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Surgical and Interventional Robotics: Part II:

Surgical CAD-CAM Systems

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Medical robotics; image-guided surgery

A large family of medical interventions can be represented by a model that is analogous to industrial manufacturing systems. If the right information is available, they can be planned ahead of time and executed in a reasonably predictable manner. We, therefore, have classified them as surgical computer-aided design (CAD)–computer-aided manufacturing (CAM) systems, having three key concepts:

1. surgical CAD, in which medical images, anatomical atlases, and other information are combined preoperatively to model an individual patient; the computer then assists the surgeon in planning and optimizing an appropriate intervention
2. surgical CAM, in which real-time medical images and other sensor data are used to register the preoperative plan to the actual patient and the model and the plan are updated throughout the procedure; the physician performs the actual surgical procedure with the assistance of the computer, using appropriate technology (robotics, mechatronics, optical guidance, perceptual guidance, etc.) for the intervention
3. surgical total quality management (TQM), which reflects the important role that the computer can play in reducing surgical errors and in promoting more consistent and improved execution of procedures.

Successful procedures are also included in procedural statistical atlases and fed back into the system for pre- and intraoperative planning. This article, primarily concerned with robotics and mechatronics, concentrates on the surgical action (surgical CAM), although for the sake of completeness, major issues in surgical planning (surgical CAD) and postoperative data analysis (surgical TQM) are also included. This article is the second installment of a three-part series on surgical and interventional robotics.

Medical Imaging Devices

All stages of surgical CAD-CAM are inseparable from medical imaging, which necessitates a brief review of imaging modalities used with surgical CAD-CAM. Fluoroscopy produces a projective live X-ray image on a television screen. It is versatile, easy to use, widely available, and relatively affordable. Fluoroscopy's soft tissue resolution is poor, but it shows bony anatomy quite well. It lacks depth perception and exposes the patient and surgeon to radiation. Fluoroscopic images are often distorted by electromagnetic noise. Computed tomography (CT) is essentially a tissue density map produced by rotating an X-ray imager. CT has good soft

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tissue and excellent bone visualization, but unfortunately, it is not generally real time. Some newer units can produce coarse real-time images but at the expense of even higher X-ray doses. Ultrasound (US) scanners transmit sound waves to the tissue and detect the echoes that they compute into images. US scanning is inexpensive, nontoxic, safe, and portable. However, image quality is dependent on the operator's skill, and fidelity is diminished by speckle, shadowing, multiple reflections, and reverberations. Soft tissues are perpetually deformed under the probe's pressure. Among all imagers, US imager alone does not show the surgical tool before introducing it into patient's body. Magnetic resonance imaging (MRI) creates a strong (1.5–3 T) static magnetic field around the patient. During scanning, magnetic dipoles resident in the human tissue are disturbed by magnetic pulses, and relaxation times are measured with induction coils. Relaxation times are closely related to soft tissue properties, and as a result, MRI produces the finest soft tissue imaging among all current imagers. Unfortunately, MRI is very expensive, lack of space inside the magnet excludes direct access to the patient, and high magnetic fields make instrumentation very difficult.

Driving Clinical Application Areas

Percutaneous Needle-Based Interventions

Image-guided percutaneous (through the skin) needle placement interventions have become the standard of care in many procedures, such as biopsies, aspiration, or tissue ablations. Needles offer several obvious advantages over traditional surgery, including less scarring, lighter anesthesia, reduced postoperative pain, reduced complications, and faster discharge from the hospital. Freehand needle punctures typically include three decoupled tasks: 1) touch down with the needle tip on the skin entry point, which requires three-dimensional (3-D) Cartesian motion, 2) orient the needle by pivoting around the skin entry point, which requires two independent rotations about intersecting axes, and finally 3) insert the needle into the body along a straight trajectory, which requires one-dimensional translation, possibly combined with some drilling effect. Releasing the therapeutic payload (injection, deployment of implanted seeds or markers, etc.) or collecting tissue (firing biopsy guns, etc.) may require additional degrees of freedom (DoF). Needle-based surgeries can be exceedingly complex interventions, where translation, rotation motions, bending and insertion forces make up a delicate procedure. A variety of methods exist from handheld tools to point-and-click robotic systems, with the system's complexity depending on the capabilities of the image guidance used and the accuracy requirements of the application, usually about 1–2 mm. One of the typical surgical CAD-CAM applications is prostate brachytherapy, where 80–100 radioactive pellets of the size of a rice grain are implanted into the prostate to kill cancer by emitting ionizing radiation. Under transrectal US (TRUS) imaging, the implant needles are inserted through a pre-planned pattern of guide holes drilled in a template jig [26]. Robotic assistance lends itself naturally to image-guided needle placement. Following a flurry of initial activities, a few systems have actually entered clinical trials for TRUS-guided prostate brachytherapy [6] (Figure 1) and CT-guided (Figure 2) and MRI-guided abdominal biopsies [4].

