Chapter 4
Surgical Robotics: Innovations, Development, and Shortcomings

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Abstract Robotic devices have been used in the industrial field for over 40 years, while their introduction has been slower into the medical field with many requirements driven by the nature of human tissue and safety. These surgical assistance systems provide intelligent, versatile tools that augment a physician's ability to treat patients. Steerable robotic catheters may overcome many of the limitations of standard catheter technology, enhance target vessel cannulation, and reduce instrumentation, while improving overall physician performance. External robotics allows access to a body cavity through percutaneous ports with a high precision, high magnification manipulation of tissue. Robotics-driven imaging systems enhance dynamic data acquisition and provide high speed integration, facilitating image-guided navigation and augmenting other robotic systems. A lack of haptics remains a significant safety issue.

Keywords Computer-assisted interventional systems • Flexible robotics • Minimally invasive surgery • Surgical robotics • 3-D imaging

4.1 Introduction

Although industry has enjoyed the widespread application of robotics, the first case of surgical robotics was reported by Kwoh et al. in 1985 [1]. The robot was used to facilitate neurosurgical biopsies. Currently, some form of robotics is used in orthopedics, neurosurgery, gynecologic surgery, cardiothoracic surgery, urology, general,

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and vascular surgery. In great part the exponential increase in development and usage is based on current trends, with increasing emphasis on minimally invasive surgical techniques, and the widespread availability of 3-D imaging data.

Robotic devices have been used in the industrial field for over 40 years, and the requirements are obviously very different than those for the surgical domain, as are the safety mechanisms. In industry, safety precautions are in place to keep the robot away from people, whereas in medicine the robot is often physically coupled to the human operator. Therefore in general the high speeds or torques required in industry are undesirable attributes in surgery, although some exceptions do exist [2]. Medical robotics is motivated by desire to enhance effectiveness of a procedure by coupling information to action, in contrast to industrial robots, which are developed to automate dirty, dull, or dangerous tasks [3]. Unlike industrial robotics where the robot generally interacts with inanimate objects, in surgical robotics there is always the potential for injury to the patient's tissue, organs, etc… As surgeons we would therefore like to be able to have better haptics and visualization.

The significance is that surgeons need to have visualization beyond the skin's surface. Therefore, the ability to use this robotic technology and do so safely has in great part been achievable as a result of the enhancement of imaging techniques. Three-dimensional imaging techniques are widely available and provide reliable data, with which robotic navigation for surgical interventions can be performed with a high degree of confidence.

As efforts have been made to improve these robotic procedures, much emphasis has also been placed on the appearance of future operating rooms, as these operating theatres will have completely new requirements. Integrating the increasing number of surgical instruments, information systems, monitoring and imaging devices as well as communication networks, requires a significant financial commitment and is essential for its implementation [4].

It is well understood that medical care requires careful human judgment and reasoning in order to handle the uncertainty, variability, and complexity of cases. Therefore, medical actions are based on physician experience, general medical knowledge, and patient-specific data. This personalization of medicine and need for judgment and reasoning has driven the field of surgical robotics to focus on two key technological capabilities. First, computer-assisted interventional systems can acquire and display information to the physician in meaningful ways that enhance the physician's effectiveness. With the addition of robots, the information can influence how a particular procedure is performed, with the potential to improve the quality and consistency of the clinical result. Second, surgical assistance systems provide intelligent, versatile tools that augment the physician's ability to treat patients, such as eliminating hand tremor or enabling dexterous operation inside the patient's body. Regardless of the technology, the value of surgical robotic systems is measured in their ability (1) to treat otherwise untreatable conditions, (2) to reduce morbidity or error rates, (3) to shorten operative times, and (4) in the case of flexible (endovascular) robotics, reduce radiation exposure (Tables 4.1 and 4.2) [5].

Table 4.1 Advantages and disadvantages of conventional laparoscopic surgery and robot-assisted surgery using a master/slave device (adapted from Lanfranco AR et al. (2004) Ann Surg 239:14–21)

	Advantages	Disadvantages
Conventional laparoscopic surgery	Well-developed technology Affordable and ubiquitous Proven efficacy	Loss of touch sensation Loss of 3-D visualization Compromised dexterity Limited degrees of motion Fulcrum effect Amplification of physiologic tremors
Robot-assisted surgery	3-D visualization Improved dexterity Seven degrees of freedom Elimination of fulcrum effect Elimination of physiologic tremors Ability to scale motions Micro-anastomoses possible Tele-surgery possible Ergonomic position	Absence of touch sensation Expensive High start-up cost May require extra staff to operate New technology Unproven benefit Requires square footage (large)

