COMPUTERS IN IMAGING AND GUIDED SURGERY

The authors review the main technical issues in computer-integrated surgery systems. They illustrate with examples of working systems the state of the art in the field and provide perspectives on deployment and future developments.

The growing demand for complex, precise, and minimally invasive surgery is driving the search for ways to use computers for linking preoperative plans and human tools. Computers, used in conjunction with advanced surgical-assist devices, will fundamentally alter the procedures carried out in 21st-century operating rooms. Computer-integrated surgery systems will be able to log and track all relevant data, leading to a new level of quantitative patient outcome assessment and treatment improvement analogous to Total Quality Management in manufacturing.

CIS systems are designed to enhance surgeons' dexterity, visual feedback, and information integration. Today's medical equipment can help perform specific tasks, but it is the synergy between these capabilities that gives rise to an emerging paradigm: human–computer cooperation to accomplish delicate and difficult tasks. In some cases, surgeons will supervise CIS systems that carry out specific treatment steps, such as inserting a needle or machining bone. In other cases, CIS systems will provide information to help surgeons execute tasks manually—for example, using computer graphic overlays on a surgeon's field of view. In some cases, these modes are combined. The goal is to complement and enhance surgeons' skills, never to replace them.

From an engineering systems perspective, there are two kinds of CIS systems:

- *Surgical CAD/CAM systems* transform preoperative images and other information into models of individual patients, help clinicians develop optimized intervention plans, match preoperative data to patients in the operating room, and use a variety of appropriate means, such as robots and image overlay displays, to help execute the planned interventions accurately.
- *Surgical-assistant systems* work interactively with surgeons to extend human capabilities. They have many of the same components as surgical CAD/CAM systems, but the emphasis is on intraoperative decision support and skill enhancement rather than careful preplanning and accurate execution.

The CIS paradigm began to emerge from research labs in the mid-1980s, with the intro-

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Table 1. Key advantages of CIS systems.

Advantage	Important to whom	How to quantify	Key leverage points
New treatment options	Clinical researchers, patients	Clinical and preclinical trials	Transcend human sensory–motor limits, enable less invasive procedures with real-time image feedback, speed clinical research through greater consistency and data gathering.
Quality	Surgeons, patients	Clinician judgment, revision rates	Significantly improve the quality of surgical techniques, improving results and reducing the need for repeat surgery.
Time and cost	Surgeons, hospitals, insurers	Hours, hospital charges	Reduce time in some interventions, reduce costs from healing time and repeat surgery, provide effective intervention to treat patient condition.
Less invasiveness	Surgeons, patients	Qualitative judgment, recovery times	Provide crucial information and feedback needed to reduce the invasiveness of surgical procedures, thus reducing infection risk, recovery time, and costs.
Safety	Surgeons, patients	Rate of repeat surgery and complication	Reduce surgical complications and errors, lowering costs, improving outcomes, and shortening hospital stays.
Real-time feedback	Surgeons	Qualitative assessment, quantitative comparison of plan to observation, rate of repeat surgery	Integrate preoperative models and intraoperative images to give surgeons timely and accurate information about the patient and intervention, assure that the doctor has in fact accomplished the planned intervention.
Accuracy or precision	Surgeons	Quantitative comparison of plan to actual	Significantly improve the accuracy of therapy dose pattern delivery and tissue manipulation tasks.
Documentation and follow-up	Surgeons, clinical researchers	Databases, anatomical atlases, images, clinical observations	Log more varied and detailed information about each surgical case than is practical in conventional surgery. Over time, this ability, coupled with CIS systems' consistency, might significantly improve surgical practice and shorten research trials.

duction of the first commercial navigation and robotic systems in the mid-1990s. Since then, a few hundred CIS systems have been installed in hospitals and are in routine clinical use, and a few tens of thousands of patients have been treated; this number is growing rapidly. Several key technical factors have enabled the development of these systems: the increasing availability of powerful imaging modalities such as computer tomography (CT), magnetic resonance imaging (MRI), nuclear medicine imaging (NMI), and live video; powerful computers with graphics capabilities; novel algorithms for model construction and navigation; and integrative systems and protocol development.

