Computers in Imaging and Guided Surgery

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1. Introduction

The growing demand for complex and minimally invasive surgical interventions is driving the search for ways to use computer-based information technology as a link between the pre-operative plan and the tools utilized by the surgeon. Computers, used in conjunction with advanced surgical assist devices, will fundamentally alter the way that are procedures are carried out in 21st Century operating rooms.

Computer Integrated Surgery (CIS) systems make it possible to carry out surgical interventions that are more precise and less invasive than conventional procedures, while judiciously tracking and logging all relevant data. This data logging, coupled with appropriate tracking of patient outcomes, will make possible a totally new level of quantitative patient outcome assessment and treatment improvement analogous to "total quality management" in manufacturing.

The goals of CIS systems are to enhance the dexterity, visual feedback, and information integration of the surgeon. While medical equipment is currently available to assist the surgeons in specific tasks, it is the synergy between these capabilities that gives rise to a new paradigm. The goal is to complement and enhance the surgeon's skills and always leave him in control, never to replace him.

CIS systems are instances of an emerging paradigm of human-computer cooperation to accomplish delicate and difficult tasks. In some cases, the surgeon will supervise a CIS system that carries out a specific treatment step such as inserting a needle or machining bone. In other cases, the CIS system will provide information to assist the surgeon's manual execution of a task, for example through the use of computer graphic overlays on the surgeon's field of view. In some cases, these modes will be combined.

From an engineering systems perspective, the objective can be defined in terms of two inter-related concepts:

- *Surgical CAD/CAM systems* transform preoperative images and other information into models of individual patients, assist clinicians in developing an optimized interventional plan, register this preoperative data to the patient in the operating room, and then use a variety of appropriate means, such as robots and image overlay displays, to assist in the accurate execution of the planned interventions.

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- ***Surgical assistant systems*** work interactively with surgeons to extend human capabilities in carrying out a variety of surgical tasks. 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 pre-planning and accurate execution.

Table 1 summarizes the main factors that must be considered in assessing the value of CIS systems with respect to their potential application.

Advantage	Important to whom	How quantify	Summary of key leverage
New treatment options	Clinical researchers Patients	Clinical and pre-clinical trials	Transcend human sensory-motor limits (e.g., in microsurgery). Enable less invasive procedures with real time image feedback (e.g., fluoroscopic or MRI-guided liver or prostate therapy). Speed clinical research through greater consistency and data gathering.
Quality	Surgeons Patients	Clinician judgment; Revision rates	Significantly improve the quality of surgical technique (e.g., in microvascular anastomosis), thus improving results and reducing the need for revision surgery
Time and cost	Surgeons Hospitals Insurers	Hours, Hospital charges	Speed OR time for some interventions. Reduce costs from healing time and revision 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 times and costs (e.g., percutaneous spine surgery).
Safety	Surgeons Patients	Complication & revision surgery rates	Reduce surgical complications and errors, again lowering costs, improving outcomes and shortening hospital stays (e.g., robotic THR, steady hand brain surgery).
Real time feedback	Surgeons	Qualitative assessment Quantitative comparison of plan to observation Revision surgery rates	Integrate preoperative models and intraoperative images to give surgeon timely and accurate about the patient and intervention (e.g., fluoroscopic x-rays without surgeon exposure, percutaneous therapy in conventional MRI scanners). Assure that the planned intervention has in fact been accomplished
Accuracy or precision	Surgeons	Quantitative comparison of plan to actual	Significantly improve the accuracy of therapy dose pattern delivery and tissue manipulation tasks (e.g., solid organ therapy, microsurgery, robotic bone machining).
Documentation and follow-up	Surgeons Clinical researchers	Data bases, anatomical atlases, images, and clinical observations	CIS systems inherently have the ability to log more varied and detailed information about each surgical case than is practical in conventional manual surgery. Over time, this ability, coupled with CIS systems' consistency, has the potential to significantly improve surgical practice and shorten research trials.

Table 1: Key advantages from CIS Systems.

The CIS paradigm started to emerge from research laboratories in the mid-eighties, with the introduction of the first commercial navigation and robotic systems in the mid-nineties. Since then, a few hundreds of CIS systems have been installed in hospitals and are in routine clinical use, and a few tens of thousands of patients have been treated, with their number rapidly growing. The clinical areas for which these systems have been developed are neurosurgery, orthopedics, radiation therapy, and laparoscopy. Preliminary evaluation and short-term clinical studies indicate improved planning, execution precision, which results in a reduction of complications and shorter hospital stays. However, some of these systems have in some cases a steep learning curve and longer intraoperative times than traditional procedures, indicating the need to improve them.