Table 4.2 Advantages and disadvantages of robotic-assisted and conventional vascular catheterization

Human strengths	*Human limitations*
Strong hand-eye coordination	Limited dexterity outside natural scale
Dexterous	Prone to tremor and fatigue
Flexbile and adaptable	Limited geometric accuracy
Can integrate extensive and diverse information	Limited ability to use quantitative information
Rudimentary haptic abilities	Limited sterility
Able to use qualitative information	Susceptible to radiation and infection
Good judgment	
Easy to instruct and debrief	
Robot strengths	*Robot limitations*
Good geometric accuracy	No judgment
Stable and untiring	Unable to use qualitative information
Scale motion	Absence of haptic sensation
Can use diverse sensors in control	Expensive
May be sterilized	Technology in flux
Resistant to radiation and infection	More studies needed

4.2 Classification of Medical Robotics

Computer-assisted interventional systems are often referred to as surgical CAD/CAM, where pre-operative planning is implied by the CAD (computer aided design) acronym, and intervention is implied by the CAM (computer aided manufacturing) acronym. Surgical CAD/CAM systems are typically realized as a closed-loop process. First, using 3-D imaging data, a patient-specific model is constructed and an interventional plan is created. Second, the model and plan are registered to the patient. Third, technology (possibly robotics) is used to assist in carrying out the plan. Finally, the result is assessed.

Surgical assistance systems provide intelligent, versatile tools that augment the physician's ability to treat patients. For example, such systems may improve the existing sensing capabilities of the physician, or improve their manipulation. Alternately, the system may actually increase the number of sensors and manipulators available to the physician. Such capabilities may include improved visualization using X-ray, ultrasound, magnetic resonance imaging, or other techniques; reduction or elimination of hand tremor; and enabling dexterous operation inside the patients using minimally invasive techniques. The physician is typically provided one or more direct control interfaces such as joysticks, motion tracking, or voice recognition and control. Such systems can also include intelligence to reduce the cognitive workload on the physician and improve their attention.

Surgical CAD/CAM procedures are intimately bound to medical imaging, but the imaging modality used can be any of a number including ultrasound (US), magnetic resonance imaging (MRI), computed tomography (CT), or fluoroscopy. The procedures, which can drive this technology, include percutaneous/transcutaneous and intracavitary interventions, as well as neurosurgical and orthopedic procedures. One of the main limitations to these systems is that the robotic navigation needs to be coupled to the imaging system; therefore, it demands an imaging technique that can provide real-time feedback so that the intended target is reached. This becomes even more important when one considers the different demands of industry and medicine. Surgical interventions will inflict some tissue deformation, and how that feedback is provided to the robot is instrumental in the success of the robotic intervention.

The introduction of new skills and technology needs to be executed in a safe and systematic manner. This means that rather than introducing new techniques by a technology driven approach, one would like to see that new technology is introduced based on a disease-based approach where a broad based knowledge of the disease is founded at least in part upon the practice patterns of the surgeon, evidence for the support of the technology and the needs of the community [5, 6]. The advantages of minimally invasive surgery are obvious among surgeons, patients, and insurance carriers. Incisions are smaller, the risk of infection is less, hospital stays are shorter, if necessary at all, and convalescence is significantly reduced.

4.3 Flexible Robotics

Hansen Medical is the lead developer of robotic technology for accurate 3-dimensional control of catheter movement. This technology is currently being applied in cardiology, more specifically in electro-physiology, for cardiac ablation therapy in the treatment of aberrant cardiac rhythms. That is because this is the only application for which it is FDA approved. More recently, surgeons have used the Hansen robot (Fig. 4.1) to assist in the placement of endovascular grafts for exclusion of an abdominal aortic aneurysm, and in our own experience it has been able to facilitate placement of stents in the pulmonary circulation. Although these endografts are placed routinely without such advanced technology, surgeons are often presented with complex anatomy. This recent success speaks not only for its feasibility, but also its safety.

Fig. 4.1 The Sensei System and Artisan™ Control Catheter from Hansen Medical. ©2010 Hansen Medical, Inc. Used with permission

Fenestrated, branched grafts for exclusion of thoracoabdominal aneurysms have been shown to have satisfactory result [7, 8], but these grafts remain available only in select centers in the United States. Elsewhere, factors such as the inherent delay in manufacturing of fenestrated branched grafts, high degree of planning, and cost limit its widespread use. Riga et al. circumvented this limitation by performing robot-assisted antegrade in-situ fenestrated stent grafting using the Hansen Robotic system. The versatility of the Sensei robotic system, its accurate positional orientation, minimum instrumentation of the vessel wall, and the ability to reproducibly and precisely return to locations of interest during the procedure was found to be fundamental for success [9].