Transcutaneous Interventions

Transcutaneous interventions are truly noninvasive, as they do not require surgical access. External beam radiation therapy (EBRT) is delivered by high-energy X-ray beams generated using a linear accelerator (linac), irradiating the patient from several directions. Based on a CT scan, the treatment is carefully planned and simulated (surgical CAM). Generally, the EBRT dose is fractionated and spread out over several weeks to give normal cells time to recover, thereby demanding precise positioning of the patient before (and also during) each treatment fraction under the X-ray beam. EBRT delivery was among the first medical robot applications. Typically, the linac is placed on a large counterbalanced gantry that rotates around the patient lying on the couch. The couch has 3-DoF prismatic motion and 1-DoF rotation (recently, 3

DoF is used most often), where the axes of the gantry and couch rotations intersect in a single isocenter where the X-ray beam is aimed. Following the publicized Therac-25 accident [15], EBRT regulations were extremely conservative until the late 1990s. For example, no parameter other than gantry rotation was permitted to change while the beam was on. Nowadays, coach and gantry can move simultaneously while the beam is being collimated in real time by dozens of small shutters driven by separate stepper motors, in a process called intensity-modulated radiation therapy (IMRT). Modern treatment planning systems prescribe full four-dimensional motion sequences for the linac, couch, and beam collimator controller. At Stanford University, Adler et al. mounted a low-energy linac on a serial industrial robot. This system, available commercially under the name CyberKnife, specializes in precision treatment of tumors of the central nervous system [9].

In high-intensity focused US (HIFU) imaging, acoustic waves travel through the tissue, while part of them is absorbed and converted to heat. By focusing the beam, a precise zone of cell death can be achieved deep in tissue. Ideally, the HIFU unit is integrated with the image-guidance tool, such as MRI in [12] (Figure 3). First, the patient is scanned, and a precise sonification plan is created. During treatment, the temperature is monitored in real-time MRI. When the thermal dose reaches the prescribed level, sonification stops and the system moves to making the next lesion. Finally, a volume scan confirms the ablation zone, and additional sonification is used to patch up cold spots. Another HIFU variant is the Sonablate (Focus Surgery, Inc.) used for transrectal ablation of benign prostate enlargement.

Intracavity Interventions

Interventions may be performed from within naturally accessible cavities of the body, such as the rectum, vagina, or cervix. (Interactive surgical assistant robots have been developed recently for surgeries in the nasal cavity and the throat, to be discussed in Part III of this tutorial series.) The most prevalent intracavity intervention today is core needle prostate biopsy performed through the rectum under TRUS guidance, where a spring-loaded biopsy gun is inserted into the prostate gland through a guide sleeve rigidly attached to the TRUS probe. Two inexhaustible sources of problems are found: 1) the prostate gland is under constantly varying deformation and dislocation during the procedure and 2) TRUS imaging provides poor imaging of prostatic tissues. TRUS-guided biopsy has poor sensitivity, and cancers as large as a sugar cube are routinely missed, a fundamental flaw that propelled MRI guidance to the attention of prostate cancer research. With a 3-DoF pseudorobotic device actuated manually by torsion cables, Krieger et al. performed accurate transrectal needle biopsies and implants in more than 50 patients using closed high-field MRI scanners [13]. Others proposed to make MRI-based targeting more affordable by real-time fusion of TRUS imaging and prior MRI (e.g., [30]).

Neurosurgery

Neurosurgery was one of the first clinical applications of surgical CAD-CAM, first with passive tool positioning devices (e.g., [2], [27]) and later with active robots (e.g., [14], [16]). The entry and target points are planned on CT or MR images, the robot coordinate system is registered to the image coordinate system (typically with fiducials affixed to the patient’s head), and then, the robot positions a needle or drill guide (Figure 4). The fiducial structure may be a conventional stereotactic head frame, or, as in the Neuromate system, registration was achieved by simultaneous tracking of the robot and fiducials attached to the patient’s skull [16].

Orthopedic Surgery

Orthopedic surgery is also a natural surgical CAD-CAM application. Bone is rigid and is easily imaged in CT and fluoroscopy, and surgeons are accustomed to doing preplanning based on these images. Geometric accuracy in executing surgical plans is very important. Spine surgery often requires screws and other hardware to be placed into vertebrae without damage to the spinal cord, nerves, and nearby blood vessels. In osteotomies, accurate cutting and placement of bone fragments are mandatory. Similarly, in joint replacement surgery, bones must be shaped accurately to ensure proper fit and positioning of components. The ROBODOC system [25] (described in Part I of this series [31]) represents the first clinically applied robot for joint reconstruction surgery in hip and knee replacement surgeries. In the surgical CAD phase, the surgeon interactively selects the desired prostheses and specifies their positions in preoperative CT images. In the surgical CAM phase, the robot is moved up to the operating table, the patient's bones are attached rigidly to the robot's base, and the robot is registered to the CT images by the use of either implanted fiducial pins or a 3-D digitizer to match bone surfaces to the CT images. After registration and initial positioning, the robot autonomously machines the desired shape with a high-speed rotary cutter while the surgeon monitors progress. Subsequently, other robotic systems for joint replacement surgery have been investigated, including the hands-on guided Acrobot system [11] for knee surgery or various small robots that attach directly to the patient's bones (e.g., [3], [21], [22], [29]).

Point and Click Surgery

Surgical CAD: Intervention Planning

During the surgical CAD phase, the preoperative images are processed, and a computational model of the patient is created and interactively visualized for the surgeon. Often multiple imaging modalities are fused. Based on this patient-specific model, a surgical plan is created. The plan can be as simple as entry and target points for a biopsy, but it may be as delicately complex as an IMRT plan described earlier in the "Transcutaneous Interventions" section. Next, the physician simulates the surgery by performing a virtual dry run, like a computer game. For example, Figure 2(b) shows a screen from a simulation of robot-assisted spinal needle placement, with detailed 3-D rendering of the anatomy and a visual representation of the moving robot. In this case, for clinically more realistic planning, the robot was placed in the CT scanner with the patient during imaging. The robot was registered to CT image space with the fiducial frame attached to the end effector. In other applications, such as EBRT or brachytherapy, various approaches are tried out before converging on the optimal plan that envelops the target in the prescribed therapeutic dose while sparing the healthy tissues from collateral damage.

