IMAGE-GUIDED ROBOTIC UROLOGIC INTERVENTIONS

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Abstract: Today's most successful surgical robots are perhaps surgeon-driven systems, such as the da Vinci (Intuitive Surgical Inc., USA, www.intuitivesurgical.com). These have already enabled surgery that was unattainable with classic instrumentation; however, at their present level of development, they have limited utility. The drawback of these systems is that they are independent self-contained units, and as such, they do not directly take advantage of patient data. The potential of these new surgical tools lies much further ahead. Integration with medical imaging and information are needed for these devices to achieve their true potential.

Many different robotic systems have been developed for invasive medical procedures. Surgical robots and especially their subclass of image-guided systems require special design, construction and control compared to industrial types, due to the special requirements of the medical and imaging environments. Imager compatibility raises significant engineering challenges for the development of robotic manipulators with respect to imager access, safety, ergonomics, and above all the non-interference with the functionality of the imager.

Keywords: medical robot, image-guided robot, MR compatible

1. INTRODUCTION

A robot is a mechanical device controlled by a computer. The first industrial robot was created by J. Engelberger and G. Deroe in 1961 and consisted of an articulated arm used in the automobile industry. The economic advantages, increased precision, and improved quality demonstrated by industrial robots stimulated the application of robots for health care delivery. The utilization of robots in surgery was pioneered in the 1980s in the fields of neurosurgery and orthopedic surgery [1]. Surgical robotics has since expanded to other surgical applications, including urology [2].

The development of surgical robots is highly demanding, compared to other fields, due to the enhanced safety, sterilization, compactness, operating-room (OR) requirements, compatibility with medical imaging equipment, and special ergonomics required. Testing and evaluation of surgical robots is a laborious process involving several nonclinical stages and endorsements before clinical assessment. Moreover, robotics for soft-tissue operations, such as the urologic systems, should adapt to the deformability and mobility of the operated organ. Although these difficulties delayed the evolution of surgical robotics until the late 1980s, recent research has allowed the development of several purpose-designed systems [3].

Over the past few decades technological advances have revolutionized the way we practice medicine. Today, medicine relies heavily on technical equipment and technology is evolving even more rapidly. The field of urology has a very rich tradition of embracing the use of advanced and pioneering technology to make existing procedures more tolerable and efficient as well as developing new treatment modalities. The advent of robotics in prostate surgery is a new horizon of this tradition. Urological medical robots are robots that are defined by three essential components: the manipulator, image acquisition device and a computer.

The surgical manipulator is an electromechanical arm equipped with sensors and actuators responsible for holding and precisely moving instruments under computer control. The most commonly employed kinematic architecture for surgical manipulators is the remote central of motion (RCM) concept [4], developed in 1995 at IBM [5]. This architecture, specific to surgical robots, aims to reproduce a surgeon's natural motion during laparoscopic surgery by allowing the manipulator to consistently enable and facilitate the pivoting of instruments about a fixed point in space during the surgical procedure; that is, the point where the laparoscopic instrument enters the body.

The image acquisition device allows the robot and surgeon to visualize the surgical environment and define the operating tasks of the robot. Different imaging modalities, such as magnetic resonance imaging (MRI), ultrasound, computed tomography (CT), infrared or video, are used to communicate the visual information. Manipulators that are controlled by the surgeon throughout the whole operating procedure may use video, infrared or ultrasound in combination to give the surgeon visual cues as to the position of the instruments. For example, the da Vinci Surgical System, a master-slave remote manipulator, in which the surgeon (master) remotely directs the robot (slave) through each task, uses stereo endoscopes to give the surgeon a 3D view of the region of surgery. The image acquisition aspect of a surgical robot becomes particularly important if the robot is to perform surgical tasks on its own. In this instance, the image modalities used must be of a very high resolution and accuracy, so that they are correctly interpreted by the image processing algorithms in the computer. For soft tissue surgeries, MRI is the imaging modality of choice, offering high-definition images that could easily be converted into 3D volumes to allow precise motion planning, trajectory following and target location. Alternatively, fluoroscopic markers can be inserted into a soft tissue to give the proper orientation cues, but that is more invasive to the patient and thus mainly used during testing procedures.

