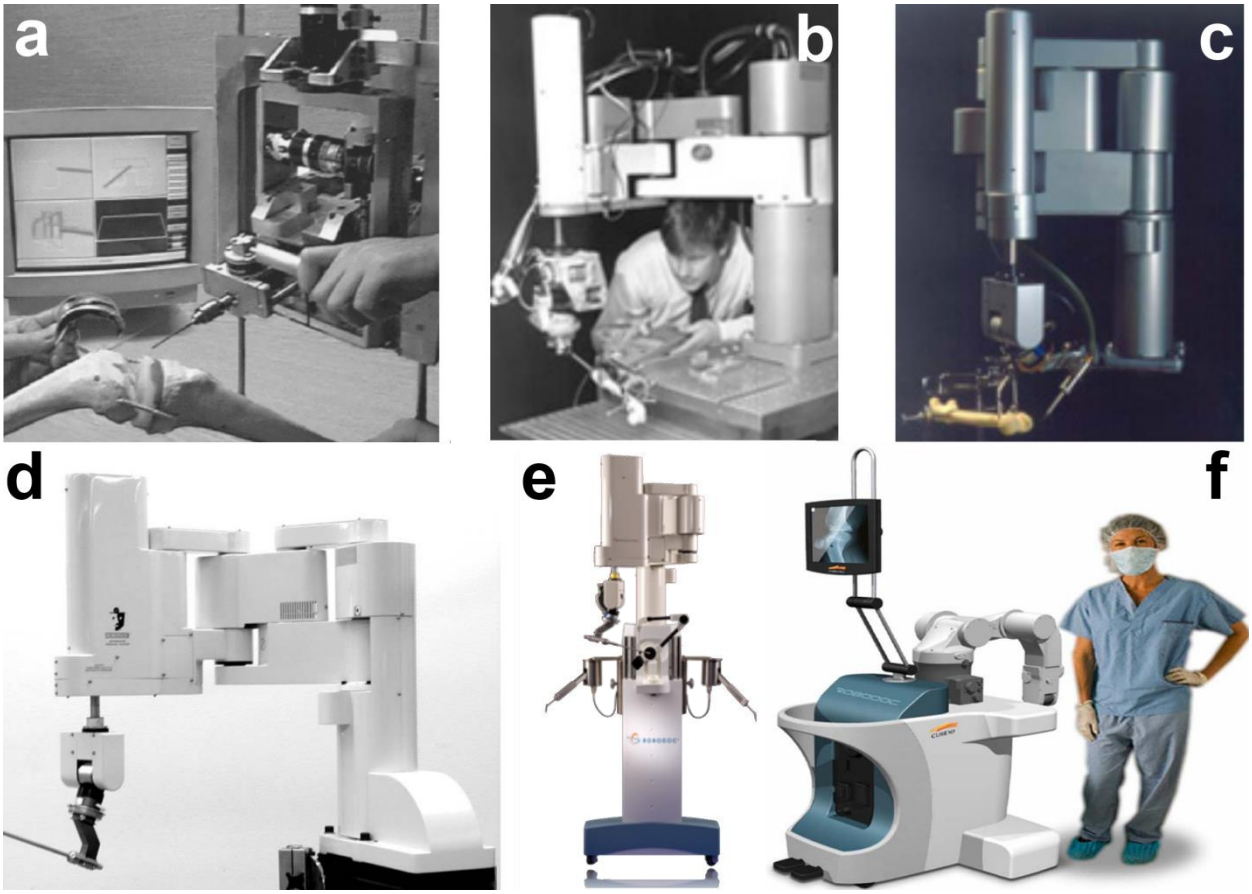

Figure 6. a) The first engineering prototype of orthopedic robot at IBM T.J. Watson Center, created for canine hip surgery. b–c) Early prototype of the ROBODOC system. d) The ROBODOC, as sold by ISS until the early 2000s. (Courtesy of ISS Inc.) e) The ROBODOC in its current form. f) Concept figure of the next generation prototype. (Courtesy of Curexo Tech. Co.)

CyberKnife radiosurgery system

One of the most successful robotic applications is the *CyberKnife* from Accuray Inc. (Sunnyvale, CA). This stereotactic radiosurgery system integrates IGS with robotic positioning. The 6 MeV *Linear Accelerator* (LINAC) relatively light-weight photon device is mounted on a KUKA KR 240, 6 DOF industrial manipulator (Fig. 7). The idea was to combine existing hardware components to create an innovative device. This approach allows for faster prototyping, and shorter system development cycle. More than 200 units have been sold worldwide. The same concept has been used by SIEMENS lately with their *Artis Zeego* system for actuated X-ray imaging (SIEMENS, 2014).

CyberKnife's primary deployment is the irradiation of brain and spine tumors. X-ray cameras are used to track the spatial displacement of the patient and compensate for motion caused by e.g., breathing. The overall accuracy of the system is 0.42 ± 0.4 mm, while patient skin motions are detected with a 0.35 mm precision (Dieterich et al., 2003). The CyberKnife moves the radiation beam by physically repositioning the radiation source. It uses intra-corpuscular markers and Polaris (NDI Inc., Waterloo, ON) infrared cameras to track the patients' moving body surface. To improve the accuracy, radioopaque fiducial markers can be implanted in/near the tumor region, several days before CT scanning for treatment planning. The fiducials—which are detectable in X-ray images—are used as reference markers to locate and track tumor location during patient alignment and treatment delivery. The *Synchrony Respiratory*

Tracking System builds a correlation model between the positions of periodically detected fiducials and the real-time locations of optically tracked markers placed on the chest to track tumor location. It uses 4D CT (imaging through time) to measure respiratory tissue motion and deformation and to account for the effect of displacement and deformation through the irradiation (Urshel, 2007).

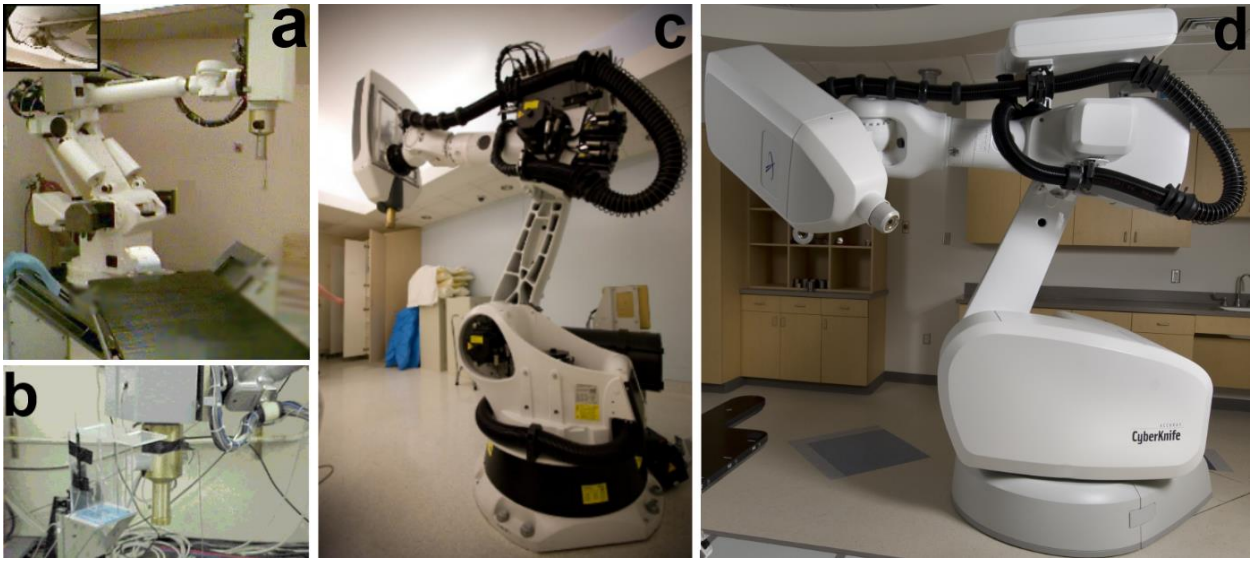

Figure 7. a–b) First prototypes mounted on a Fanuc robot. c–d) The first and second commercially available versions of the CyberKnife radiosurgery system mounted on a KUKA robot. (Courtesy of Accuray Inc.)

Cleared by the FDA to treat tumors anywhere in the body since 2001, more than 70,000 patients had been treated and more than 180 systems were installed worldwide by 2009, and by 2012, over 100K procedures had been performed with over 244 systems sold. Despite the fact that it is significantly more expensive than the da Vinci (~€3M, and €10.000/ treatment), it has not set Accuray Inc. to such a speed profit curve simply because the consumables for a procedure do not scale that nicely. The company introduced the M6 version, with multiple treatment planning, fiducial tracking, fixed collimators, variable aperture collimator and so (Fig. 8).