Researchers have developed systems for neurosurgery, orthopedics, radiation therapy, and laparoscopy. Preliminary evaluation and short-term clinical studies indicate improved planning and execution precision, which results in reduced complications and shorter hospital stays. However, some of these systems have a steep learning curve and longer intraoperative times than traditional procedures, indicating the need for improvement. Table 1 summarizes the main

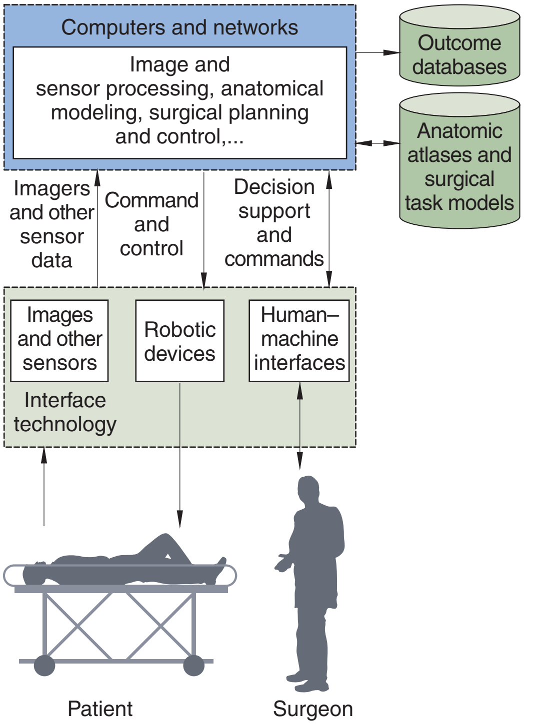

Figure 1. A CIS system's architecture.

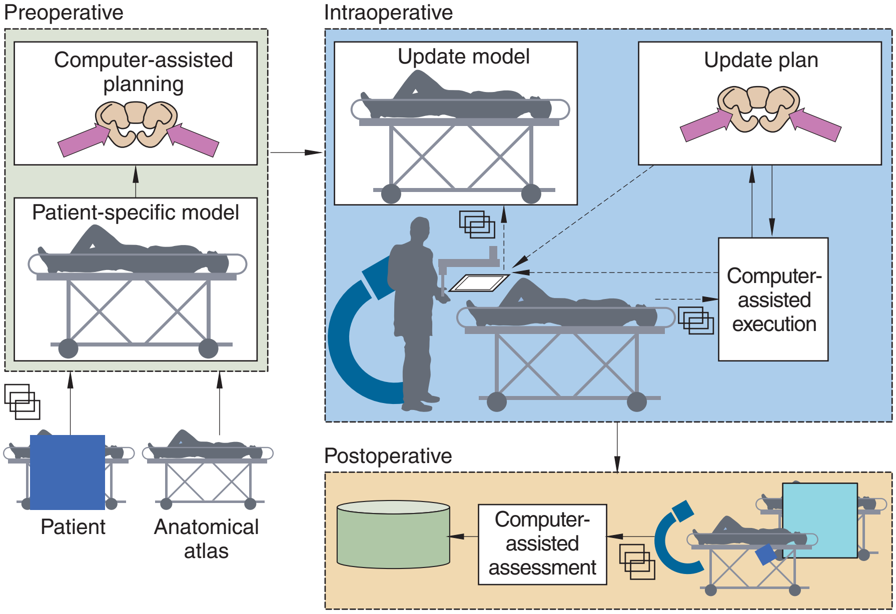

Figure 2. The major information interfaces in CIS systems.

factors to consider in assessing the potential value of CIS systems.