The advantage of a catheter, which can be guided with a high degree of safety and precision, opens the door for a multitude of applications in vascular surgery. One immediately thinks of procedures, which are today particularly challenging as current catheters surrender a tremendous amount of "pushability" and direction. Surgeons are often in the situation where a multitude of catheters are necessary to get to the site of the intended intervention. This is because diagnostic and interventional catheters are currently limited by the ability to simply rotate around one axis. Therefore, one depends on a variety of preformed catheters to fit the existing anatomy. As vascular anatomy is not uniform, catheters are often less than adequate, and therefore present a veritable challenge. This can potentially place a patient at risk, particularly in the arterial tree with degenerative atherosclerotic disease. Having a catheter with which the surgeon can control movement in multiple planes, would allow him/her to proceed through the arterial anatomy with greater precision, confidence and safety. As endograft and stent technology improves, so must our ability to deploy these devices. It is our opinion that flexible robotics will allow us to do just that. Robot-assisted surgery enables the surgeon to make fine, predictable and consistent movements. This ultimately increases procedural speed and reliability. More recently, Riga et al. described the effectiveness of this technology in an aneurysmal silicone model. Robotic catheterization of target vessels was found to be not only feasible, but also able to minimize radiation exposure for the operator. The conclusion is that steerable robotic catheters may overcome some of the limitations of standard catheter technology, enhance target vessel cannulation, reduce instrumentation, while improving overall performance scores [10].

4.4 Surgical Robotics

In 1995, Intuitive Surgical created the computer enhanced robotic system known today as the da Vinci Surgical System (Fig. 4.2). The goal of this device was to create familiar hand movements from open surgery all the while performing operations via a minimally invasive approach. This could effectively remove the difficulties that many surgeons experience using the laparoscopic technique. The system essentially has as its primary goal to enhance or extend the hands and eyes of the surgeon during the surgical procedure. The advent of robotics in cardiovascular surgery has suddenly made a technically challenging procedure practicable. This rationale is further supported by the development of EndoWrist (Intuitive Surgical, Inc., Sunnyvale, CA). EndoWrist is a form of telemanipulation which facilitates eye-hand coordination similar to the human brain, and provides dual-channel (3-dimensional) vision necessary for the more dexterous maneuvers required in creating vascular anastomoses [11]. The main drawback to the robotic device is lack of haptic feedback. That is, the da Vinci robot is not able to give the surgeon feedback as to the driving forces, hence tissue deformation etc. Essentiality, the surgeon learns by what is termed "visual tactility". Ultimately, sufficient training and perspective is what allows the surgeon to learn the concept of forces exerted. In 1999, Mohr and colleagues were already successful in performing five coronary artery bypasses and four mitral valve repairs using the da Vinci system [12]. During that same time Martinez and colleagues evaluated a voice-activated robotics system in a porcine model for total endolaparoscopic repair of the infrarenal aorta. In this animal model, grafts were successfully implanted in all 24 animals, although a conversion rate to mini-laparotomy of 10% was experienced. Further animal studies confirmed the benefits of robotics, and more specifically the da Vinci Surgical System, in that it was shown that the time required to perform an anastomosis, clamp time and total operative times were reduced [11, 13, 14].

Fig. 4.2 The Intuitive Surgical *da Vinci*® System

4.5 Robotic Imaging

The new Artis zeego® imaging system by Siemens (Fig. 4.3) is probably one of the best representations of how surgery and industry can convene. The application of this robotic system is for vascular, cardiac, neurological, etc., minimally invasive interventional procedures. The use of industrial robot technology in angiography systems and in general in the operating room is entirely new in medical engineering, as safety is a considerable issue due to high rotational speeds and large articulating parts which are in the proximity of a patient. This system allows the treating interventionalist or surgeon to visualize vessels and other pathology from all sides with exceptional precision. The advantage of combining a C-arm with a powerful industrial robot provides the physician with almost unlimited freedom of movement. The flat detector of this system rotates around the patient at such high velocity CT-like images are produced that gain more anatomical details than ever feasible before with an angiography system. Actually, the speed at which the device rotates around the patient is the rate-limiting step in further improving the image quality anatomic detail. For the safety of the patient, the speed is reduced and the quality