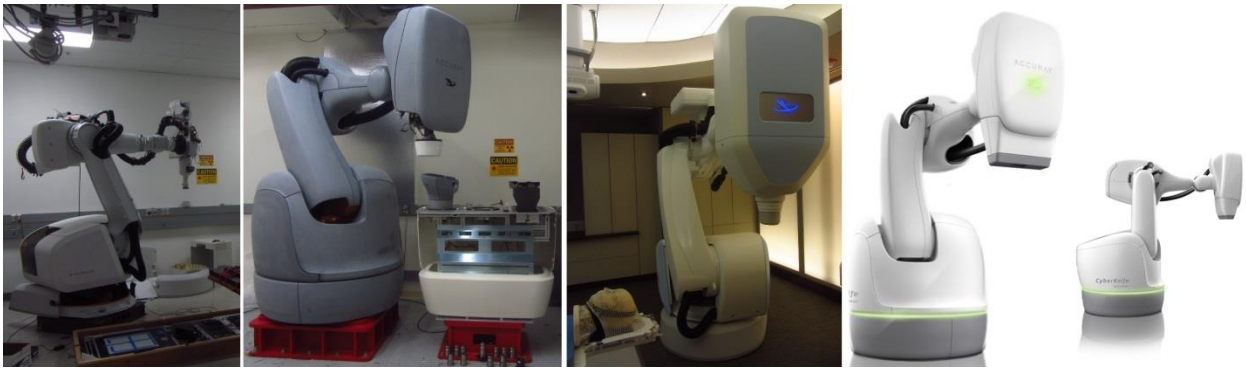

Figure 8. a–c) First versions of the new CyberKnife M6 series. d) Designs of the consumer product. (Courtesy of Accuray Inc.)

The iSYS systems

A robotic system for CT and ultrasound-guided biopsies was initiated at the robotics laboratory of *ARC Seibersdorf Research* (Austria). The system used to be called B-Rob, and it was a 7 DOF robot integrated

on a mobile rack. A 4 DOF positioning stage was employed to direct the needle to the desired skin entry point. The complete system was thoroughly tested on needle-penetrable phantoms, where its application accuracy was 1.48 ± 0.62 mm, which was shown to be better than the traditional free-hand technique (Cleary et al., 2006). They broke with the concept of using large, universal manipulators to navigate tools, rather employed specialized hardware to suit the clinical needs of percutaneous procedures. This small-scale system better integrates with the OR (Fig. 9a–b).

The development of the second prototype (Fig. 9c–d) was motivated by the aim to provide a modular setup for a variety of clinical applications, to allow easy integration with other systems, while reducing technical complexity and costs. The robot is equipped with a *Needle Positioning Unit* (NPU) for fine orientation. The first gel phantom tests of the B-Rob II showed 0.66 ± 0.27 mm application accuracy in IG positioning. In-vitro trials with ultrasound guided biopsy specimen harvests followed, where the mean deviation of the needle tip from the center of the target was 1.1 ± 0.8 mm. The technology was licensed by iSYS Medizintechnik GmbH, and the robot got redesigned, to better fit the market (Fig. 9e–g). It has recently gained ISO certification and CE marking, and FDA approval in early 2014.

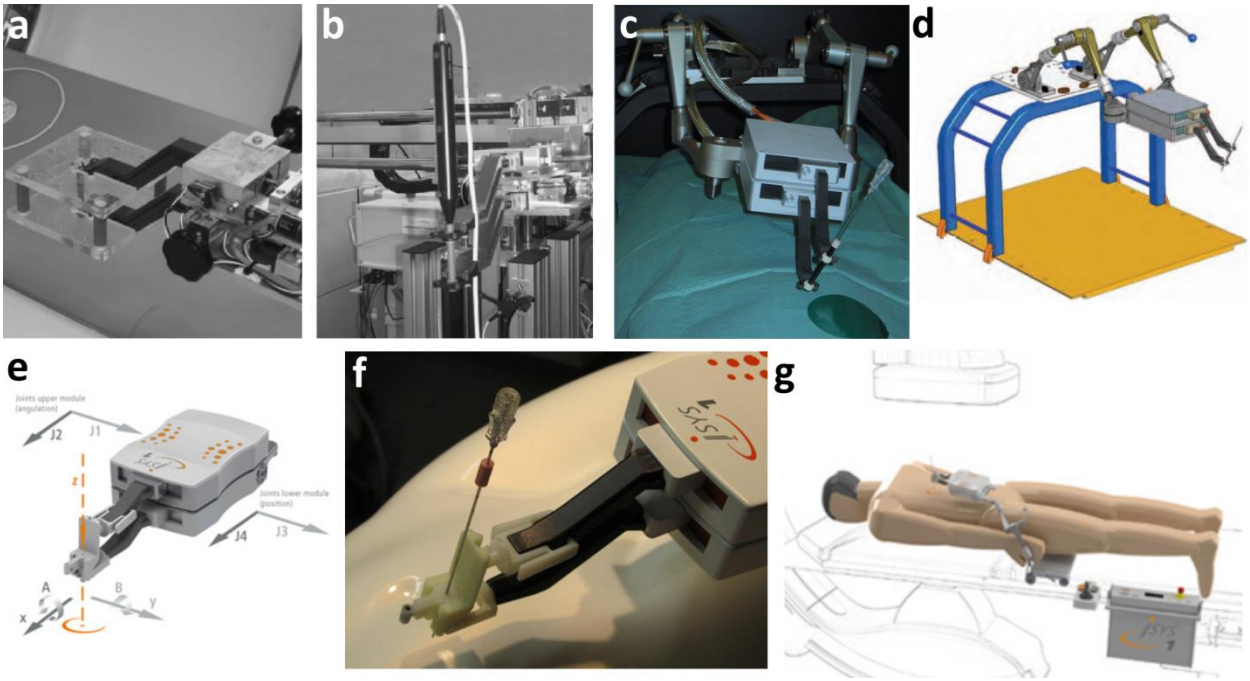

Figure 9. *a–b) The B-ROB I. c–d) the B-ROB II prototypes (Cleary et al., 2006). e–f) The new design, created by iSYS and now commercially available (iSYS, 2014).*

SYSTEM CAPABILITY ASSESSMENT

A major step in the evaluation of a system is performance assessment, especially in terms of spatial accuracy and safety. Thorough tests are required, as the overall precision may be the highly non-linear function of the intrinsic- and registration accuracies. After 20 years of development, there is still a strong need for objective measures in medical robotics. In this section, different test methods are presented to define system characteristics, working towards their validation.

Accuracy numbers are used to convince the medical community about the improved patient outcome that robots can provide, therefore it is essential to have clear and well-founded metrics.

In CIS, registration and accuracy metrics have been commonly borrowed from industrial robotics (precision, repeatability, etc.) and image analysis (FRE, TRE, etc.), but it is important to understand the

validity and limitations of these concepts. Similarly, the differences between intrinsic (technical) accuracy, registration accuracy and application accuracy are to be well observed. Examples of accuracy measurement techniques are presented here, illustrating the importance of correct, consistent reporting, facilitating the comparison of different devices.

Precision of robotic systems can be represented by the accuracy and repeatability of the device to characterize the overall effect of the encoders' fineness, rigidity of the structure and the compliance of the hardware elements (the servo motors, the gears or the links). Both terms are defined for industrial robots in the *International Organization for Standardization* (ISO) 9283 standard (ISO TC-184/SC2 Robots and Robotic Devices). Accuracy refers to a robot's ability to position its end at a desired target point within the working volume. Generally, the absolute positioning accuracy shows the error of the robot when moved to a prescribed joint angle or Cartesian position. This expresses the mean difference between the actual pose (position and orientation) and the pose calculated from the mathematical model of the robot. "*Repeatability is the ability of the robot to reposition itself to a position to which it was previously commanded or trained*", as defined in (Nof, 1999). It is the standard deviation of the positioning error acquired through multiple trials to reach the same joint values (Fig. 10). Repeatability is typically smaller for manipulators than accuracy, while both numbers are largely dependent on speed, payload and the range of motion (Stiehl et al., 2007). From the clinical point of view, the accuracy of treatment delivery is important, to know the task specific uncertainty. However, this may be difficult to measure routinely; it requires mock operations, cadavers or the use of pre- and post-operative imaging combined. Some manufacturers have tried to construct advanced measurement tools to facilitate system assessment. Alternatively, phantoms (artifacts) can also be used to replicate clinical conditions as much as possible.

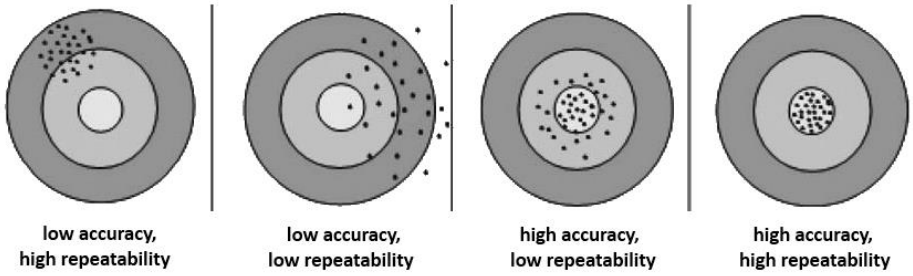

Figure 10. Difference between accuracy and repeatability. Based on (Stiehl et al., 2007).

There are three different types of accuracies (in terms of spatial errors) that can be specified with different error numbers (determined in general) according to (Grunert et al., 2003) and (Kronreif, 2011):

- intrinsic (technical) accuracy (0.1–0.6 mm),
- registration accuracy (0.2–3 mm),
- application accuracy (0.6–10 mm).