The structure of CIS systems

Figure 1 illustrates the key CIS system elements and interfaces. At the core is a computer (or network of computers) running various modeling and analysis processes, including image and sensor processing, creation and manipulation of patient-specific anatomical models, surgical planning, visualization, monitoring, and control of surgical processes. After receiving information about the patient from medical imaging devices, some CIS systems act directly on the patient using specialized robots or other computer-controlled therapy devices. They also communicate with the surgeon through various visualization subsystems, haptic devices, or other human–machine interfaces. The surgeon remains in overall control of the procedure and, indeed, might do all of the actual work using hand tools, with information and decision support from the computer. The computer's modeling and analysis processes often rely on databases of a priori information such as anatomical atlases, implanted device design data, or descriptions of common surgical tasks or subtasks. The computer can also retain essentially all information developed during surgical planning and execution and store it for postoperative analysis and comparison with long-term outcomes.

CIS systems include devices and techniques to provide interfaces between the virtual reality of computer models and surgical plans and the actual reality of operating rooms, patients, and surgeons. Broadly, there are three related categories of CIS interface technology:

- *novel sensors and imaging techniques* to improve patient information;
- *robotic devices, systems, and control methods* that extend human precision, geometric accuracy, and ability to work in confined spaces; and
- *human–machine communication devices*, including haptic interfaces and superimposed visual displays.

Research in these areas draws on a broad spectrum of core engineering research disciplines, including materials science, mechanical engineering, control theory, device physics, and others. The fundamental challenge is to extend the sensory, motor, and human-adaptation abilities of computer-based systems in a demanding and constrained environment. Particular needs include compactness, precision, biocompatibility, imager compatibility, dexterity, sterility, and human factors.

Figure 2 illustrates the overall information flow of CIS systems from the perspective of the surgical CAD/CAM paradigm. These systems combine preoperative and intraoperative modeling and planning with computer-assisted exe-

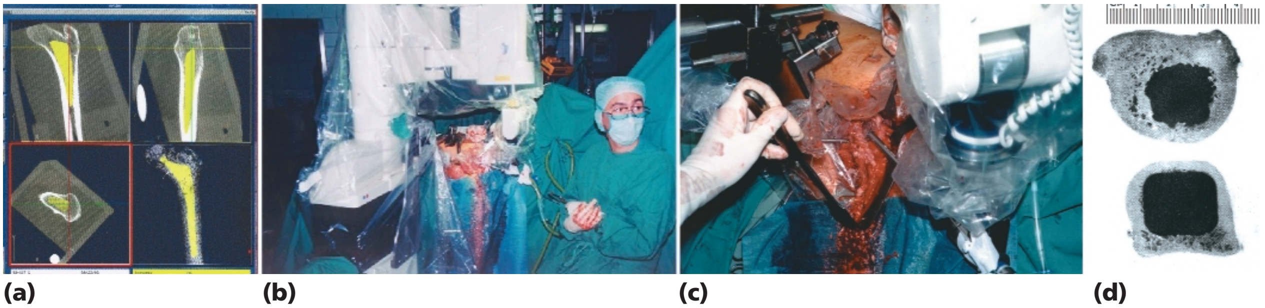

Figure 3. The Robodoc system. (a) A screen of Orthodoc, the preoperative planning module. Three windows show orthogonal cross sections of the CT; the fourth (lower right) shows a 3D reconstruction of the femur. The yellow shape is the implant, which the surgeon has chosen and positioned before the surgery. (b) The six-axis robot covered by a sterile protection drape. The machining tool (in the center) is tilted to provide better access to the exact place on the femur canal. (c) Robodoc in action: the robot milling the femoral canal. (d) Cross sections of a manually cut femur (top) and a robotically machined femur (bottom), which has superior surface finish and fit. (Photos courtesy Integrated Surgical Systems.)

cution and assessment. The structure of surgical-assistant systems is similar, except that many more decisions are made during the operation, and preoperative models and plans are sometimes less important.