Linking CAD and CAM: Registration

Geometric relationships are fundamental to surgical CAD-CAM, and the registration of actors (robots, sensors, images, and the patient) is a perennial issue (e.g., [20], [23]).

As the final goal of registration is to determine the position of a surgical tool relative to the pathology targeted for intervention, it is desirable to perform the registration based on the image itself. One of the first uses of image-based registration was stereotactic neurosurgery [2], where a precision-machined a priori known rigid fixture (fiducial frame) was secured to the patient's head. After segmenting marks of the fiducial frame in CT, the transformation between the fiducial frame and image space was calculated. Since its initial introduction three decades ago, fiducial frames have taken the shape of helices, ellipses, lines, points, and endless combinations of these. Fiducial frames have appeared on the patient [Figure 4(a)], on end effectors of surgical robots [Figures 2(a) and 4(a)], and on surgical tools, and they have been used with all imaging modalities.

When a fiducial frame is not applicable, free fiducials are used in a more or less arbitrary constellation. Fiducials may be attached to the patient's skin (e.g., needle placement procedures), drilled in the patient's bone (e.g., orthopedic surgery, stereotactic neurosurgery), or locked in internal organs (e.g., clamps in breast surgery). In some cases, anatomical landmarks are picked as free fiducials. Intuitively, free fiducials are significantly less accurate and robust than precision machined fiducial frames, especially when the markers move relative to one another between planning and surgery.

When image-based registration is not practical or possible, external localization is applied. Typical external localizers are electromechanical, optical, electromagnetic, or ultrasonic, each with different pros and cons [20]. In some cases, optical lasers are used for indirect registration. For example, in EBRT setup, carefully calibrated laser lines mark the linac's isocenter. On typical CT and MRI scanners, transverse and parasagittal laser planes are available to align the patient and surgical tools. Lasers are usually used with bare eyesight or in combination with computational methods (e.g., [7], [19].)

Registration error analysis and prediction of the distribution of error over the region of interest have sizable literature to aid the developer in placing fiducials and tracking devices in the surgical scene. Generally, we are concerned with three metrics of registration performance: accuracy, consistency, and robustness, and, they are often at odds with one another. It may be counterintuitive but nonetheless true that accuracy is the least important of the three. Generally, surgeons can compensate for inaccuracies as long as the registration is robust and the error is consistent.

Surgical Augmentation Techniques

Robotic Assistant Devices—The mechanical design of a surgical CAD-CAM robot depends crucially on its intended application. (A comprehensive review of design principles and the state of the art is available in [23] and [24].) For example, robots with high precision, stiffness, and (possibly) limited dexterity are often suitable for orthopedic bone shaping or stereotactic needle placement, and medical robots have been developed for these applications (e.g., [16], [11], [21]). Other robots for needle placement surgeries in soft tissues require compactness, dexterity, and responsiveness. These systems (e.g., [4], [6], [17]) frequently have relatively high-speed, low-stiffness, and highly back-drivable mechanisms. Many medical robots (e.g., [9], [11]) were essentially modified industrial robots. This approach has many advantages, including low cost, high reliability, and shortened development times. If suitable modifications are made to ensure safety and sterility, such systems can be very successful clinically, and they can also be invaluable for rapid prototyping for research use. However, the specialized requirements of surgical applications have tended to encourage more specialized designs. One example is mechanically constrained motion of the surgical tool to rotate about a remote center of motion (RCM) distal to the robot's structure. In surgery, the robot is positioned so that the RCM point coincides with the entry point into the patient's body. This approach has been used by numerous research groups, using a variety of kinematic designs (e.g., [4]). Although most surgical robots are mounted to the surgical table, to the operating room ceiling, or to the floor, there has been some interest in developing systems that directly attach to the patient (e.g., [3], [21], [22], [29]), so the robot is stationary if the patient moves. Mechatronic and robotic systems intended for use in specific imaging environments pose additional design challenges. First, there is the geometric constraint that the robot (or at least its end effector) must fit within the scanner along with the patient. Second, the robot's mechanical structure and actuators must not interfere with the image formation process, and the constraints for MRI are especially difficult (e.g., some examples in [4]). A perennially difficult issue is mounting robots inside imaging scanners. Standard clinical equipment is not designed to receive auxiliary structures, and their physical modification annuls the warranty. The most severe restrictions apply to the X-ray imagers with which integration of any sort is specifically forbidden.

Passive and Semiautonomous Devices for Needle Placement—A few researchers have proposed the use of passive, encoded manipulator arms for image-guided needle placement. After a registration step, these systems track the position and orientation of a passive needle guide and display the corresponding needle path in real time on CT or MR images. Semiautonomous systems allow remote, interactive image-guided placement of the biopsy tool. For example, Krieger et al. performed transrectal prostate interventions in a closed MRI environment [13]. The device is driven from outside the bore with torsion cables, while the needle driver is tracked in the MRI system with active coils and monitored using an interactive graphical interface.

Freehand Surgical Navigation Systems—In tracked surgical navigation systems, the positions of instruments relative to the reference markers on the patient are tracked using specialized electromechanical, optical, electromagnetic, or sonic digitizers or by more general computer vision techniques [20]. After the relationships among the key coordinate systems (patient anatomy, images, surgical tools, etc.) are determined through a registration process (explained previously), a computer workstation provides graphical feedback to the surgeon to assist in performing the planned task, usually by displaying the instrument positions relative to medical images. The main advantages of tracked surgical navigation systems are their versatility, their relative simplicity, and their ability to exploit the surgeon's natural dexterity and haptic sensitivity. Surgical navigation systems are achieving increasing acceptance in such fields as neurosurgery; ear, nose, and throat surgery; and orthopedics.