Intrinsic accuracy applies to certain elements, such as the robot or the navigation system. It describes the average error of the given component in operational use. Random errors (e.g., mechanical compliance, friction, loose hardware), resolution of the imaging device, inadequate control and noise can all result in low intrinsic accuracy. On the user interface side, discretized input and modeling errors may further decrease precision.

Registration errors are also present, as computational methods involve some kind of residual errors. It is only possible to find a normalized (e.g., least squares optimized) solution for a mathematical fitting problem. In IGS, a major source of error can originate in the localization of the markers (different types, forms and materials), displacement of the fiducials and determination of the center of the fiducials. Even

though the distribution of error for one fiducial in a particular set of measurements is usually Gaussian, the aggregated error for many fiducials can only be approximated to collide with it.

Application accuracy refers to the overall targeting error of the integrated system while used in a clinical procedure or a mock setup. It realistically measures the task specific effectiveness of a system and is commonly used for validation. The application accuracy depends on all other sources of errors in a complex, non-linear way, therefore typically phantom, cadaver or clinical trials are required to determine it. Further problems arise with the simple, ergonomic expression of spatial errors. Physicians may need a single number showing the precision of the system. In many applications, only the absolute distance from a desired location matters, therefore the *Root Mean Square Error* (RMSE) is given for the system:

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - x)^2}, \qquad (1)$$

where N is the number of measurements, x is the desired point and x_i is the i^{th} measured point. The RMSE is only an unbiased representation of isotropic and independent errors in the 3D space. For other cases, the covariance matrix of the error distribution should be used.

Eq. (1) does not incorporate the angular errors of the system, even though any 3D registration or tracking component with a rotational error will affect the translational accuracy. Even worse, the factor of degradation is dependent on the value of the translational vector, due to the nature of the homogeneous transformation matrix multiplication. This is especially bothersome in the case of intra-operative navigation systems that are supposed to be used with a *Dynamic Reference Base* (DRB), therefore the rotational inaccuracy's effect on the linear accuracy will depend on the distance between the camera and the patient, and will have anisotropic distribution. This model is valid for zero-mean Gaussian distributions, and RMSE gives a single value even to multi-dimensional distributions.

In IGS, typically not only robots, but tracking devices are also incorporated, providing the necessary information for navigation. In the case of IG therapies, the same metrics could be applied; however the effect of imperfect registrations and coordinate transformations has major contribution to the overall error. Performance estimation focuses on precision, noise, static/dynamic accuracy or latency. Medical device manufacturers typically provide maximum spatial error values with standard deviations, and publish limited experimental results on the distribution of errors. According to (Frantz et al., 2004), two conditions are necessary to correctly assess a positioning system's performance:

- characteristic statistics (defining trueness and precision),
- a specifically defined assessment protocol (on which the measurement is based).

Evaluating robotic systems usually involves not only mathematical modeling and simulation, but also extensive accuracy tests. One of the difficulties in assessing an IG robot is to acquire the ground truth—the gold standard. This is feasible through the use of a significantly more precise device (e.g., laser scanner, accurate camera system), the use of a measurement phantom or other trusted method (providing the ground truth). In industrial robotics, accuracy measures and tests have been widely used, and some got straight applied to CIS (Haidegger et al., 2010). Most commonly, the medical device is guided (directed) to different positions and orientations along a precisely known set of landmarks (fiducials) or an accuracy board. The positions can also be recorded with an independent localizer.

STANDARDS AND METRICS TO FOLLOW

To make any robot system available on the market, it has to comply with various regulations and standards. Safety is paramount for any surgical device, especially in the case of autonomous actuation. This issue has been addressed by many researchers, governmental bodies and scientific societies in the

past years, pushing for a unified standardization effort to ensure patient and medical staff safety in the operating room. System assessment is paramount for any prototype, and in interventional medicine, the device is most commonly in direct contact with the patient. This section collects the relevant regulations, focusing on the general approach, trends and requirements they implement. At this stage of development in advanced robotics worldwide, it is crucial that both the developers of new commercial systems and the authorities (working on new legislation for the field) understand the importance of accurate categorization and well defined methods to assess the capabilities and associated risk factors of the various systems (Virk et al., 2012).

Current accuracy standards

International bodies are exerting great effort to standardize medical robotics similarly to industrial robotics. However, there are no widely accepted regulations. Some of the existing robotic and medical device standards are applicable to CIS. (While these are changing periodically, the reader should be able to find the most up-to-date versions of the relevant regulations based on the ones listed here.)

In 2004, the *American Society for Testing and Materials* (ASTM) initiated a new standards committee (ASTM F04.05) under the title *Standard Practice for Measurement of Positional Accuracy of Computer Assisted Orthopaedic Surgical Systems* (CAOS). The goal was to develop an international standard for metrology, validation and performance of CAOS systems (Stiehl et al., 2007). The first draft (dating from 2007) deals with the localizer functions of navigation systems (optical, mechanical or electromagnetic). The defined generic measurement board—nicknamed *Nebraska phantom*—was machined from aluminum-alloy, and was tested with three different CIS systems (Barrera et al., 2007). It is a multi-surface object with 47 identical fiducial points (0.75 mm deep cone-shape holes) distributed on its surfaces (Fig. 11a).

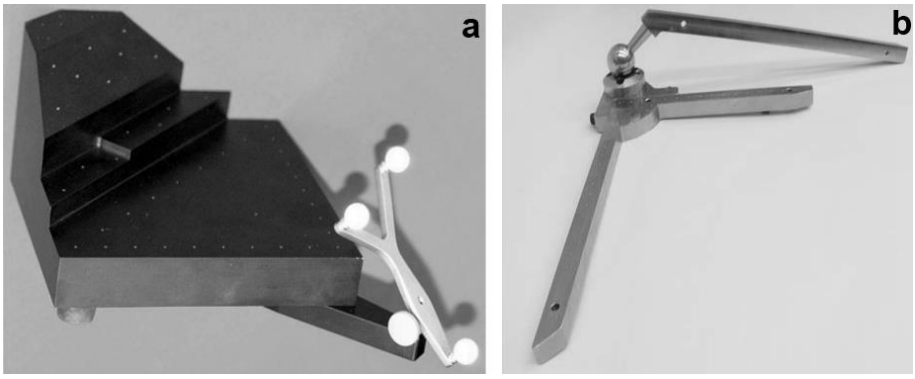

Figure 11. a) ASTM CAOS draft standard accuracy phantom (Stiehl et al., 2007).
b) NIST CAOHS Artifact for the verification of hip replacement surgery (Dagalakis et al., 2007).

ASTM F04.05 developed a set of standard for specific tasks (cutting, drilling, milling, reaming), distinct surgical applications (joint replacement, implant nailing, plating, osteotomy) and imaging modalities (fluoroscopy, CT, MR, ultrasound). Supporting the ASTM group, a multi-institution technical committee presented a white paper, calling for standardization in many areas of CIS (Kazanzides, 2006), (Chiao, 2008). Based on technological and economic analysis, metrology and standards should be applied especially to the following categories of medical devices:

- computer-assisted navigation and surgery,
- surgical robots (mostly in manual control mode),
- surgical robots and phantom (artifact) devices,
- stimulation devices,

- drug-delivery and physiologic monitoring devices.

After a long time of preparation, it came to existence, the ASTM F2554 –10 *Standard Practice for Measurement of Positional Accuracy of Computer Assisted Surgical Systems* (2010). The final version addresses the techniques of measurement and reporting of basic static performance (accuracy, repeatability, and so forth) of surgical navigation and/or robotic positioning devices. It employs a highly accurate optical tracking system to perform system assessment.

Another clinical phantom (*the Computer-Assisted Orthopaedic Hip Surgery—CAOHS Artifact*) was built at the *National Institute of Standards and Technology* (NIST) to quantify task specific measurement uncertainty. It was designed to mimic hip joint using magnetic ball-and-socket to be able to simulate hip replacement procedures (Fig. 11b).

Accuracy measurement standards relevant to the field

Several standards exist for medical devices in general (e.g., from the *International Electrotechnical Commission* – IEC), separately for industrial robotics and for safety-related systems; FDA has its *Quality System Regulation* (QSR) and the *Process Validation Guidance* (GHTF). However, none of these addresses surgical robotics directly. The ISO 10360 standard "Acceptance and reverification tests for *coordinate measuring machines* (CMM)" from 1994 (current version: 2011) can be applied to surgical robots in many cases (mostly to semi-autonomous systems). It defines the protocol for CMM based on *Volumetric Length Measuring Error* (VLME) and *Volumetric Probing Error* (VPE).

Telesurgery requires additional regulations. A report from (Gartner 2008) discusses technical and human issues based on the existing standards according to 1993/42/EEC, *Medical Devices Directive* (MDD) and the third edition of the IEC 60601-1 (2006) for tele-neurology. According to it, manufacturers of telemedical systems for neurology are required to:

- determine the medical purpose §3.10 of MDD,
- carry out risk classification and risk management (according to DIN EN ISO 14971),
- completely meet the requirements of MDD Annex I.