CIS applications comprise three phrases:

- *Preoperative phase*. With support from the system, the surgeon develops a surgical plan from a patient-specific model that is generated from preoperative images and a priori information about human anatomy contained in an anatomical atlas or database. Planning is highly application-dependent, because surgical procedures differ greatly. Some cases might involve a relatively straightforward interactive simulation or selection of some key target position, such as performing a tumor biopsy in neurosurgery. In other cases, such as in craneofacial surgery, planning can require sophisticated optimizations incorporating tissue characteristics, biomechanics, or other information contained in atlases and adapted to the patient-specific model.
- *Intraoperative phase*. The images, patient-specific model, and plan information are brought into the operating room and registered to the patient based on information from a variety of sensors, usually including a 3D localization system or imaging device. Depending on the images, the model and the plan might be further updated by the CIS system with directions from the surgeon. The computer then uses various interface devices—perhaps active devices such as robots, "smart" hand tools, or information displays—to help the surgeon execute the surgical plan. As the operation proceeds, the doctor might order additional images or other measurements to assess progress and provide feedback for controlling tools and therapy delivery. On the basis of this feedback, the system can update the patient model during the procedure. The surgeon might use this updated model to refine or update the surgical plan to ensure it will meet the desired goals. Ideally, intraoperative imaging and other feedback can ensure that the surgery has achieved its technical goals before the patient leaves the operating room. Furthermore, the computer can identify and record a complete record of pertinent information about the procedure without significant additional cost or overhead.
- *Postoperative phase*. The preoperative and intraoperative information are combined with additional images and tests, both to further verify the procedure's technical results and to assess the longer-term clinical results for the patient. Moreover, the system can match many of the procedures to an anatomical atlas to facilitate statistical studies relating surgical techniques to clinical outcomes.

These descriptions apply to a generic CIS system; actual systems do not necessarily require all these capabilities. Also, as we will see later, some of these capabilities are beyond the current state of the art.

From a surgeon's perspective, the key difference between advanced medical equipment and CIS systems is the information integration, both between phases and within each phase. This new capability requires in most cases modifications to existing surgical protocols, and in a few cases radically new protocols. It could also enable more surgeons to perform difficult procedures that require much coordination and knowledge available to only a few experienced specialists or to perform procedures that are currently not feasible.

Example systems

We now illustrate these concepts with examples in the two categories of CIS systems: surgical CAD/CAM systems and surgical-assistant systems.

Surgical CAD/CAM systems

Surgical CAD/CAM systems typically include a mechanical device that acts directly on the patient based on the surgeon's directions. With the system's help, the surgeon elaborates an action plan based on preoperative CT or MRI images.

A typical system is the Robodoc system[1,2] for robotic joint surgery, developed by Integrated Surgical Systems based on an IBM T.J. Watson Research Center prototype created in the late 1980s (see Figure 3). Both Robodoc and a later, similar system called Caspar[3] were originally used for cementless primary total hip replacement surgery; other applications, notably total knee replacement surgery and revision hip surgery,[4] have subsequently used them. Primary total hip replacement replaces a damaged joint connecting the hip and the femur with a metallic implant that is inserted into a canal broached in the femur. Robodoc's goal is to reduce the complications associated with canal broaching and to improve the canal's surface finish for a better implant fit.

Robodoc assists surgeons in planning the procedure preoperatively by selecting and positioning an implant with respect to a CT study and then intraoperatively milling the corresponding canal in the femur with a high-speed tool controlled by a robotic arm. The system consists of interactive preoperative planning software, called Orthodoc, and an active robotic system for intraoperative execution. Preclinical testing showed an order-of-magnitude improvement in precision and repeatability in preparing the implant cavity. As of fall 2001, 40 systems were in clinical use, having performed over 8,000 procedures with no serious complications due to the robot and positive results reported.

Researchers have proposed and (in a few cases) applied other robotic systems to hip and knee surgery.[5–8] Surgeons have extensively used surgical CAD/CAM systems relying on human, manual manipulation of surgical instruments in spine,[9] pelvis, fracture,[10] hip,[11,12] and knee surgery.