External tracking is superfluous in applications such as in most CT- or MRI-guided superficial needle placements (e.g., spinal nerve blocks and facet joint injections), where skin markers are used to locate the exact entry point, the scanner's alignment laser is used to control needle direction, and markers on the needle are used to control depth. In fluoroscopy, the typical procedure is to align the X-ray system so that it looks directly along the desired needle path, place the needle and stand it up so that its X-ray image is a dot, turn the X-ray system to look from the side, and insert the needle until it reaches the target. In US imaging, the primary reliance is on surgeon experience or the use of a needle guide attached to the probe in the plane of imaging. A variety of handheld mechanical guides have been tried out for use with all common image modalities. Computer-aimed laser guidance and augmented reality optical systems (e.g., [7]) have also been also proposed.

Adaptive Surgical CAD-CAM

Patient and Tool Tracking

Few issues are more important than tracking the anatomical target and surgical tool relative to one another, but this problem is still largely unsolved. Most current imaging modalities, except fluoroscopy, were originally designed for diagnostic imaging and thus are suboptimal for tracking the surgical tools and the anatomy. First, real-time image feedback is seldom available. With X-ray modalities, real-time imaging is not practical because of high doses. Commercial MRI installations do not allow sending imaging requests to the scanner, other than manual commands from the operator console. (Companies sometimes offer privileged access to research groups to the MRI scanner's internal application programming interface under research agreement.) Recently, open-architecture US scanners have appeared, permitting unfettered access to the beam former, thereby opening the way for real-time quantitative image guidance. For the first time, RF US image data can be utilized in the analysis of spectra and biological tissue speckle. Thus, in most applications, we are relegated to intermittent imaging and suffer from the fact that between two snapshots the anatomy and tool may have moved beyond the capture range of tracking. For example, target tracking has been a fundamental problem in EBRT delivery, where onboard X-ray imagers cannot show soft tissues, so surrogates are applied. One method is to implant radiopaque markers in the target and track those using X-ray image. One of the new exciting techniques is implanting active radar beacons (Calypso system by Calypso Medical Systems, Seattle, WA), which broadcasts a live homing signal for the couch controller to reposition the patient under the beam. On the negative side, implanted markers need some degree of surgery to get into the body in the first place, but this may be affordable in EBRT where regimens are spread into 25–40 fractions over several weeks. As a noninvasive option in EBRT, US imager can augment the linac's onboard X-ray imagers, but unfortunately therapists are usually not sufficiently trained in the acquisition and interpretation of US images. Other noninvasive methods include tracking of skin fiducials with optical localizers and various forms of respiratory gating, which are generally helpful but not quite accurate or reliable. In lieu of true image-based tracking, one must resort to surrogates. Surgical tools are often tracked externally (with optical or electromagnetic sensors), from which the tool tip can be predicted with reasonable accuracy, and some researchers track the tool tip with in-built electromagnetic sensors. Driven by the specific needs of image-guided surgery, some manufacturers started offering real-time tracking devices for navigation inside MRI scanners (e.g., EndoScout by Robin Medical, Inc.). In summary, intraoperative patient and tool tracking, combined with controlling the treatment delivery mechanisms (robots), is a problem-rich research area in which major breakthroughs are needed.

Tool Steering

Needles are widely used in surgical CAD-CAM procedures (see the "Percutaneous Needle-Based Interventions" section). Although classic needles have the advantage of being very minimally invasive, they have two major problems: 1) they may deviate slightly from the desired path and thus miss the target and 2) they cannot reach targets inaccessible by straight (or close to straight) paths. Surgeons and interventional radiologists have long known that needles could be steered by hand, but methods for optimizing this technique have only recently been developed. New results in needle and tissue modeling, robot motion planning, and image-based control, as well as the design of specialized devices, have enabled steering of needles inside soft tissue, which improves targeting accuracy and avoids delicate areas or impenetrable anatomic structures.

There are two primary methods for steering needles: using the needle to manipulate the tissue and using the tissue to manipulate the needle. In the former method, significant forces are applied to the base of needles that are stiff relative to the tissue. This causes the tissue to deform, so that the needle's insertion direction is changed relative to obstacles or targets within the tissue (e.g., [5], [8]). In the latter method, needles have a lower structural stiffness than that of the tissue, and an asymmetric bevel tip or prebent tip causes the needle to bend when it is inserted into tissue. By pushing the needle forward from the outside and spinning it around its main axis, a robot can control the needle to acquire targets in a 3-D space with minimal trauma to the tissue, while avoiding obstacles as shown in Figure 5 (e.g., [18], [28]). In both methods, path planning should be used to determine the optimal insertion point and the sequence of the forces and torques (or velocities) applied to the needle base to both reach the target and avoid any obstacles along the way. The plan can be updated as the procedure progresses. The actual needle path for a given set of inputs is highly dependent on the tissue and needle properties, as well as the mechanics of their interaction [1]. Since patient-specific tissue models are difficult to acquire, real-time image-based control is essential to achieve the desired paths.