Examples of accuracy measurements

In indirect IGS, 3–5 mm RMSE application accuracy is considered acceptable, whereas 2 mm is recommended for IG neurosurgery. In the meantime, sub-millimeter precision is recommended for robot assisted procedures—direct IGS (Grunert et al., 2003). When CIS system accuracies are reported in research papers, many times, neither of the generic standards is followed. Instead, custom metrics, protocols and measurement boards are used. As a consequence, it is extremely hard to effectively evaluate and compare the results. Most often, the experiments are not described in details (e.g., application accuracy refers only to a single component of a system). While these protocols are better regulated in the industry, the assessment techniques are numerous both in the case of medical robots and surgical navigation systems.

Table I summarizes the published accuracy measures for well-known surgical robots. These tests were mostly conducted in engineering laboratories, following different approaches. Understandably, the control mode of the robot can greatly influence the overall accuracy of the system. It should be noted that for master–slave systems (like the da Vinci), safety originates from keeping the human in the control loop at all times through real-time sensory feedback. This means the intrinsic positioning accuracy of the robot is not crucial anymore; the surgeon uses the provided visual information to compensate for any positioning errors. However, this approach introduces the generic limitations of a human operator (such as physiological latency), and even for these systems, the intrinsic accuracy of the components has significant effect on performance.

Robot	Company	Intrinsic accuracy	Repeatability	Application accuracy
Puma 200 [1]	Memorial Medical Center		0.05 mm	2 mm
ROBODOC [2, 3, 4]	Integrated Surgical Systems Inc. Curexo Technology Corporation	0.5–1.0 mm		1.0–2.0 mm 1.05 mm
NeuroMate [5, 6, 7]	Innovative Medical Machines Int. Integrated Surgical Systems Inc. Renishaw plc	0.75 mm 0.6 mm 0.36 ± 0.17 mm[a]	0.15 mm	0.86 ± 0.32 mm[b] 1.95 ± 0.44 mm[c]
da Vinci [8]	Intuitive Surgical Inc.	1.35 mm[a] 1.02 ± 0.58 mm[d]		
da Vinci S [9]	Intuitive Surgical Inc.	1.05 ± 0.24 mm[d]		
CyberKnife [10, 11]	Accuray Inc.			0.42 ± 0.4 mm 0.93 ± 0.29 mm
B-Rob I [12] **B-Rob II** [13]	ARC Seibersdorf Research ARC Seibersdorf Research		1.48 ± 0.62 mm 0.66 ± 0.27 mm	 1.1 ± 0.8 mm
SpineAssist [14]	Mazor Surgical Technologies			0.87 ± 0.63 mm

Table I Different accuracies published for major surgical robot systems. Details of the experiments are not disclosed in many cases. (Values are given with mean ± standard deviation.) [a] *Target Registration Error* [b] *registration performed with a stereotactic frame (head fixator)* [c] *registration in frameless mode* [d] *Fiducial Localization Error.*

References: [1] *(Kwoh et al., 1988);* [2] *(Paul et al., 1992);* [3] *(Taylor, 2001);* [4] *(Nishihara et al., 2006);* [5] *(Li et al., 2002);* [6] *(Varma et al., 2006);* [7] *(Haidegger et al., 2008);* [8] *(Kwartowitz et al., 2006);* [9] *(Kwartowitz et al., 2007);* [10] *(Dieterich et al., 2003);* [11] *(Jang et al., 2006);* [12,13] *(Cleary et al., 2006);* [14] *(Lieberman et al., 2006).*

Safety standards and methods for CIS

Safety is paramount for any surgical devices, and many kinds of errors may lead to critical conditions in the OR. According to (Satava, 2005), errors in interventional medicine can be categorized as:

- commission: doing the wrong thing,
- omission: not doing the right thing,
- execution: doing the right thing incorrectly.

For most of the CIS systems, failing at execution is typical, while diagnostic (decision support) systems can also generate other types of errors. Errors can be either systematic (a series of errors resulting in an adverse event) or specific (the event itself is a form of error).

Failure mode analysis and risk assessment methods both for hardware and software in general have been addressed by many standards (Varley, 1999; Kazanzides et al., 2008; Kazanzides, 2009):

- IEC 60812 International Standard on Fault Mode and Effects Analysis (1985),
- IEC 1508 Functional Safety: Safety-Related Systems (1995),
- ANSI/RIA R15.06-1999 for Industrial Robots and Robot Systems —Safety Requirements
- *European Norm* (EN) 1441 on risk management (1997),
- *American National Standards Institute* (ANSI) R15.06 standard for industrial robot safety (1999),
- GHTF/SG3/N99-10:2004 Quality Management Systems—Process Validation Guidance (2004),
- IEC 62304 on Medical Device Software—Software Life Cycle Processes (2006),
- IEC 61025 Fault Tree Analysis (Ed. 2.0, 2006),
- ISO 14971 Application of Risk Management to Medical Devices (2007),
- ISO 10218-1 Robots and robotic devices - Safety requirements for industrial robots—Part 1: Robots,

- ISO 10218-2 Robots and robotic devices - Safety requirements for industrial robots—Part 2: Robot systems and integration,
- IEC 60601 international standard on Medical Electrical Equipment (Ed. 3.0, 2010),
- IEC 1508 draft standard on Functional Safety for software developers,
- ISO 13482 Robots and robotic devices - Safety requirements for nonindustrial robots - Non-medical personal care robot.

Several groups have published methodologies to support the principles of safe design and development of robotic surgical devices. A generic one is the *Hazard Identification and Safety Insurance Control* (HISIC) policy, that has been applied to multiple surgical robotic systems so far (Fei, 2001). HISIC breaks down the issue into seven principles:

- definitions and requirements,
- hazard identification,
- safety insurance control,
- safety critical limits,
- monitoring and control,
- verification and validation,
- system log and documentation.

Further, a *Computational Evolution* method (Varley, 1999) and a *Unified Modeling Language* (UML) based approach have been successfully prototyped (Guiochet & Vilchis, 2002), relying on safe design, safe execution and risk assessment as cornerstones. Risk management in general is a key component of the entire medical device safety. This includes (Guiochet & Vilchis, 2002):

- risk analysis (system definition, hazard identification and risk estimation),
- risk evaluation (determine risk tolerance levels),
- risk control (implementing the right action for maximum safety).

CLEARANCE PROCEDURES

Testing a prototype is only the first step towards commercialization, acquiring certification involves many other issues. To objectively evaluate the performance of a robot-assisted system, it is crucial to understand and apply consistent measurement methods. However, many other factors determine the success of a surgical robot beyond spatial precision. The accuracy of treatment delivery remains the baseline for applicability; a medical robotic system should still address the questions of complexity, cost and ergonomics. Different systems should be measured and assessed through the same validated experiments.

The existing industrial standards and medical robotics related drafts should be extended to all major areas of CIS. Surgical robot systems typically have an application accuracy between 1–2 mm. This means lower precision that of industrial robots, mainly due to the accumulation of different errors in IGS, preventing sub-millimeter accuracy. (Although sometimes, sub-millimeter inherent robot accuracy is wrongly claimed as overall precision.) A robot must be intuitive and require minimal maintenance and engineering skills to operate (Kazanzides et al., 2008). The user acceptance of a system will eventually determine the value of the device, therefore one of the major directives of development is to minimize the change to the existing clinical workflow. These ideas are typically represented in the medical device regulations.

International regulations for CIS

Clearance applications (and the following continuous communication with the regulatory bodies) include discussion of electronics design, imaging systems' performance, embedded software analysis and clinical trial design and patient outcome validation. The procedures both in Europe and in the U.S. are focusing on the safety and transparency of systems (Taylor & Kazanzides, 2008). Most prototype development and testing begin with the official approval of the *Institutional Review Board* (IRB), legally taking responsibility for the primer operations.
In the EU, the CE mark must be obtained, certifying that the product complies with the essential requirements of the relevant EU health, safety and environmental protection legislation. The approval procedure is managed by independent *Notified Bodies* (NB), accredited by Brussels centrally. There are over 75 international, non-governmental NB for medical devices. ISO 9000 Quality Standards family is applied to verify the production management of a company (*www.iso.org/iso/iso catalogue.htm*). ISO 9001:2000 combines three previous standards (9001, 9002 and 9003), addressing design and development procedures under the title "Quality management systems—Requirements".

For CIS systems, the ISO 13485:2003 (*Medical devices—Quality management systems—Requirements for regulatory purposes*) is in effect. It is possible for ISO 9001 complied companies to self-certify (CE mark) their products within certain limitations, and the NB would periodically audit them.

U.S. practices

In the U.S. only the federal Food and Drug Administration can clear medical systems (*www.fda.gov/MedicalDevices/ProductsandMedicalProcedures/default.htm*), since the 1976 *Medical Device Amendments*. The *Safe Medical Device Act* (1990) defined the present regulatory structure requiring that all medical devices should ensure safe and effective use (DiMaio et al., 2011). "*An* Investigational Device Exemption *(IDE) allows the investigational device to be used in a clinical study in order to collect safety and effectiveness data required to support a submission to FDA. (FDA, 2011)*" For initial trials, FDA requires an IRB approval certifying that the device in question poses only insignificant risk. If an investigational use of a new system (or with a new procedure) poses significant risk to the patient, the IDE needs an FDA approval. Next, to allow further clinical investigation of a new device, the IRB and the FDA must determine the followings (Bronzino, 1990):

1. risks to subjects are minimized,
2. risks to subjects are reasonable in relation to the anticipated benefit and knowledge to be gained,
3. subject selection is equitable,
4. informed consent materials and procedures are adequate,
   provisions for monitoring the study and protecting patient information are acceptable.