Figure 4. A surgical CAD/CAM system used for navigation in neurosurgery. (Photo courtesy Image Guided Technologies.)

One of the first uses of surgical robots was in percutaneous therapy—the positioning of needle guides in neurosurgery.[13,14] This is a natural application, since the skull provides a rigid frame of reference. However, the potential application of localized therapy is much broader, and a number of groups are trying to extend the use of image-guided, robotically assisted percutaneous therapy to other parts of the body. Work at Johns Hopkins is typical of this activity. One early experimental system[15] helped establish the feasibility of inserting radiation therapy seeds into the liver under biplane x-ray guidance. In this work, small pellets were intraoperatively inserted according to a planned pattern and later located in the CT images. After this experiment and related work in the kidney established the basic feasibility of this approach, subsequent work focused on developing a modular family of robots for use in various imaging and surgical environments. Figure 5 shows an elegant, compact remote-center-of-motion device,[16] together with a novel end-effector[17] that lets the computer determine the needle pose with respect to a CT or MRI scanner using a single image slice. This arrangement can have significant advantages in reducing setup costs and time for in-scanner procedures and in eliminating many sources of geometric error.

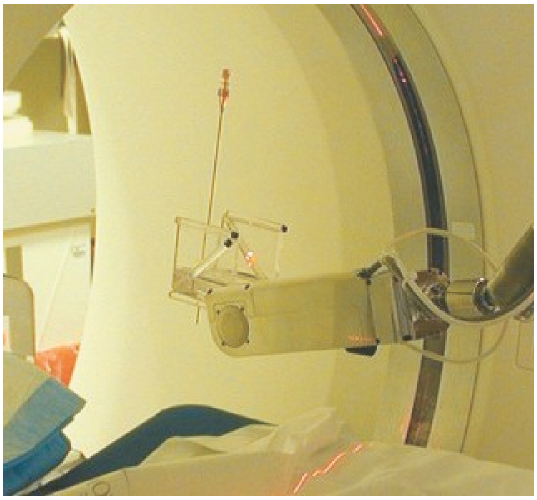

Figure 5. The remote-center-of-motion robot uses an injection system during a CT procedure. Markers on the driver enable localization of the needle from a single CT image.