Process Monitoring and Plan Optimization

There are hardly any surgical CAD-CAM applications, except perhaps intracranial EBRT and some orthopedic surgeries, where the target anatomy is guaranteed not to deform or change between planning and execution. As the surgery progresses, deviations from the original plan are inevitable. As a result, certain aspects of the surgical plan, such as target location, tool trajectory, or therapeutic dose, need reoptimization before and/or during surgery. Some trivially occurring problems are patient motion, tissue deformation, and target dislocation, the detection and tracking of which we discussed in the previous section. In the simplest cases, such as biopsies, the surgical plan is essentially an ordered list of targets and preferred tool trajectories, and these can be more or less automatically updated if the target and tool are tracked (which, as we saw, is a significant problem in itself). The situation is more complicated when the clinical goal is to deliver some therapeutic dose over a prescribed target volume, such as radioactive seeds in the prostate or thermal dose to ablate a liver or kidney tumor. Here, the spatial and temporal accumulation of dose must be monitored and the plan reoptimized accordingly. This, in turn, increases the demand for sensitive, accurate, and fast intraoperative imaging techniques, as well as smart surgical instruments that incorporate physiological biosensors in the tooltip. Some current imaging modalities are capable of biological process monitoring, e.g., MRI can visualize tissue temperature [12] and both MRI and US imaging can show changes in tissue elasticity, but the present signal methodologies are not nearly sufficient to make use of these capabilities. Often, multiple spatially and temporally coregistered imaging modalities are needed for guiding and monitoring the surgery. For example, in prostate brachytherapy, a TRUS scanner visualizes the prostate, and a fluoroscope can show the implanted seeds [10]. Such a scenario, however, complicates the clinical workflow and increases procedure time and costs.

Future Directions

Regarding surgical CAM, the phase that most closely relates to robotics, a number of areas of future research can be identified.

- Highly dexterous and compact surgical robots that carry the surgical device inside the fields of intraoperative imaging devices, which need to be multipurpose, independent of imagers, and deployable in various clinical applications with minimum adjustment
- Robust registration and tracking of the surgical robot to the medical imager and the patient
- Steering and more dexterous manipulation of the tooltip based on imaging feedback to account for motion and tissue deformation
- Real-time target tracking and stabilization of instruments
- Smart end effectors combined with biosensors to detect biomechanical (stiffness), physiological (bleeding, edema, oxygenation), and morphological/pathological characteristics of tissues around the tooltip
- Building medical imaging devices with the resolution and accuracy of control required for interactions in the millimeter range and ultimately in the submillimeter range.

Effective surgical CAM requires that we integrate imaging and tracking devices into the robotic end effectors or surgical tools themselves to physically couple image and device coordinate frames, thus eliminating the traditionally greatest source of inaccuracy and operational hazard. The ultimate goal is local imaging, local guidance, and local actuation, all in one device.

As the capabilities of systems continue to evolve, the use of computer systems to model dynamically changing patient-specific anatomy will become more important. A diverse research community in medical image computing is addressing a broad range of research topics, including the creation of patient-specific models from medical images, techniques for updating these models based upon real-time image and other sensor data, and the use of these models for planning and monitoring of surgical procedures. As computing power and in-room imaging techniques improve, the planning and action come closer to each other, transforming the classic sequential paradigm to adaptive surgical CAD-CAM.

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Gabor Fichtinger received his B.S. and M.S. degrees in electrical engineering and his Ph.D. degree in computer science from the Technical University of Budapest, Hungary, in 1986, 1988, and 1990, respectively. He has developed image-guided surgical interventional systems. He specializes in robot-assisted image-guided needle-placement procedures, primarily for cancer diagnosis and therapy. He is an associate professor of computer science, electrical engineering, mechanical engineering, and surgery at Queen’s University, Canada, with adjunct appointments at the Johns Hopkins University.

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References

1. Abolhassani N, Patel R, Moallem M. Needle insertion into soft tissue: A survey. Med Eng Phys 2007;29 (4):413–431. [PubMed: 16938481]
2. Brown RA, Roberts TS, Osborne AG. Stereotaxic frame and computer software for CT-directed neurosurgical localization. Invest Radiol 1980;15(4):308–312. [PubMed: 7009485]
3. Chung JH, Ko SY, Kwon DS, Lee JJ, Yoon YS, Won CH. Robot-assisted femoral stem implantation using an intra-medulla gauge. IEEE Trans Robot Automat Oct;2003 19(5):885–892.
4. Cleary K, Melzer A, Watson V, Kronreif G, Stoianovici D. Interventional robotic systems: applications and technology state-of-the-art. Minim Invasive Ther Allied Technol 2006;15(2):101–113. [PubMed: 16754193]
5. DiMaio SP, Salcudean SE. Needle steering and motion planning in soft tissues. IEEE Trans Biomed Eng June;2005 52(6):965–974. [PubMed: 15977726]
6. Fichtinger G, Fiene J, Kennedy C, Iordachita I, Kronreif G, Song DY, Burdette EC, Kazanzides P. Robotic assistance for ultrasound guided prostate brachytherapy. Med Image Anal. to be published
7. Fischer GS, Deguet A, Schlattman D, Fayad L, Zinreich SJ, Taylor RH, Fichtinger G. Image overlay guidance for MRI arthrography needle insertion. Comput Aided Surg Jan;2007 12(1):2–14. [PubMed: 17364654]
8. Glozman D, Shoham M. Image-guided robotic flexible needle steering. IEEE Trans Robot June;2007 23(3):459–467.
9. Hara W, Soltys SG, Gibbs IC. CyberKnife robotic radiosurgery system for tumor treatment. Expert Rev Anticancer Ther Nov;2007 7(11):1507–1515. [PubMed: 18020920]
10. Jain A, Deguet A, Iordachita I, Chintalapani G, Blevins J, Le Y, Armour E, Burdette C, Song D, Fichtinger G. Intra-operative 3D guidance in prostate brachytherapy using a non-isocentric C-arm. Med Image Comput Comput Assist Interv Int Conf Med Image Comput Comput Assist Interv 2007;10(2):9–17. [PubMed: 18044547]
11. Jakopec M, Harris SJ, Baena FRy, Gomes P, Cobb J, Davies BL. The first clinical application of a hands-on robotic knee surgery system. Comput Aided Surg 2001;6(6):329–339. [PubMed: 11954064]
12. Jolesz FA, McDannold N. Current status and future potential of MRI-guided focused ultrasound surgery. J Magn Reson Imaging Feb;2008 27(2):391–399. [PubMed: 18219674]
13. Krieger A, Susil RC, Menard C, Coleman JA, Fichtinger G, Atalar E, Whitcomb LL. Design of a novel MRI compatible manipulator for image guided prostate intervention. IEEE Trans Biomed Eng Feb;2005 52(2):306–313. [PubMed: 15709668]