The *FDA review team* incorporates experts from various fields, and if needed, they may hold a *Public Advisory Panel* meeting, to obtain a second opinion from external professionals.

Before the whole clearance procedure is initiated, it is a good idea to ask for a pre-submission meeting from FDA, where it is possible to get informal feedback from an FDA review team on the preliminary data and concept. Clearance can be done primarily in the form of a *Pre-Market Approval* (PMA) procedure—which is for new devices—requiring extensive clinical trials and huge amount of documentation. Table II summarizes these requirements for different kinds of systems. A PMA submission can costs approximately $240K, although a reduced pricing is applied for small businesses, and it has 180-day review cycle.

On the other hand, the *Premarket Notification* pathway, the *510(k)* is for equipment that can be proved to be "*substantially equivalent*" to an existing device, already approved by FDA. Substantial equivalence is meant in terms of safety and effectiveness with respect to intended use and design, compared to a predicate device. It has a 90-day-long review cycle, and may still require clinical trials, but less extensive than for PMA. All systems must comply with FDA *Quality System Regulations/Medical Device Good Manufacturing Practices* (*Code of Federal Regulations* Title 21, Part 820) (Lowery et al., 1996).

While there are 3–4000 independent 510(k) submissions annually, only 30–50 PMAs arrive to FDA. The basic idea behind these regulations is to prevent failures and issues originating from bad design. The clinical use and patient outcome might not even be verified during the validation. At the most, the system should show the capability to perform a procedure with the same effectiveness as an existing (manual) technique. FDA is used to rely on the selectivity of the market, which should only allow for the existence of well-sustained systems with significant added value to the surgical procedure.

Systems are classified into three main categories, depending on the risk they pose to the patient, the user and the based on the intended way of use:

- Class I: low risk devices (45% of the submissions, many exempt),
- Class II: medium risk devices (45%, usually 510(k)),
- Class III: devices involving high risk to the patient, e.g., life-sustaining equipment (<10%, typically PMA).

Device Type	Regulatory Class	Bench Testing	Animal Testing	Software Validation	Clinical Data
Preoperative planning	II			X	
Stereotactic frames	II	X			
Computer-assisted or navigation device Computer-assisted intraoperative planning and surgical guidance	II	X		X	X
Robotic operating assistants Computer-assisted intraoperative planning and surgical guidance or action	II or III	X		X	X
Fly-by-wire	II or III	X		X	X
Robots	Unclassified	X	X	X	X

Table II Summary of classification of CIS devices and their testing requirements in the U.S. (Janda & Buch, 2009).

The da Vinci robot was originally categorized as Class III, and initiated its clearance procedure via PMA. Later, it was advised to convert to 510(k), and eventually got approved as a Class II device. When performing objective system assessment, FDA looks into the following issues in the case of CIS systems (Janda & Buch, 2009):

- How accurately do the system's actions reflect the operator's intent?
- Does the device enhance surgical capabilities?
- How does the computer "intermediary" affect operative flow?
- How easily are glitches in the technology handled?
- Are there procedures and/or anatomic sites that are more or less amenable to this technology?
- How steep is the learning curve?
- What criteria are used to "optimize" a preoperative plan?
- How and when should the user override the recommendations of the system?
- How does the system define anatomic references and axes?
- How does the system dictate the surgical workflow, and how does this differ from traditional techniques?

General requirements for medcial software

Since robots also consist of software parts, it is important to know that for all software and apps that meet the definition of a medical device, the EN62304:2006 regulatory guidance is applicable

(http://www.mhra.gov.uk/Howweregulate/Devices/Software/index.htm). Software, which drives a device or influences the use of a device automatically falls into the classification of that. Regarding robotic devices, there are a few more thumb rules:

- Active therapeutical devices are generally Class IIa, yet potentially hazardous ones are Class IIb.
- Active devices intended for diagnosis are generally Class IIa – or Class IIb, if hazardous
- Other, non-hazardous Active Devices fall under class I.

While compliance to Class I devices is based on self-declaration by the manufacturer, all other devices require use of a notified body to assess compliance. Clinical data is required for all medical devices and for some novel software clinical investigations may be needed. Manufacturers have a responsibility to implement an effective post-market surveillance system to ensure that any problems or risks associated with the use of their device once freely marketed are identified early, reported to competent authorities, and acted upon. This is known as the medical devices vigilance system. For software, a system of registration/activation may aid the manufacturer trace devices that have been distributed by third party distributors or by app stores. This is important when undertaking any corrective action such as a recall.

The ROBODOC case

The clearance procedure of the ROBODOC system stretched long and full of edifying stories. It was the first robotic system that tried to get through the FDA clearance procedure, and it was forced into the PMA category, since no equivalent technology existed (Curexo, 2009).

- October 1992, the FDA granted an IDE approval to conduct limited clinical trials (at Sutter General Hospital in Sacramento).
- November 7, 1992, the world's first robotic joint replacement surgery was performed.
- A biomedical engineer for the FDA outlined comprehensive investigative testing designed to test the safety of the robotic control software.
- 1993, ISS began the PMA clearance procedure. The ROBODOC software and hardware had to comply with robust motion control restrictions to prevent accidental tissue and bone damage.
- 1996, it received the European CE mark and approval for THA procedures.
- 2002, the FDA re-assigned the ROBODOC system to the 510(k) path. Unfortunately, by this time, ISS no longer had sufficient capital to support the procedure.
- By 2004, the significant R&D cost related to further testing and re-submission caused ISS to cease operations.
- November 2007, all assets and IP were transferred Curexo Technology Corporation, and $12M was invested to continue operations.
- The fresh money allowed to finish trials, and to complete the robot's commercialization via FDA 510(k).
- In August 2008, the system finally received a 510(k) clearance from FDA, yet the change of times forced the company to return to the design boards to develop a new version of the system.

Throughout these years, all the FDA-cleared surgical robots (e.g., da Vinci, NeuroMate, CyberKnife, ROBODOC, MAKO Arm, SpineAssist) went down the 510(k) procedure, proven to be substantially equivalent to existing (manual) technologies. FDA's emphasis has gradually shifted from the robotic technology itself to approving the results of the use of the robotic systems. It is now believed that the equivalence stands between the already-approved surgical techniques and the results attained through robotic interventions.

Current trends

Regulatory bodies have realized the need for a better approach to the dynamically growing field of CIS. Since 2010, the 2007/47/EC (*European Council*) regulation extended the existing 1993/42/EEC MDD,

requiring specific clinical data for new devices and companies are expected to do to ensure safety and demonstrate the performance of their product, regardless of the classification of the device. The directive also requires risk and benefit analysis, and the sustained and coordinated clinical post market surveillance of the products. It came into effect in 2012 in Europe and in Canada, and from June 2013 in the U.S. In addition, software developed for diagnostic or therapeutic purposes has become classified as a medical device in the EU.

A workgroup was created in 2009 to prepare an extension to the existing ANSI/AAMI ES60601-1:2012 standard on *Medical Electrical Equipment*, focusing on medical robotics and personal care robots. Working together with the subcommittee of the ISO TC 184, dealing with robotic devices, the priorities of the new standard are:

- defining medical software systems and associated technical requirements,
- streamlining the application of risk management,
- clarifying the definition of essential performance,
- identifying essential performance and mitigating risk.

The ISO/TC 184/SC 2 technical sub-committee on *Robots and Robotic Devices* proposed the formation of a joint work group with the IEC/SC 62A subcommittee (Common Aspects of Electrical Equipment used in Medical Practice) under IEC administration to develop a new proposal for a Collateral Standard within the IEC 60601 family. The scope of the standard would be to the basic safety and essential performance requirements for medical electrical equipment and in addition, systems employing robotic technology (i.e., medical robots).

In the EU, updates to the IEC 60601-1 means that regulatory bodies decided to require supportive medical data as evidence for the safety and performance of new systems. Beginning in June 2012, risk assessment and analysis for every medical device designer and *Original Equipment Manufacturer* (OEM) will be mandatory.

The FDA's 510(k) procedure is going under major revision based on the complaints filed by the device manufacturers. Two committees were created: *510(k) Working Group* and the *Task Force on the Utilization of Science in Regulatory Decision Making* (CDRH, 2010). Improvements should include the clarification on clinical data requirements and the implementation of more transparent, science-based decision making structure, specifically:

- When and what type of manufacturing data to submit?
- When a pre-clearance inspection would be conducted?
- When and what types of modifications should be periodically reported in lieu of submitting a 510(k)?
- When and what type of safety and effectiveness information for the device to be reviewed that is known to the manufacturer should be submitted as a brief description?

The aim is to reduce the number of failures through more thorough tests before the release, especially for devices such as defibrillators, hip implants and hospital pumps (FDA, 2010).