The third main component of the surgical robot, the computer, performs two main roles. Its primary role is as a coordinator, which translates the human operator's commands into specific actions performed by the robot manipulator. In doing so, the computer employs powerful algorithms that use the imaging data as a reference in order to guide the manipulator to an anatomical target specified by the surgeon. Thus, the computer is the link between the "data world" of medical information (images, sensors and databases) and the physical world of surgical actions [5]. The computer's secondary role is as a data recorder, recording the data relevant to the surgery, such as manipulator tracking and organ displacements. This data can then be used to update the intraoperative sequences of the surgery, via surgeon-assisted decision making.

Many classifications of robots can be found and depending on the specifics of the applications these can be rather numerous [4]. Robotic systems involved in urological surgical procedures, however, can be grouped in two main categories according to their mode of operation [5]. The first category is comprised of operator-driven manipulators, which exhibit low integration with the medical environment, and where the surgeon continuously controls the position of the robot and decides what task needs to be performed. These systems are designed primarily to scale a surgeon's movement, eliminate tremor and improve instrument accuracy. Endoscopic manipulators such as the Automatic Endoscopic System for Optimal Positioning (AESOP) and the ZEUS™, a surgical robotic system, master-slave remote manipulator, both built by Computer Motion (CA, USA), as well as the da Vinci master-slave manipulator, built by Intuitive Surgical (CA, USA) fall under this category.

The second category of urologic robotic systems consists of computer-integrated surgical systems for which the operator defines the task and the system accomplishes the task on its own. Such systems are image-driven and are made to excel at reaching a target specified by the surgeon. These systems are connected to a medical imager (ultrasound, fluoroscopy, CT, MRI, etc.) and allow the physician to control the intervention under image feedback. Special algorithms are used to drive the robots in the space of the image (robot to image registration and navigation). With these and other image-guidance methods, the robots become more autonomous in executing the task, which is defined and monitored by the physician. The progress of surgical robots is most likely to emerge from the image-guided field, because these systems augment information that is not commonly available. Moreover, unlike humans, robots and imagers are digital devices and may establish a digital platform for image-guided interventions.

Surgical robots should become elements of a complex information system especially designed to work in an operating room, an entire continuity of healthcare from pre-op planning, to image-guidance and intra-operative navigation, to post-op care and, nevertheless, follow-up [6]. Surgical robots should be components of computer-integrated surgical systems, information-to-action integrated biomedical systems. Intraoperative medical imaging is the richest informational component of these systems [7]. People used to think that eyes were good enough for surgery, but in fact they are limited to the visual spectrum. Tumors can look like healthy tissue to the naked eye, and even when visible, additional malignant tissue may be obstructed. As such, advanced imaging equipment should be incorporated.

Due to the technical challenges involved, image-guided robots are not yet as popular. However, several systems have been developed. Most of these apply to needle interventions, because needle procedures have a large area of utility, are relatively simple, and have the potential to significantly improve upon the traditional manual access. Percutaneous robotic interventions are particularly promising in the field of urology. The kidneys and the prostate are commonly accessed percutaneously for diagnosis and therapy and improved targeting has the potential to significantly improve the outcomes.

One of the main challenges of image-guided robots is that no imager is perfectly suited. The common ultrasound has relatively reduced imaging quality and its geometric consistency is not entirely reliable. X-ray fluoroscopy is also real-time, but is two-dimensional (2D) and its use is limited by the admissible radiation levels. The CT is a "disciplined" geometrically consistent imager, but only a few advanced models deliver real-time 3D images, and this is done at the expense of significant radiation. Finally, MRI based imagers are slow, notorious for their magnetism related restrictions, and impede direct access to the patient within the scanner for intervention purposes.