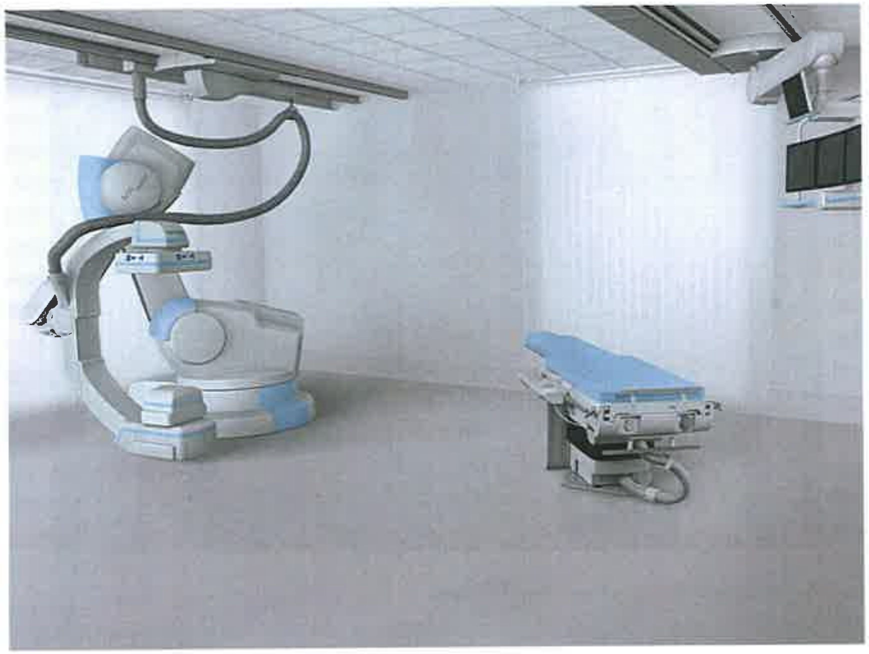

Fig. 4.3 The Siemens Artis zeego® system. Reprinted with permission. Images Courtesy of Siemens Healthcare

of the image is somewhat sacrificed, a constraint which is inevitable as industrial robots enter the medical field. The overall result of bringing this technology to the operating room is that is allows for intraoperative imaging, thereby obviating a need for a preoperative CT scan, which ultimately provides better care, higher accuracy, and less time so presumably less radiation exposure.

4.6 Technical Challenges

To further advance the field of surgical robotics, a number of technical challenges must be overcome. Advances are needed in the areas of manipulation, sensing, registration, user interfaces and visualization, system design, and new application areas such as simulation training and assessment. These robotic systems must operate safely in a workspace that is shared with humans, and must operate in a sterile environment. To maximize applicability of surgical robots, they must demonstrate high dexterity in small spaces, and further, it would be advantageous if they could operate in the proximity of an MRI scanner. Additional sensing would significantly advance the field. For example, internal sensors would enable greater feedback to the operator. External sensors must be able to adapt to unstructured and changing environments. Real-time imaging would be beneficial in that it would enable the

physician to see subsurface structures and understand and visualize tissue properties. Direct measurement of physiologic properties would further extend the capabilities of the physician to globally monitor the patient's status and react accordingly. To fully integrate 3-D imaging with robotics, geometric relationships between portions of the patient's anatomy, images, robots, sensors, and equipment must be clearly defined and known. A challenge is that non-rigid registration is often necessary, since many anatomical features change shape during a procedure. In terms of user interfaces and visualization, standard computer input devices are generally not appropriate for surgical environments since it is difficult to use them in proximity with other medical instrumentation while maintaining sterility. As a result, alternate input devices are employed, such as foot pedals, pendants, master manipulators, and graphical displays. These devices may compromise the ergonomics of the surgical suite and may be intrusive, and therefore new solutions are needed. System design is a key technical challenge since standards do not exist. A few open source tools for medical image visualization and processing are available, but many systems remain one-off prototypes existing only in research laboratories.

4.7 Conclusion

Robotic technology is set to revolutionize the manner with which cardiovascular surgery is performed. It has the potential to expand on current surgical treatment modalities beyond the limits of human ability and visualization. As we learn how to incorporate these machines in proximity to patients, all the while maintaining patients' safety, we will be able to treat patients in more minimally invasive manners. Some issues such as lack of haptics remain a significant safety issue, and would add another level of safety, when resolved. It remains to be seen whether or not the benefit of its usage overcomes its cost. Although feasibility has largely been shown, more prospective randomized trials evaluating efficacy and safety must be undertaken. Further research must evaluate cost effectiveness or a true benefit over conventional therapy for robotic surgery to take full root.

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Part III

Pumps and Flow