The *Institute of Medicine* (IOM) concluded that it would be better to develop an integrated pre-market and post-market regulatory framework that provides a reasonable assurance of safety and effectiveness throughout the device life cycle (IOM, 2011). "The new framework should be:

- based on sound science,
- clear, predictable, straightforward and fair,
- risk-based,
- be self-sustaining and self-improving,
- facilitate innovation that improves public health by making medical devices available in a timely manner and ensuring their safety and effectiveness throughout their lifecycle,

- use relevant and appropriate regulatory authorities and standards throughout the life cycle of devices to ensure safety and effectiveness."

FUTURE RESEARCH DIRECTIONS

In the past 10 years, we have seen the dynamic growth of the field of CIS, and the best surgical robots gradually reached clinical application. Da Vinci is dominating the market, however, several competitors are on the way, relying on the reputation surgical robots have already achieved. The success of Intuitive's system inspired many groups:

The development of the Telelap ALF-X system (*Advanced Laparoscopy through Force- RefleCT(X)ion)* began around 2008 at SOFAR S.p.A., (a pharmaceutical company in Milan), with retrofitting industrial manipulators to create a da Vinci competitor (Fig. 12a). They are supported by an EU joint effort, and operating under the academic assistance of the *New European Surgical Academy* (NESA). Next, they teamed up with *Immersion Corp*. to ensure a good haptic interface (*TouchSense*) for their robot, and submitted numerous patents. Features of the robot include force control, preoperative simulation, intra-operative virtual reality overlay, automated fulcrum point identification and real-time patient monitoring. Their system is capable of 1.5 mm application accuracy and under 60 ms latency in the control. The system's main application would by gynecology. Preclinical trials with the robot have been performed, focusing on hysterectomy, salpingo oophorectomy, myomectomy, partial and radical nephrectomy, total pelvic exenteration and cholecystectomy (Tinelli et al., 2011).

Figure 12. b) CE marked version of the ALF-X system (Tinelli et al., 2011). d) The Raven II from the BioRobotics lab at University of Washington. (Courtesy of UW.) c) Sofie, developed at Eindhoven University of Technology. (Courtesy of EUT.) d–e) The Canadian SPORT system. (Courtesy of Titan Medical Inc.)

The *KUKA Lightweight arms* (LW) and *iwa* are the commercialized version of the *DLR III arm* (7 DOF, fully sensorized, compliant) is preferred solution for many procedures (e.g., for the Active FP7 project), and now *KUKA LBR Med* is sold by the company directly for medical applications as well (http://www.kuka-labs.com/en/medical_robotics/). It is also an important feature that the KUKA robot does not use cable-drive, therefore does not collide with Intuitive's patents on the technology.

The *BioRobotics Lab* at *University of Washington* has developed a portable surgical robot that can be a compromised solution to install on space crafts with its 22 kg overall mass (Fig. 12b). The robot—called *Raven*—has two articulated arms, each holding a stainless steel shaft for different surgical tools. It can

easily be assembled even by non-engineers, and its communication links have been designed for long distance remote-control. Besides the possibility of haptic feedback, additional sensors are mounted on the robot to provide more information to the surgeon and to avoid any critical failures due to communication delay. Throughout the entire development, compactness was handled as priority, the creators optimized the robot's dimensions and range-of-motion by computer, minimizing the space it occupies without compromising on manipulation capabilities (Lum, 2008). The new generation robot, Raven II was distributed to seven university clinics and research labs in North America and Western Europe, and is now commercialized as an open research platform by Applied Dexterity Co. (*http://applieddexterity.com/*).

The *Surgeon's Operating Force-feedback Interface Eindhoven* (Sofie) is a surgical robot developed at the *Eindhoven University of Technology (*van den Bedem, 2010*)*. It is a compact surgical robot, integrating force feedback to allow the surgeon to feel what he or she is doing (Fig. 12c). Tactile feedback is provided in the master side joysticks. This counter pressure enables a surgeon to feel exactly what force he applies when making a suture or pushing aside a bit of tissue. Sofie is smaller, bed-mounted, hence it is less of an obstacle in the operating theater and above the patient. This avoids the otherwise necessary re-arrangement when the operating table and the patient are moved or tilted. Further, Sofie makes it possible to approach an organ from different sides thanks to its flexible tools.

In 2009, a Canadian company—*Titan Medical Inc.* (Toronto, Ontario Canada)—announced its new four-armed manipulator system, the *Amadeus*, now called the *SPORT* (Rayman, 2009). The robot is being built in cooperation with *Bell Canada*'s Health Division to integrate Internet Protocol based advanced telesurgery capabilities for Amadeus. Titan Inc. announced in 2011 that they would use KUKA arms for the setup, yet they switched to a single-port solution licensed from Columbia University, and renamed the system to *Single Port Orifice Robotic Technology*—SPORT (Fig. 12d–e). Strategic agreements have been made with Canadian hospitals for the trial of the system, and currently a first clinical prototype is undergoing animal trials. The commercial product is expected in 2016.

An Italian spinoff company of the University of Verona—Surgica Robotica Ltd.—has been developing *Surgenius* since 2009. This robot is based on NASA's RAMS system that was developed in the mid-1990s. It was recognized by the euRobotics Technology Transfer Award. After is passed pre-clinical (in-vivo, in-vitro) trials for system validation, it got CE mark in 2012. Currently, it is waiting for further funding to reach commercial status.

Future evolution of the field

Current research projects are trying to increase the utility of the surgical equipment along different strategies. They are mainly focusing on three areas for improvement:

- augmenting the overall accuracy and/or efficacy of the classic stereotactic systems,
- increasing the added-value of the equipment,
- further enhancing the capabilities of the human surgeon, providing smarter tools.

The following ongoing research examples give insight to how these issues are addressed and what are the benefits for future patients. Safety is paramount in all cases, and should determine the way research is conducted. Patient safety is addressed differently in each discussed system.

Improvement of stereotactic surgery

A good example of this concept was the European Union's FP7 project—ROBOCAST (*Robot and Sensors Integration for Computer Assisted Surgery and Therapy*)—aimed to augment existing IGS techniques and to find new ways to perform high-precision keyhole neurosurgery (Comparetti et al., 2011). The modular system consisted of two manipulators and one smaller probe, actively cooperating in a bio-mimetic sensory-motor integrated framework (Fig. 13a). Mazor's (Caesarea, Israel) *SpineAssist* was used as a robotic end effector by itself, enhanced with a linear drive for needle insertion (Lieberman et al.,

2006). The 6DOF *PathFinder* system (Prosurgics Inc., UK) forms the larger positioning robots. (The stereotactic PathFinder used to be available on the European market for other IG procedures.) It works with the CT or MRI images of the patient and automatically registers the position of the probe (with at least 1.25 mm accuracy). In general practice, it is capable of aligning the surgical tools within 1 mm of the target. The ROBOCAST system used optical trackers for patient safety (to monitor and compensate for any change in the patient's position) and provided visual information of the surgical field. Given an accurate registration, the controller could use the preoperative diagnostic information to plan the path of the intervention.

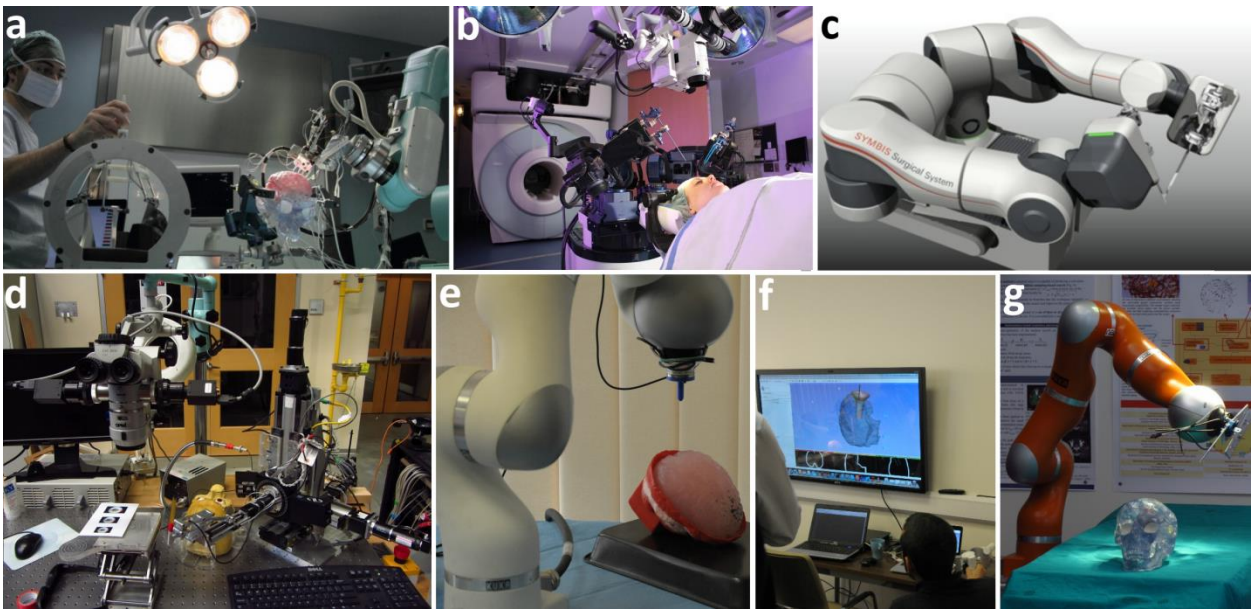

Figure 13. a) The final demonstration of the ROBOCAST system (Comparetti et al., 2011). b) The first clinical prototype of the MRI-compatible neuroArm. (Courtesy of University of Calgary.) c) Concept design for the commercial version of neuroArm—SYMBIS. (Courtesy of IMRIS.) d) The Steady-Hand/Eye Robot at JHU. (Courtesy of the Johns Hopkins University.) e–g) Experimental setups of the ACTIVE system (ACTIVE, 2014).