14. Kwoh YS, Hou J, Jonckheere EA, Hayati S. A robot with improved absolute positioning accuracy for CT guided stereotactic brain surgery. IEEE Trans Biomed Eng 1988;35(2):153–161. [PubMed: 3280462]
15. Leveson NG, Turner CS. An investigation of the Therac-25 accidents. IEEE Computer July;1993 26 (7):18–41.
16. Li Q, Zamorano L, Pandya A, Perez R, Gong J, Diaz F. The application accuracy of the NeuroMate robot—A quantitative comparison with frameless and frame-based surgical localization systems. Comput Assist Surg 2002;7(2):90–98.
17. Masamune K, Fichtinger G, Patriciu A, Susil RC, Taylor RH, Kavoussi LR, Anderson JH, Sakuma I, Dohi T, Stoianovici D. System for robotically assisted percutaneous procedures with computed tomography guidance. J Comput Aided Surg 2001;6(6):370–383.
18. Okazawa S, Ebrahimi R, Chuang J, Salcudean SE, Rohling R. Hand-held steerable needle device. IEEE/ASME Trans Mechatron June;2005 10(3):285–296.
19. Patriciu A, Solomon SB, Kavoussi LR, Stoianovici D. Robotic kidney and spine percutaneous procedures using a new laser-based CT registration method. Proc MICCAI 2001 :249–257.
20. Peters, T.; Cleary, KR. Image-Guided Interventions: Technology and Applications. Berlin: Springer-Verlag; 2008.
21. Plaskos C, Cinquin P, Lavallee S, Hodgson AJ. Praxiteles: A miniature bone-mounted robot for minimal access total knee arthroplasty. Int J Med Robot Comput Assist Surg 2005;1(4):67–79.
22. Shoham M, Burman M, Zehavi E, Joskowicz L, Batkilin E, Kunicher Y. Bone-mounted miniature robot for surgical procedures: Concept and clinical applications. IEEE Trans Robot Automat 2003;19 (5):893–901.
23. Taylor, RH.; Menciassi, A.; Fichtinger, G.; Dario, P. Medical robots and systems. In: Siciliano, B.; Khatib, O., editors. Springer Handbook of Robotics. Vol. ch 52. Berlin: Springer-Verlag; 2008.
24. Taylor RH, Stoianovici D. Medical robotics in computer-integrated surgery. IEEE Trans Robot Automat 2003;19(5):765–781.
25. Taylor RH, Paul HA, Kazanzides P, Mittelstadt BD, Hanson W, Zuhars JF, Williamson B, Musits BL, Glassman E, Bargar WL. An image-directed robotic system for precise orthopaedic surgery. IEEE Trans Robot Automat 1994;10(3):261–275.
26. Wallner, K.; Blasko, JC.; Dattoli, M. Prostate Brachytherapy Made Complicated. Vol. 2. Seattle, WA: SmartMedicine; 2001.
27. Watanabe E, Watanabe T, Manka S, Mayanagi Y, Takakura K. Three-dimensional digitizer (neuronavigator): New equipment for computed tomography-guided stereotaxic surgery. Surg Neurol 1987;27(6):543–547. [PubMed: 3554569]
28. Webster RJ III, Kim JS, Cowan NJ, Chirikjian GS, Okamura AM. Nonholonomic modeling of needle steering. Int J Robot Res May–June;2006 25(5–6):509–525.
29. Wolf A, Jaramaz B, Lisien B, DiGioia AM. MBARS: mini bone-attached robotic system for joint arthroplasty. Int J Med Robot Comput Assist Surg Jan;2005 1(2):101–121.
30. Xu S, Kruecker J, Guion P, Glossop N, Neeman Z, Choyke P, Singh AK, Wood BJ. Closed-loop control in fused MR-TRUS image-guided prostate biopsy. Med Image Comput Comput Assist Interv Int Conf Med Image Comput Comput Assist Interv 2007;10(1):128–135. [PubMed: 18051052]
31. Kazanzides P, Fichtinger G, Hager GD, Okamura AM, Whitcomb LL, Taylor RH. Surgical and interventional robotics—Core concepts, technology, and design. IEEE Robot Automat Mag June; 2008 15(2):122–130.