As such, the development of image-guided intervention (IGI) robots is a very challenging task. Special systems and methods need to be derived in order to take advantage of the imager's capabilities while accounting for their deficiencies and requirements and still satisfying the combined medical safety, sterility, and precision of the intervention.

A robot's compatibility with a medical imager refers to the ability of the robot to safely operate within the confined space of the imager while performing its clinical function, without interfering with the functionality of the imager [8]. The combination of imager compatibility and clinical requirements has been met with the development of customized systems for specific applications. Several urology examples of these dedicated robots that were developed in our laboratory are included in the following table and will be presented subsequently.

2. ROBOTIC ACCESS OF THE KIDNEY

One of the first robots to be specifically made for urology applications is PAKY (Percutaneous Access of the Kidney) [9], which was developed in our institution. PAKY is a very simple motorized needle driver that enables the active insertion of a needle.

Table 1: Several image-guided robots for urology

System	Status	Imaging Modality	Organ
PAKY-RCM	Animal Models, Human trials	Fluoroscopy and CT	Kidney
AcuBot	Mockup, Cadaver Studies, Animal models, Clinical trials	Fluoroscopy and CT	Kidney Prostate
MrBot	Mockup, Cadaver studies, Animal models	MRI	Prostate

The system helped in accessing the kidney for stone removal interventions, and has been used in numerous clinical cases [10]. In its second version, an automated orientation module was added, the RCM [6]. The entire system comprises 3 motorized degrees of freedom (DOF): translation allowing insertion of the needle and 2 rotations allowing orientation of the needle (Figure 1).

Fig. 1. PAKY-RCM system during fluoroscopy guided kidney intervention.

This is made of radiolucent materials so that the structure of the driver does not impede the visualization of the kidney. Several clinical studies were performed under fluoroscopy guidance and joystick control [11]. Intraoperative access variables (number of access attempts, time to successful access, estimated blood loss and complications) were recorded in a parallel blinded study of 46 patients who underwent either the robotic or standard manual procedure. The robot was successful in obtaining access in 87% (20 of 23) of cases. No statistically significant difference was found between the access variables in the two groups. This was expected because image-guidance was not used in controlling the robot, but it showed the feasibility of the robotic procedure and allowed for future image-guided developments. This robot was also successfully tested in telesurgical applications between our institution and several hospitals in Europe [12-15] and Brazil [16].

The true advantages of robotics are given by their ability to directly use the imaging information. In doing so however, special algorithms are required in order to coordinate the motion of the robot in the image space. Many groups have contributed to the development of these registration and image-guidance algorithms [17-19]. The photograph in Figure 2 shows a radio-frequency (RF) ablation performed under direct image guidance in the CT scanner [20].

Fig. 2. IGI RF kidney ablation using the PAKY-RCM robot in CT scanner.

An IGI robot with full mobility (6DOF) was also made in our laboratory for CT needle interventions, the *AcuBot* [21]. The robot mounts on the mobile table of the CT scanner, has a bridge like structure over the patient and its distal part is sufficiently small to fit with the patient in the bore of the scanner. The system was successfully used in several IGI cases for the kidneys and demonstrated outstanding targeting performance and reduced the radiation levels for the patient and medical personnel [20, 22]. The robot has also performed the first kidney ablations with CT preplanning of the ablation regions and robotic implementation of the plan [23].