Integrating imaging devices

The other main direction of development is to integrate the robots with advanced imaging devices to increase their utility by allowing intraoperative imaging (Tsekos et al., 2007). This can be very challenging technically, as the robot has to be constructed of non-magnetic and dielectric materials such as plastics, ceramics and rubber. MR compatibility is considered to be one of the greatest advantages a robot may have, allowing continuous image-guidance through intra-operative imaging, and avoiding the need of image registration (Gassert et al. 2008). MRI gives a fine resolution picture of soft tissues within an acceptable timeframe, while avoiding patient and surgeon radiation exposure. MR compatible robotics has been in the focus of research interest since the mid '90s, and numerous systems have been developed.

NeuroArm (Sutherland et al., 2013) is a teleoperated anthropomorphic robot from a *University of Calgary* led consortium (Fig. 13b). The MR safe robot (compatible up to 1.5 Tesla magnetic field) is designed for stereotaxis and microsurgery. Beyond motion scaling and high definition visual feedback, the neuroArm is able to provide very accurate 3D information of its two 7 DOF arms. It uses three displays to give complete visual coverage of the operating environment, showing in parallel the 3D stereoscopic view of the operation, the MR image of the patient and the control panel. The system has been used on a few

human patients so far, and after further clinical trials, it may hit the market within a few years in a new format, designed and engineered by the Canadian IMRIS (Fig. 13c). A major barrier however is the increased cost of the MR compatible components.

At Johns Hopkins University, researchers have already developed several generations of MR compatible robots, mostly for prostate brachytherapy (Krieger et al., 2011). They are considered to be the leading center in brachytherapy system development, together with Queens University in Kingston, ON (Fichtinger et al., 2012).

Other groups, such as the Automation and Interventional Medicine Laboratory at WPI target similar procedures, such as *Deep Brain Stimulation* (DBS) with significantly smaller scale robots that can fit into the gantry of conventional, diagnostic MRI (Cole et al., 2009, 2014). Closed, high-field scanners are used for guiding DBS electrode placement interventions relying real-time guidance. It may be used for treatment of Parkinson's disease and other disorders including severe depression and Alzheimer's disease.

Hands-on surgery with advanced features

Another neurosurgical research project at the JHU is a good example of the cooperative control concept (Fleming et al. 2008). The hands-on system—called formerly the Steady-Hand, and now the Eye Robot—is capable of significantly increasing the performance of human surgeons (Fig. 13d). The robot holds interchangeable tools and the force sensor that has low-threshold silicon strain gauges built in to detect forces. The force measurements are coupled to the control system after tremor filtering and smoothing. This approach has the advantage of simplicity, less expensive implementation and provides greater immediacy for the user. However, the possibility of teleoperation is completely lost. Surgeons may be more willing to accept this form of robotized equipment, as it still supports the classical way of doing the procedure. The robot is based on a Cartesian stage (allowing three orthogonal translational motions) and a RCM stage (with two orthogonal rotational DOF) that helps to keep a user-defined point (RCM) of the robot at the same position in space. This allows safe surgery through the abdomen (or other tissue layers), where the incision point limits the motion in space (*https://ciis.lcsr.jhu.edu/dokuwiki/doku.php?id=research.eyerobots*).

Another EU FP7 consortium has been formulated for the development of advanced robotic systems, under the name ACTIVE: *Active Constraints Technologies for Ill-defined or Volatile Environments*. A lightweight and agile 20 DOF redundant robotic cell is to be created (Fig. 13e–g). An advanced processing unit for pre- and intra-operative control operates both autonomously and cooperatively with humans. Two cooperating KUKA LW robots interact with the brain that prone to deform for the tool, blood pressure, breathing and deliquoration. Automated compensation techniques are developed for patient motion. The setup is primarily aimed to help with neurosurgery procedures, such as awake DBS for the treatment of epilepsy (ACTIVE, 2014).

There are other concepts and approaches that seek to find ways to better serve the clinicians. Any new strategy must be developed using the same strategic principles:

- the system should pose minimal risk to the patient (compared with classical methods),
- there shall be major clinical advantages to justify its use and finally,
- the investment and maintenance costs should be reasonable for medical centers.

Minimally invasive surgical techniques

Minimally invasiveness has been in the focus of clinical practice and the development of new systems, to the extreme of making no visible scars on the patient. *Natural Orifice Transluminal Endoscopic Surgery* (NOTES) was born 5 years ago to support surgical technique performed with a flexible endoscope and tools passed through a natural orifice (mouth, urethra, anus, etc.) then through an internal incision in the stomach, vagina, bladder or colon, thus avoiding any external incisions or scars. The name was invented at the Johns Hopkins Medical Institution, when first used on animals by Dr. Kalloo, as a developed

version of single port laparoscopy (also called Single Incision Laparoscopic Surgery—SILS). The first human operation was in June 2007, a transgastric cholecystectomy (Dallemagne et al., 2009.)

NOTES provides numerous patient benefits, such as reduced pain, faster recovery, better cosmetic outcome (making it popular e.g., among models) and lower risk of infection. One of the great advantages is that theoretically no sterile environment is required, only sterile equipment. On the other hand, it is easier to cross-contaminate different compartment within the body. The single port entry means serious limitations in spatial motion, but also making laparoscopy manageable in obese patients, children or burnt patients. Hyper-redundant endoscopes must be used to achieve in-body navigation, and many surgeons are needed to manipulate these devices. Research labs all around the world are trying to provide an automated tool for NOTES. One example is the *MASTER* (*Master And Slave Transluminal Endoscopic Robot*) from the Nanyang Technological Institute, Singapore, which uses a bigger, 16 mm endoscopic tube to introduce a two-armed manipulator to the surgical field. Some limited clinical trial (endoscopic submucosal dissection) of the system has been conducted (Kok, 2011) (*http://clinicaltrials.gov/show/NCT01394861*).
There are many other ways to advanced MIS this technology, such as combining it with real-time 3D visualization and augmented reality applications, such as the MUSTOF endoscope (*Multi-Sensor-Time-Of-Flight*) from *Friedrich-Alexander University*, Germany (Höller, 2010).

As of today, NOTES is still looking for a good clinical application that would best benefit from the development and justify the higher patient risk, costs and limited ergonomics of the procedures. The main goals of the *Natural Orifice Surgery Consortium for Assessment and Research* (NOSCAR, *www.noscar.org*) working group are to solve the question of stability and navigation in the next five years while providing more advanced tools with the capability of triangulation, and additional features such as stapling and closing.

Catheter robots

Catheter-based procedures are wide-spread and representing an emerging field, therefore various robotic systems are aiming to improve these procedures (Antoniou et al., 2011). Hansen Medical's *Magellan* peripheral intravascular interventions robotic heart ablation system (FDA approved in 2011), and they also have the *Sensei X* robotic system for heart ablation on the market. Navigation of catheters is a key issue, and also in the focus of numerous research projects, such as the EU FP7 *Smart CATheterization* (SCATh) project, led by the *Katholieke Universiteit Leuven*. It is focusing on the improvement of visual and haptic tools for robust and accurate catheter guidance by fusing preoperative patient-specific anatomical and mechanical models and intra-operative data streams from in situ sensors. A remote-controlled catheter guiding robot was used in Milan in 2006 to automatically perform cardiac ablation, initiated and supervised by a group of professionals from Boston, MA. The robot used high magnetic fields to insert the catheter to the desired location, taking advantage of the pre-operative CT scans of the patient and real-time electromagnetic navigation. Initial trials were performed on 40 patients before the telesurgical experiment took place. The novelty of the system was that it could create the surgical plan on its own, relying on an anatomical atlas built on 10,000 patients' data (Pappone et al., 2006).

One of the recent competitors, FLEX emerged in for ENT applications. Howie Choset invented a cool snake-like robot for climbing poles at CMU, and with NIH funding created the first generation prototype with 11 millimeters in diameter. It was called CardioARM, featuring 102 joints. In 2009, they founded Cardiorobotics, and started limited trials the next year in the Czech Republic. However, soon they realized that cardiac procedures are just too complex and patient-specific to robotize efficiently. Thus Medrobotics Inc. was born, with a focus on head-and-neck surgery. By the end of 2011, the company has raised $28.3M in three rounds, from business angels, and since then, they raised another $43.6M, and eventually about to gain FDA approval in 2014 (*http://surgrob.blogspot.hu/2014/06/updates-on-flex-system.html*). The Flex is capable of integrating third party manufactured instruments fitting into the tool channel, and equipped with (only) 2D HD camera with adjustable depth-focus.