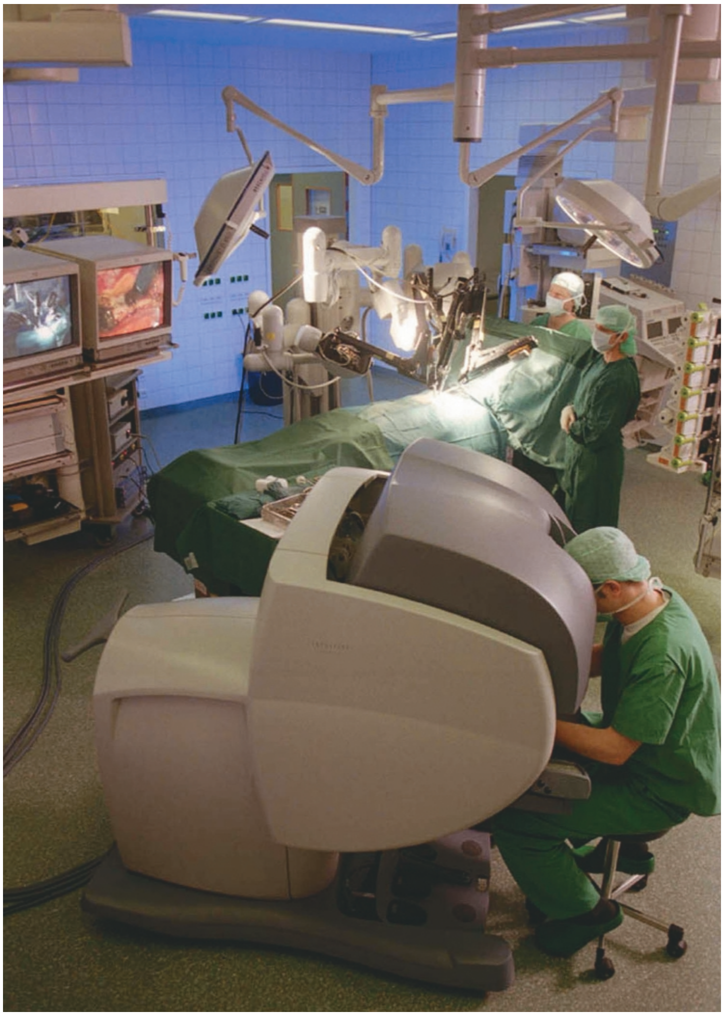

Figure 6. Telesurgical robot for laparoscopic surgery. (Photo courtesy Intuitive Surgical Systems.)

Surgical-assistant systems

Besides helping execute procedures, CIS systems can also act as surgical assistants providing useful information to a surgeon. These systems are widely deployed, and their use is rapidly becoming the standard of care in brain surgery and certain spine procedures. Figure 4 shows a typical system (Image Guided Technologies).[18] This system lets surgeons visualize in real time, during surgery, the relative locations of surgical tools and anatomy. The anatomical model used for navigation is constructed from preoperative CT or MRI data. The system obtains the instruments' locations and the patient's rigid anatomy in real time by attaching to them frames with light-emitting diodes that it tracks with a stereoscopic optical tracking camera. The system matches the preoperative model to the intraoperative situation by touching predefined landmarks on the anatomy surface with a tracked probe. Intraoperative navigation enables less invasive surgery and more precise localization without needing to repeat x-rays or ultrasounds during surgery. For example, to biopsy a brain tumor, the surgeon uses the images to direct the instrumented drill on the patient's skull and drills directly toward the tumor, instead of making an incision on the skull and then visually looking for the tumor.

Surgical-assistant robots can also enhance human performance and efficiency in surgery. Much of the past and current work on assistants has emphasized teleoperation.[19–21] Figure 6 shows a typical telesurgical system, in this case the Intuitive Surgical DaVinci system.

Another approach, developed extensively at Johns Hopkins and explored independently,[7] emphasizes cooperative manipulation, in which the surgeon and robot both hold the surgical tool (see Figure 7). The robot senses forces exerted on the tool by the surgeon and moves to comply. Initial experiences with this mode in Robodoc and later with the LARS system[22,23] indicated that it was popular with surgeons: It helped augment human performance while maximizing the surgeon's natural hand–eye coordination. Subsequent work has focused on extending this work into microsurgery, including extending the basic cooperative-control paradigm to close compliance loops and using other sensors such as visual processing.

Other systems commonly help with mundane tasks such as manipulating endoscopes[22,24] or surgical retraction. More recently, there has been interest in developing similar systems for use with ultrasound.[25–27]

The development of innovative CIS systems has seen a boom in the last 10 years, and we expect this to continue. Together with technological advancements, we see more short-term and mid-term clinical studies to evaluate the methods' clinical benefits and cost effectiveness. We predict that CIS will have the same impact on health care in the coming decades that computer-integrated manufacturing has had on industrial production in the recent past. CIM introduced an unprecedented level of information integration across all processes of product design and manufacturing, from early design to recycling and disposal. It brought with it total information and quality management, which made a qualitative difference.

Achieving this vision will require both significant advances in basic engineering knowledge and the development of robust, flexible systems that make this knowledge usable in real clinical application.

It is important to remember that the ultimate payoff for CIS systems will be improved and more cost-effective health care. Quantifying these advantages in practice can be problematic, and the final answer could take years to be demonstrated. The consistency, enhanced data logging, and analysis made possible by CIS systems might help in this process, but figuring out how to apply these capabilities will not be easy.