3. ROBOTIC ACCESS OF THE PROSTATE

A new robot, MrBot [24] (Figure 3), has been recently developed at Hopkins for fully-automated image guided access of the prostate gland. The robot is customized for transperineal needle insertion and designed to be compatible with all known types of medical imaging equipment. This includes uncompromised compatibility with MRI scanners of the highest field strength, size accessibility within closed bore tunnel-shaped scanners, and clinical intervention safety. The robot is designed to accommodate various end-effectors for different percutaneous interventions such as biopsy, serum injections, or brachytherapy. The first end-effector developed is customized for fully-automated low dose radiation seed brachytherapy. For MR compatibility the robot is exclusively constructed of nonmagnetic and dielectric materials such as plastics, ceramics, and rubbers and is electricity-free. The system utilizes a new type of motors specifically designed for this application, the pneumatic step motors (PneuStep) [25]. These uniquely provide easily controllable precise and safe pneumatic actuation. Fiber optic encoding is used for feedback, so that all electric components are distally located outside the imager's room. Motion repeatability tests performed in the MRI scanner show mean errors of 0.076 mm.

Fig. 3. MR compatible robot developed for prostate brachyterapy.

The robot was found to be compatible with all types of imaging devices [25]. A linear PneuStep motor was tested in a small-bore high-strength magnet (7T). This showed very precise positioning accuracy of $27 \pm 4 \mu m$. No problems were encountered with the operation of the PneuStep motor in the 7T MRI environment, and no image deterioration or artifacts were observed due to the presence of the device at the isocenter or its motion during imaging. The clinical utility of the system remains to be investigated. We are currently evaluating needle insertion accuracy with in vitro and ex vivo experiments. The brachytherapy injector is very instrumental in performing these studies, because the injector can automatically deploy seed-like imaging markers. Robot precision is then estimated by comparing the actual and desired location of the deployed markers. For compatibility and minimal artifacts under MRI we use specially made ceramic markers. These do not resonate but the image clearly shows the displaced volume, very close to its real size. The robot and seed injector can perform fully automated seed deployment on any specified 3D pattern. Tests performed in agar showed an average seed deployment accuracy of 0.652 mm. Experiments continue now with other in vitro IGI studies. An animal protocol has already been filed and approved for in vivo studies. An institutional review board approval was also received for human trials on robot-scanner ergonomics. The system is presently in preclinical testing with cadaver and animal experiments, but tests show very promising results and clinical trials are expected to commence in the near future.

4. CONCLUSION

Considerable progress has been made in the field of image-guided robots, clinical trials have shown their utility, and a commercial IGI robot is already available for use in Europe. These robots differ considerably from surgeon-driven systems such as the da Vinci. In contrast IGI robots bring new dimensions to the typical vision based surgeries and diagnosis imaging. These also have more autonomous functions, which is not yet of artificial intelligence but base their motions on image feedback. The physician does not directly control the robot, but defines its tasks and monitors its actions based on the image. Clinical performance no longer depends on the physician’s 3D cognition and motor skills and lets him or her free to concentrate on the critical clinical aspects of the intervention. These new characteristics have the potential to improve upon the way that current procedures are done, and also allow for new advanced diagnostic and therapeutic methods to be developed. Image-guided robots are expected to bring a new generation of robots in medicine.