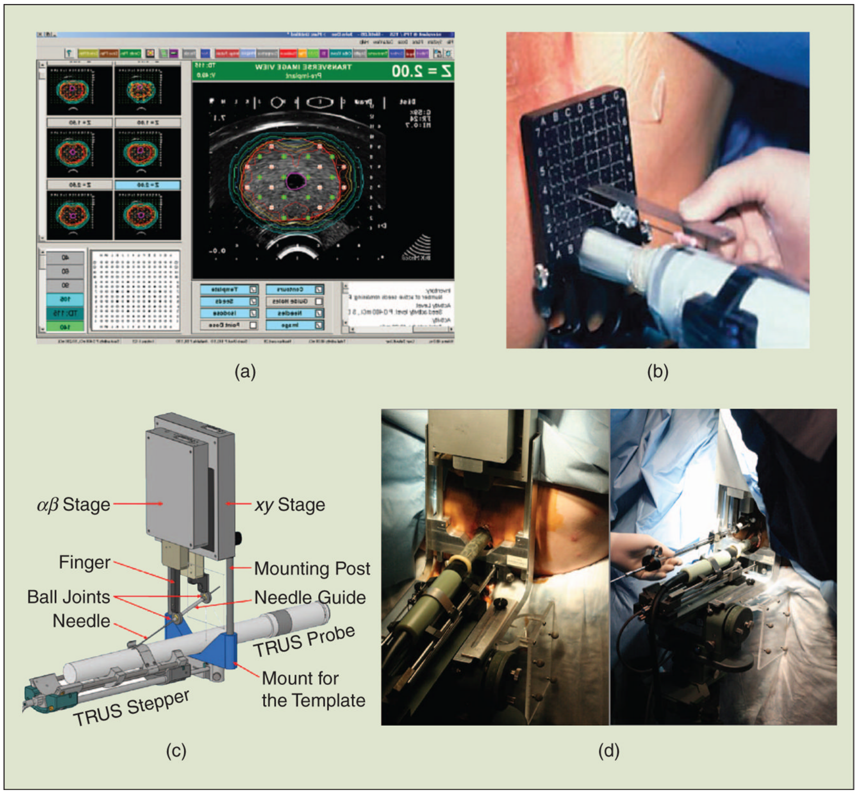

Figure 1.
Transrectal prostate brachytherapy [6]. (a) Implant and dose planning. (b) Classic manual needle placement under with template jig mounted over the TRUS probe. (c) Robotic needle positioner that replaces the template jig. (d) Patient treated with the robotic system. [Images courtesy of Everette C. Burdette (Acoustic MedSystems), Gabor Fichtinger, Danny Y. Song, and Peter Kazanzides (Johns Hopkins University).]

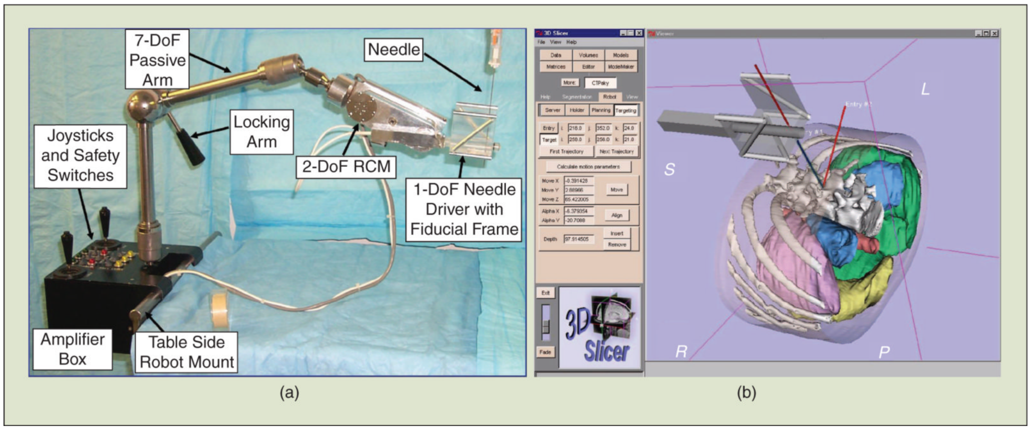

Figure 2.
System for CT-guided needle placement [17]. (a) 3-DoF remote center of motion robot is applied. The needle driver incorporates a stereotactic fiducial frame for image-based registration. (b) Screen shot of planning a spinal nerve root block, showing 3-D view of the reconstructed anatomy, end effector, and optimal needle path. [Images courtesy of Ken Masamune, Dan Stoianovici, Attila Tanacs, Russell H. Taylor, Gabor Fichtinger (Johns Hopkins University).]

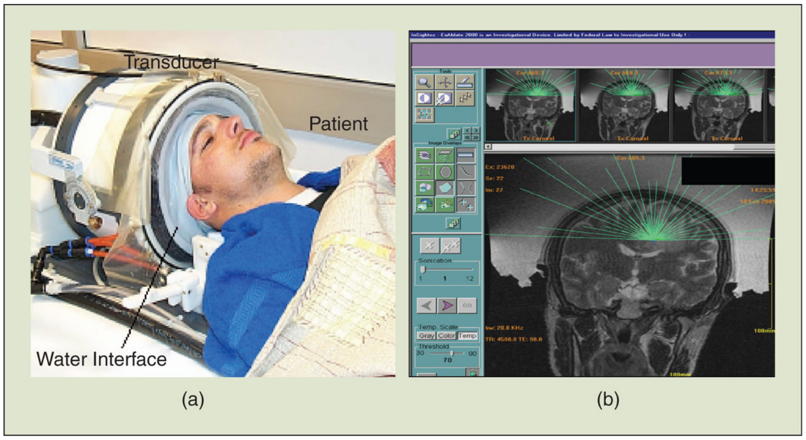

Figure 3.
MRI-guided focused US surgery of brain tumors [12]. (a) Patient in treatment position on the MRI couch. (b) Insonification planning interface. [Images courtesy of Ferenc Jolesz, Nathan Anmes (Brigham and Women's Hospital) and InSightec (Haifa, Israel).]