Issues of image processing, modeling, and analysis are ubiquitous in CIS systems. We need novel algorithms and representational methods for modeling the patient and surgical environment and for using this information in planning and executing surgical procedures.

We also need advances in each of the topics we have discussed in this article. Fundamental themes underlying this research include

- extracting and combining information from multiple sources and sensors,
- combining functional and geometric information,
- representing and reasoning about uncertainty, and
- managing complexity.

Furthermore, we must develop methods that are computationally effective—that is, that enable surgical planning and execution systems to extract and apply useful information to specific tasks in a timely fashion. Of particular interest for much of our research over the next few years will be development of near-real-time methods for segmenting intraoperative images and adapting them to prior patient models derived from preoperative images or anatomical atlases.

Figure 7. The Steady Hand microsurgical-assistant robot.

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References

1. R.H. Taylor et al., "An Image-Directed Robotic System for Precise Orthopaedic Surgery," *IEEE Trans. Robotics and Automation*, vol. 10, no. 3, 1994, pp. 261–275.
2. A. Bauer, "Primary THR Using the ROBODOC System," *3rd Ann. North Am. Program Computer Assisted Orthopaedic Surgery* (CAOS/USA 1999), Dept. of Continuing Medical Education, UPMC Shadyside, Pittsburgh, 1999, pp. 107–109.
3. J. Peterman et al., "Implementation of the CASPAR System in the Reconstruction of the ACL," *4th Ann. North Am. Program Computer Assisted Orthopaedic Surgery* (CAOS/USA 2000), Dept. of Continuing Medical Education, UPMC Shadyside, Pittsburgh, 2000, pp. 92–95.
4. R.H. Taylor et al., "Computer-Integrated Revision Total Hip Replacement Surgery: Concept and Preliminary Results," *Medical Image Analysis*, vol. 3, no. 3, 1999, pp. 301–319.
5. J.L. Garbini et al., "Robotic Instrumentation in Total Knee Arthroplasty," *Proc. 33rd Ann. Meeting Orthopaedic Research Soc.*, Orthopaepic Research Soc., Rosemont. Ill., 1987, p. 413.
6. M. Fadda et al., "Computer-Assisted Knee Arthroplasty at Rizzoli Institutes," *Proc. 1st Int'l Symp. Medical Robotics and Computer Assisted Surgery*, Carnegie Mellon Univ., Pittsburgh, 1994, pp. 26–30.
7. S.C. Ho, R.D. Hibberd, and B.L. Davies, "Robot Assisted Knee Surgery," *IEEE EMBS Magazine*, special issue on robotics in surgery, April–May 1995, pp. 292–300.
8. T.C. Kienzle et al., "An Integrated CAD-Robotics System for Total Knee Replacement Surgery," *Proc. IEEE Int'l Conf. Robotics and Automation*, IEEE Press, Piscataway, N.J., 1993, pp. 325–338.
9. L.P. Nolte et al., "A Novel Approach to Computer Assisted Spine Surgery," *1st Int'l Symp. Medical Robotics and Computer Assisted Surgery* (MRCAS 94), Carnegie Mellon Univ., Pittsburgh, 1994, pp. 323–328.
10. L. Joskowicz et al., "FRACAS: A System for Computer-Aided Image-Guided Long Bone Fracture Surgery," *J. Computer Assisted Surgery*, vol. 3, no. 6, May 1999, pp. 271–288.
11. A.M. DiGioia, B. Jaramaz, and R.V. O'Toole, "An Integrated Approach to Medical Robotics and Computer Assisted Surgery in Orthopaedics," *Proc. 1st Int'l Symp. Medical Robotics and Computer Assisted Surgery* (MRCAS 94), Carnegie Mellon Univ., Pittsburgh, 1994, pp. 106–112.