Microrobots

Another direction of development is toward small scale, in-body (typically capsule) robots (Toennies et al., 2010) and (Nelson et al., 2010). These offer great advantages, as they are always remote controlled, facilitating the spatial displacement of the physician from the patient. Instead of the massive rigid structure applied for human-scale robots, these are often modular and reconfigurable. *Micro-EectroMechanical Systems* (MEMS) allow for the design of structures or devices in the micro or even in the nano scale (Rebello, 2004). MEMS devices could either be (Cretu, 2010):

- diagnostic microsystems: for rapid point-of-care, systems on a chip, cell and molecule sorting, DNA diagnostics,
- surgical microsystems: for MIS, CAD-assisted surgery, microrobotics,
- therapeutic microsystems and prostheses: drug and gene delivery, tissue augmentation/repair, biocapsules, micro/minimally invasive surgical systems.

Researchers at the University of Nebraska developed a special mobile in-vivo wheeled robot for biopsy (Rentschler et al., 2006). Equipped with a camera, the coin-sized robot can enter the abdominal cavity through one small incision and move around the organs teleoperated. The robot is able to traverse the abdomen without causing any tissue damage, therefore reducing patient trauma. More recently, the group has developed various swallowable robots, controlled with external magnets (Lehman et al., 2009).

The CRIM group at *the Scuola Superiore Sant'Anna* (Pisa, Italy) leads an FP7 funded international research collaboration to develop tethered, partially autonomous robots to perform surgery in the endolumen: *Array of Robots Augmenting the KiNematics of Endoluminal Surgery* (ARAKNES) project (Menciassi & Dario, 2009) and (Harada et al., 2009). The project was originally aiming at tethered NOTES robot, but more recently, the groups has changes to SILS approach. Another EU FP7 project—*Vector*—targets the creation of effective capsule robots for local surgical procedures all along the gastro-intestinal tract (Eiriki et al., 2009).

Nanorobots

Nano-scale devices may be used for transporting, delivering and targeting drugs. This means the assembling and control of individual modules such as nano-actuators and nano-sensors through molecular *Computer-Aided Design* (CAD). System concepts exist to affect various biological procedures, e.g., repairing damaged cells or the DNA. Artificial red blood-cells could absorb a hundred times more oxygen, and nano-robot swarms could be directed around the body with external magnetic fields (Martel et al., 2008).

One of the most prominent groups in this area is at the Swiss Federal Institute of Technology Zurich (ETH). They are also involved in the NANOMA project, aiming at the development of a drug delivery microrobotic systems. It uses ferromagnetic microcapsules in the cardiovascular system, navigated via the induction of force from magnetic gradients generated by an MRI machine (Vartholomeos et al., 2011). The projects results were transformed into a spin-off company, AEON Scientific that developed a market-ready product (http://www.aeon-scientific.com/)

Magnetic manipulation

Magnets are used in various ways to actuate small-size surgical robots (Menciassi, 2011). Groups around the world are focusing on permanent or uniform fields for manipulation, especially in tubular structures. The use of non-uniform fields enable the generation of more powerful magnetic fields, which is desirable for in vivo applications, and it can be used e.g., steering cochlear implants, reducing the trauma of the surgery (Kummer et al., 2010). A different approach is applied in the Italian national *Microsystems for Vascular diagnosticS and intervention* (Micro-VAST) project, to have a permanent magnet mounted on an external robotic arm to control a micro-robot (Ciuti et al., 2010) . Other systems use magnets for anchoring, e.g., modular NOTES robots (Lehman et al., 2009).

Many of these initiatives are covered by Europe-wide EU FP7 coordination actions, such as EuroSurge (*http://eurosurge.eu*). This project aimed to aimed to create a conceptual integration platform for Computer and Robot Aided Surgery (CRAS) research and manufacturing, founding the bases of advanced applied research.

CONCLUSION

Advanced mechatronic systems became widely used to support complex applications, even in the realm of medical procedures. This chapter dealt with specific issues regarding the prototyping of Computer-Integrated Surgical systems and surgical robots. CIS systems are primarily developed to provide patient benefits through increased precision and minimal invasiveness. Furthermore, robotic devices may allow for refined surgical treatment unimaginable without technological support. Various system development approached have been introduced through real-life examples, also pinpointing the difficulties, such as connecting interdisciplinary technologies, validation for regulatory approvals, or entering the market, and surviving against competing treatment forms. Creating an engineering prototype is only the first necessary step toward the development of a deployable new system. Slow establishment of standards specific to this area makes it harder to comply with applicable patient safety and process verification regulations and guidelines. The chapter gave an overview of these standards in order to facilitate future surgical robot developers. Systems currently under development will offer deliver great clinical advantages and improved safety features providing benefits both to the patient and the surgeon. It is believed that gradually research projects will find easier ways to advance from early phase towards more mature prototypes. Eventually, more revolutionary devices should emerge, ready for clinical trials, validation and hopefully, clearance at the end.

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ADDITIONAL READING MATERIALS

Surgical robotics and CIS have accumulated vast literature in the past 30 years. The most prominent articles are published in *the Institute of Electrical and Electronics Engineers* (IEEE) *Transactions on Biomedical Engineering*, *Transactions on Robotics* (former *Transactions on Robotics and Automation), IEEE/ASME Trans. on Mechatronics*, *IEEE Robotics and Automation Magazine* and in the various thematic journals, such as the *Journal of Computer Aided Surgery* (Taylor and Francis), *Interntaional Journal of Medical Robotics and Computer Assisted Surgery* (Wiley), *Interntaional Journal of Computer Assisted Radiology and Surgery* (Springer), *Journal of Robotic Surgery* (Springer), *Surgical Endoscopy* (Springer) and the *Journal of Medical Devices* (ASME). These publications are all available online. Accordingly, the number of surgical robotics related publications has been steadily rising (O'Toole et al., 2010). Many books, tutorials and articles have been published on surgical robotics in the past 25 years, a subjective selection of the most notable ones include (Taylor et al., 2008), (Dario et al., 2003), (Taylor & Stoianovici, 2003), (Baik, 2010), (Ballantyne et al., 2004), (Pott et al., 2005), (Bozovic, 2007), (Faust, 2007) and (Kazanzides et al., 2008) . The more generic field of surgical robotics is well covered by conferences, journals and periodicals.

An earlier edition of this chapter appeared in IGI Book (T. Sobh & X. Xiong (Eds.) Prototyping of Robotic Systems: Applications of Design and Implementation , Bridgeport, CT.

The *Minimally Invasive Robotic Association* (MIRA), the *Society for Medical Innovation and Technology* (SMIT), the *Intl. Society and Conf. Series on Medical Image Computing and Computer-Assisted Intervention* (MICCAI) and the *Computer Assisted Orthopaedic Surgery* (CAOS) organize topical

conferences every year. The *Society of Photographic Instrumentation Engineers* (SPIE) has numerous events, out of which the *SPIE Medical Imaging* conference is most attended by CIS professionals and industrial collaborators. In addition, the *Medicine Meets Virtual Reality* (MMVR) conference series, *the Congress of Computer Assisted Radiology and Surgery* (CARS), the *Annual Intl. Conf. of the IEEE Engineering in Medicine and Biology Society* (EMBC), the *IEEE Intl. Conf. on Robotics and Automation* (ICRA), the *IEEE/RSJ Intl. Conf. on Intelligent Robots and Systems* (IROS), the *Conf. on Information Processing in Computer-Assisted Interventions* (IPCAI), *Joint Workshop on New Technologies for Computer/Robot Assisted Surgery* (CRAS) and the biannual *IEEE/ RAS–EMBS Intl. Conf. on Biomedical Robotics and Biomechatronics* (BioRob) all welcome original publications on surgical robot prototype development. In addition, several portals and websites are dedicated to information sharing and knowledge distribution, providing free tutorials, video materials and presentations to assist robot development in every stage.

It is worth mentioning some open source initiatives supporting the global research of CIS. The most widely used imaging platform is Sliced 3D (*http://slicer.org/*), offering full compatibility to common tools, such as VTK/ITK (*https://boreas.med.yale.edu/base*), IGSTK (*http://public.kitware.com/IGSTKWIKI/*) or MITK (*http://www.mitk.org/MITK*). CISST, a versatile tool for surgical robotics was developed at the *Johns Hopkins University* (*https://www.cisst.org/cisst*), and another one, PLUS at *Queens University* (*https://www.assembla.com/spaces/plus/wiki*). There is NA-MIC specifically for open source electromagnetic tracking (*http://www.na-mic.org/Wiki/index.php/Open Source Electromagnetic Trackers*).
Probably the most complete source of clinical information are *WebSurg* (*www.websurg.com*) virtual university run by the *European Institute of TeleSurgery* (EITS, Strasbourg, France), the *da Vinci Surgery* site (*www.davincisurgery.com*) and the *OR Live* (www.orlive.com). An aggregating site is the *All About Robotic Surgery* (*www.allaboutroboticsurgery.com*), the *MedGadget* internet journal (*www.medgadget.com*), the *ScienceRoll* (*scienceroll.com*) and some relevant blogs (e.g., *surgrob.blogspot.com*, managed by the author). For specific devices and systems, information brochures and teaching materials are available at the manufacturers' websites.

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