REFERENCES

1. Buckingham, R.A. and R.O. Buckingham, *Robots in operating theaters.* BMJ, 1995; 311:1479.
2. Stoianovici, D., *Robotic surgery.* World J Urol, 2000. **18**(4): p. 289-95.
3. Cadeddu, J.A., D. Stoianovici, and L.R. Kavoussi, *Robotics in urologic surgery.* Urology, 1997. **49**(4): p. 501-7.
4. Taylor, R.H. and D. Stoianovici, *Medical robotics in computer-integrated surgery.* IEEE Transactions on Robotics and Automation, 2003. **19**(5): p. 765-81.
5. Taylor, R.H., J. Funda, and D.D. Grossman, *Remote Center-of-Motion Robot for Surgery.* International Business Machines Corporation, NY, USA, 1995.
6. Satava, R.M., *The operating room of the future: observations and commentary.* Semin Laparosc Surg, 2003. **10**(3): p. 99-105.
7. Jolesz, F.A., *Neurosurgical suite of the future. II.* Neuroimaging Clin N Am, 2001. **11**(4): p. 581-92.
8. Stoianovici, D., *Multi-Imager Compatible Actuation Principles in Surgical Robotics.* International Journal of Medical Robotics and Computer Assisted Surgery, 2005. **1**(2): p. 86-100.
9. Stoianovici, D., et al. *An efficient needle injection technique and radiological guidance method for percutaneous procedures*. in *Computer Vision, Virtual Reality and Robotics in Medicine - Medical Robotics and Computer-Assisted Surgery (CVRMed-MRCAS'97).* 1997. Grenoble, France: Springer-Verlag.
10. Cadeddu, J.A., et al., *Stereotactic mechanical percutaneous renal access.* Journal of Urology, 1998. **159**(5): p. 56-56.
11. Su, L.M., et al., *Robotic percutaneous access to the kidney: comparison with standard manual access.* Journal of Endourology, 2002. **16**(7): p. 471-5.
12. Bove, P., et al., *Is telesurgery a new reality? Our experience with laparoscopic and percutaneous procedures.* Journal of Endourology, 2003. **17**(3): p. 137-42.
13. Challacombe, B., et al., *Technology insight: telementoring and telesurgery in urology.* Nature - Clinical Practice Urology, 2006. **3**(11): p. 611-617.
14. Patriciu, A., et al. *Robotic Telementoring/Telesurgical System and Randomized Evaluation Study*. in *Engineering in Medicine and Biology. Proceedings of the 27th Annual International Conference of the IEEE.* 2005. Shanghai, China: IEEE.
15. Frimberger, D., et al., *Telerobotic surgery between Baltimore and Munich [Telerobotische Chirurgie zwischen Baltimore und München].* Urologe A, 2002. **41**(5): p. 489-92.
16. Netto, R., N., Jr., et al., *Telementoring between Brazil and the United States: Initial Experience.* Journal of Endourology, 2003. **17**(4): p. 217-20.
17. Loser, M.N., N., *A New Robotic System for Visually Controlled Percutaneous Interventions under CT Fluoroscopy* in *Medical Image Computing and Computer-Assisted Intervention – MICCAI 2000*. 2000, Springer Berlin / Heidelberg. p. 887-896.
18. Patriciu, A., et al. *Automatic Targeting Method and Accuracy Study in Robot Assisted Needle Procedures*. in *Medical Image Computing and Computer-Assisted Intervention*. 2003. Toronto, Canada: Springer-Verlag.

19. Patriciu, A., et al. *Motion-based robotic instrument targeting under C-Arm fluoroscopy*. in *Medical Image Computing and Computer-Assisted Intervention*. 2000. Pittsburgh, PA: Springer-Verlag.
20. Solomon, S.B., et al., *Robotically Driven Interventions: A Method of Using CT Fluoroscopy without Radiation Exposure to the Physician.* Radiology, 2002. **225**(1): p. 277-82.
21. Stoianovici, D., et al., *AcuBot: A Robot for Radiological Interventions.* IEEE Transactions on Robotics and Automation, 2003. **19**(5): p. 926-30.
22. Solomon, S.B., et al., *Robotic guided placement of ablation probes for multiple overlapping ablations.* Journal of Vascular and Interventional Radiology, 2004. **15**: p. S191.
23. Solomon, S.B., A. Patriciu, and D. Stoianovici, *Tumor ablation treatment planning coupled to robotic implementation: a feasibility study.* Journal of Vascular and Interventional Radiology, 2006. **17**(5): p. 903-7.
24. Stoianovici, D., et al., *Multi-Imager Compatible Robot for Transperineal Percutaneous Prostate Access.* IEEE T-Ro, 2005.
25. Stoianovici, D., et al., *A New Type of Motor: Pneumatic Step Motor.* IEEE/ASME Transactions on Mechatronics, 2006: p. in press.