12. A.M. DiGioia et al., "HipNav: Preoperative Planning and Intraoperative Navigational Guidance for Acetabular Implant Placement in Total Hip Replacement Surgery," *Computer Assisted Orthopedic Surgery*, L.P. Nolte and R. Ganz, eds., Hogrefe and Huber Publishers, Kirkland, Wash., 1999, pp. 230–251.
13. Y.S. Kwoh, J. Hou, and E.A. Jonckheere, "A Robot with Improved Absolute Positioning Accuracy for CT Guided Stereotactic Brain Surgery," *IEEE Trans. Biomedical Eng.*, vol. 35, no. 2, 1988, pp. 153–161.
14. S. Lavallee et al., "Image-Guided Operating Robot: A Clinical Application in Stereotactic Neurosurgery," *Computer-Integrated Surgery*, R.H. Taylor et al., eds., MIT Press, Cambridge, Mass., 1996, pp. 343–352.
15. A. Bzostek et al., "A Testbed System for Robotically Assisted Percutaneous Pattern Therapy," *Medical Image Computing and Computer-Assisted Surgery*, Springer-Verlag, New York, 1999, pp. 35–46.
16. D. Stoianovici et al., "A Modular Surgical Robotic System for Image-Guided Percutaneous Procedures," *Medical Image Computing and Computer-Assisted Interventions* (MICCAI-98), Springer-Verlag, New York, 1998.
17. K. Masamune et al., "Development of CT-PAKY Frame System: CT Image Guided Needle Puncturing Manipulator and a Single Slice Registration for Urological Surgery," *Proc. 8th Ann. Meeting J. Japan Soc. Computer Aided Surgery*, 1999, pp. 89–90.
18. K.R. Smith, K.J. Frank, and R.D. Bucholz, "The Neurostation—a Highly Accurate Minimally Invasive Solution To Frameless Stereotactic Neurosurgery, *Comput. Med. Imaging Graph.*, vol. 18, 1994, pp. 247–256.
19. P. Green et al., "Mobile Telepresence Surgery," *Proc. 2nd Int'l Symp. Medical Robotics and Computer Assisted Surgery* (MRCAS '95), 1995.
20. A.M. Chiu, D. Boyd, and T.M. Peters, "3D Visualization from Minimally Invasive Robotic Coronary Artery Bypass (MIRCAB)," *Proc. 22nd Ann. Conf. IEEE Eng. in Medicine and Biology Soc.*, IEEE Press, Piscataway, N.J., 2001.
21. G.S. Guthart and J.K. Salisbury, "The Intuitive Telesurgery System: Overview and Application," *Proc. IEEE Int'l Conf. Robotics and Automation* (ICRA2000), IEEE Press, Piscataway, N.J., 2000, pp. 355–360.
22. R.H. Taylor et al., "Telerobotic Assistant for Laparoscopic Surgery," *IEEE Eng. in Medicine and Biology Soc.*, vol. 14, no. 3, 1995, pp. 279–288.
23. L.M. Auer, "Virtual Endoscopy for Planning and Simulation of Minimally Invasive Neurosurgery," *Proc. 1st Joint Conf. CVRMed and MRCAS*, Springer-Verlag, New York, 1997.
24. J.M. Sackier and Y. Wang, "Robotically Assisted Laparoscopic Surgery: from Concept to Development," *Computer-Integrated Surgery*, R. Taylor et al., eds., MIT Press, Cambridge, Mass., 1996, pp. 577–580.
25. P. Abolmaesumi et al., "A User Interface for Robot-Assisted Diagnostic Ultrasound," *Proc. IEEE Robotics and Automation Conf.* (ICRA 2001), IEEE Press, Piscataway, NJ, 2001.
26. R. Goldberg, *A Modular Robotic System for Ultrasound Image Acquisition*, master's thesis, Mechanical Eng. Dept., John Hopkins Univ., Baltimore, 2001.
27. E. Degoulange et al., "HIPPOCRATE: An Intrinsically Safe Robot for Medical Applications," *IEEE/RSJ Int'l Conf. Intelligent Robots and Systems*, IEEE Press, Piscataway, NJ, 1998, pp. 959–964.

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