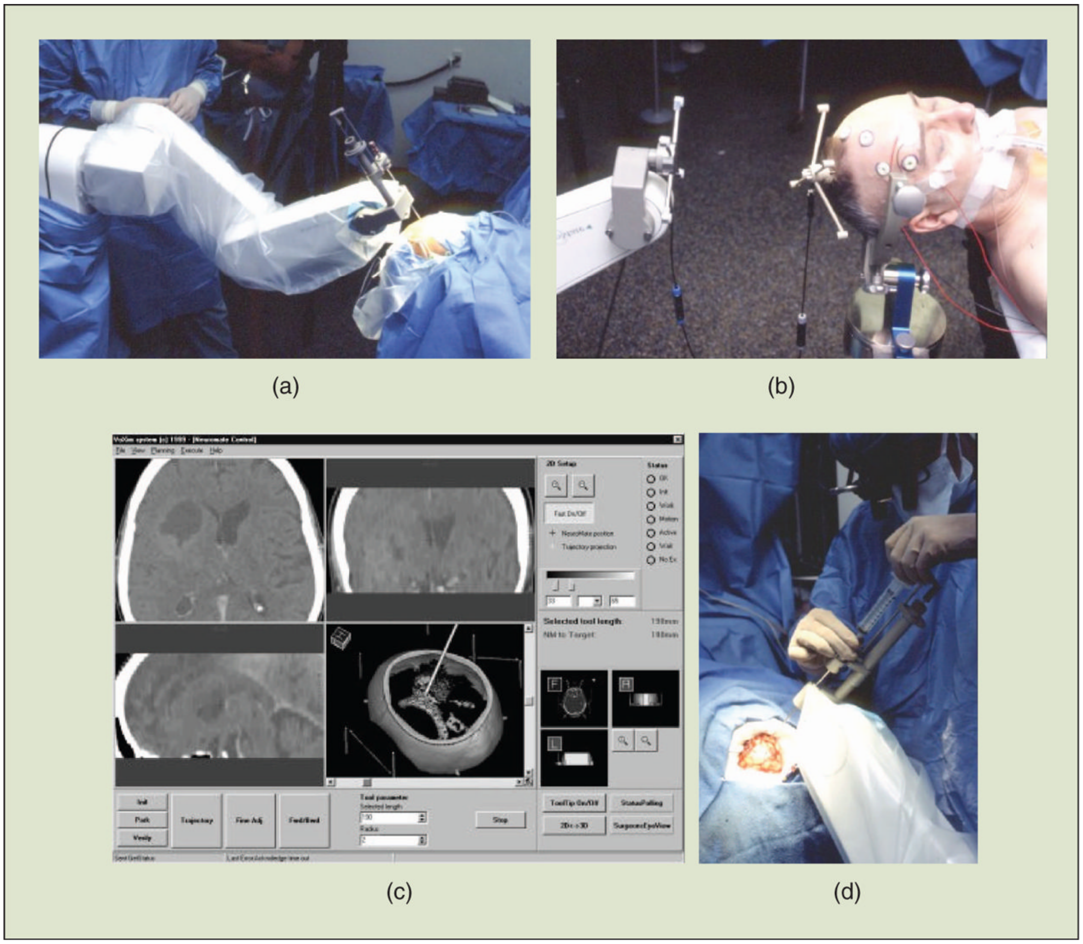

Figure 4.

Neuromate robot in brain surgery [16]. (a) The robotic arm holding an aspiration needle. (b) Robot-to-patient registration with optically tracked fiducials. (c) Screenshot from CT-based treatment planning. (d) Surgeon performing the aspiration. (Images courtesy of Integrated Surgical Systems.)

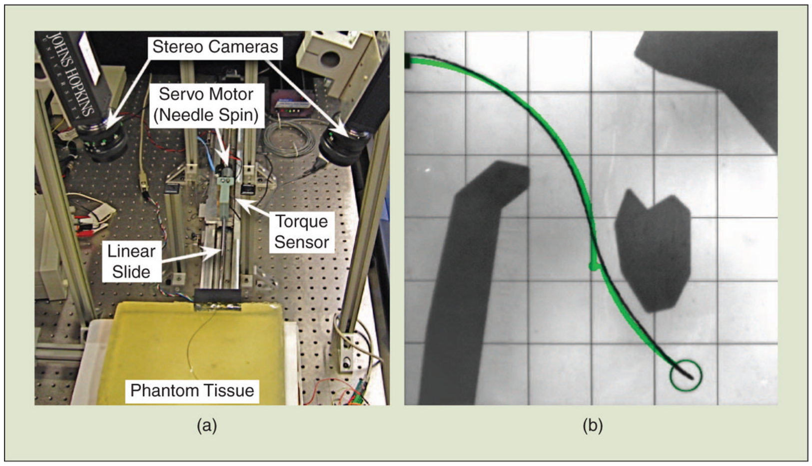

Figure 5.
Robotic needle steering [28]. (a) The vision-guided robot can work autonomously or teleoperated. (b) The needle (thin black line) follows planned trajectory (colored line) around obstacles in transparent artificial tissue. [Images courtesy of Kyle Reed, Robert Webster, Vinutha Kallem, Gregory Chirikjian, Allison Okamura, and Noah Cowan (Johns Hopkins University) and Ron Alterovitz and Ken Goldberg (University of California, Berkeley).]