The key technical enabling factors that promoted the development of these systems were the increasing availability of powerful imaging modalities, such as CT, MRI, NMT, and live video, powerful computers with graphics capabilities, novel algorithms for model construction and navigation, and integrative systems and protocol development. This article reviews the main technical issues of CIS systems. It is organized as follows: the next section briefly describes two CIS systems. The following section presents an overview of CIS systems, their main elements architecture, and information flow. The following section summarizes the main enabling technologies of CIS systems: imaging and tracking, modeling and analysis, robotics and sensing, man-machine interfaces, and systems integration technology. We conclude with a review on the state of the art and possible directions for development.

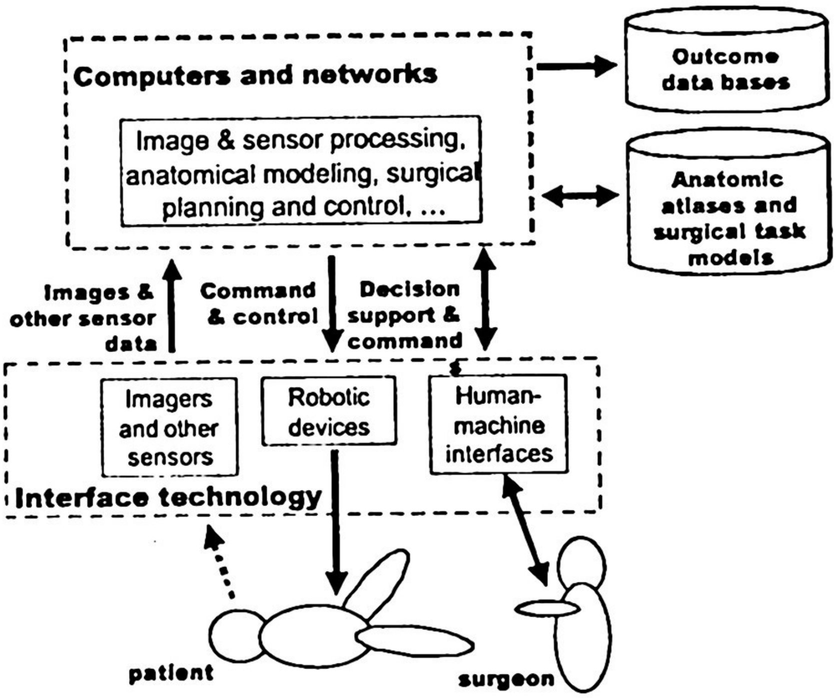

Figure 1: The architecture of CIS systems: elements and interfaces

2. The structure of CIS systems

Figure 1 illustrates the key system elements and interfaces of CIS systems. At the core is a computer (or network of computers) running a variety of 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. These processes receive information about the patient from medical imaging devices about the patient and may directly act on the patient through the use of specialized robots or other therapy devices controlled by the computer. They also communicate with the surgeon through a variety of visualization subsystems, haptic devices, or other human-machine interfaces. The surgeon remains in overall control of the procedure and, indeed, may do all of the actual manipulation of the patient using hand tools with information and decision support from the computer. The modeling and analysis processes within the computer will often rely upon databases of a priori information, such as anatomical atlases, implanted device design data, or descriptions of common surgical tasks or sub-tasks. The computer also has the ability to retain essentially all information developed during surgical planning and execution and store it for post-operative analysis and comparison with long term outcomes.

Devices and techniques to provide the interfaces between the "virtual reality" of computer models and surgical plans to the "actual reality" of the operating room, patients, and surgeons are essential elements of CIS. Broadly, we recognize three inter-related categories of interface technology:

Imaging techniques and sensory devices: Novel sensors and imaging methods are needed to improve the information available about patients.

Robotic devices and systems: Advances are needed in surgically suitable devices and control methods that extend human precision, geometric accuracy, and ability to work in confined spaces.

Human-machine interfaces: Advances are needed in 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 computer-integrated surgical systems from the perspective of the surgical CAD/CAM paradigm. These systems combine preoperative and intraoperative modeling and planning with computer-assisted execution and assessment. The structure of Surgical Assistant systems is similar, except that many more decisions are made intraoperatively, and preoperative models and plans may sometimes be relatively less important. CIS applications can be thought of as comprising three phrases:

- ***Preoperative: phase:*** A surgical plan is developed from a patient-specific model generated from preoperative images and *a priori* information about human anatomy contained in an anatomical atlas or database. Planning is highly application-dependent since the surgical procedures are greatly different. In some cases, it may be a relatively straightforward interactive simulations or selection of some key target positions, such as performing a tumor biopsy in neurosurgery. In other cases, such as in craneo-facial surgery, planning can require sophisticated optimizations incorporating tissue characteristics, biomechanics, or other information contained in the atlas 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 and/or imaging device. In some cases, the model and plan may be further updated, based on the images. The computer then uses a variety of interface devices to assist the surgeon in execution of the surgical plan. Depending on what is most appropriate for the application these interfaces may include active devices such as robots, "smart" hand tools, and information displays. As the surgery proceeds, additional images or other measurements may be taken to assess progress and provide feedback for controlling tools and therapy delivery. Based on this feedback, the patient model may be updated during the procedure, and this updated model may be used to refine or update the surgical plan to ensure that the desired goals are met. Ideally, intraoperative imaging and other feedback can ensure that the technical goals of the surgical intervention have been achieved before the patient leaves the operating room. Further, 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 technical results of the procedure and to assess the longer-term clinical results for the patient. Further, the results of many procedures may be registered back to an anatomical atlas to facilitate statistical studies relating surgical technique to clinical outcomes.

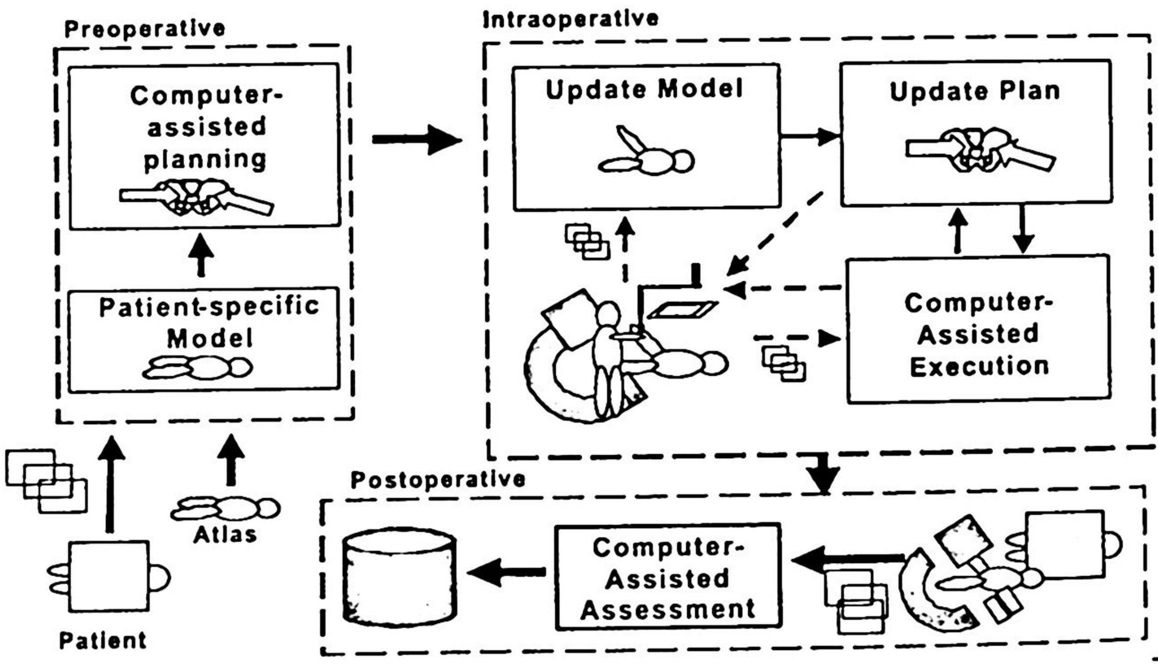

Figure 2: Major information interfaces in CIS systems

Note that the above description is of a generic CIS system, as actual systems do not necessarily require all these capabilities. Also, 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 certain difficult procedures that require much coordination and knowledge available to only a few experienced specialists, or perform procedures that are currently not feasible.

3. Examples of computer-integrated surgery systems

3.1 Surgical CAD/CAM systems

Robotic Joint Surgery: The ROBODOC[a] [1-5] system was developed clinically by Integrated Surgical Systems from a prototype developed at the IBM T.J. Watson Research Center in the late eighties (Figure 1). Both ROBODOC and a very similar subsequently introduced called CASPAR [6] were originally applied for cementless primary total hip replacement surgery, although other applications, notably total knee replacement surgery [7-9] and revision hip surgery [10, 11], have subsequently been introduced. In primary total hip replacement procedures, a damaged joint connecting the hip and the femur is replaced by a metallic implant inserted into a canal broached in the femur. The goal of ROBODOC is to reduce the complications associated with canal broaching, and improve the surface finish of the canal for a better implant fit.

ROBODOC allows surgeons to plan preoperatively the procedure by selecting and positioning an implant with respect to a Computer Tomography (CT) study and intraoperatively mill the corresponding canal in the femur with a high-speed tool controlled by a robotic arm. It 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, 2000, 17 systems were in clinical use, having performed over 6,000 procedures, with no serious complications due to the robot and very positive results reported (e.g., [8, 12-14].

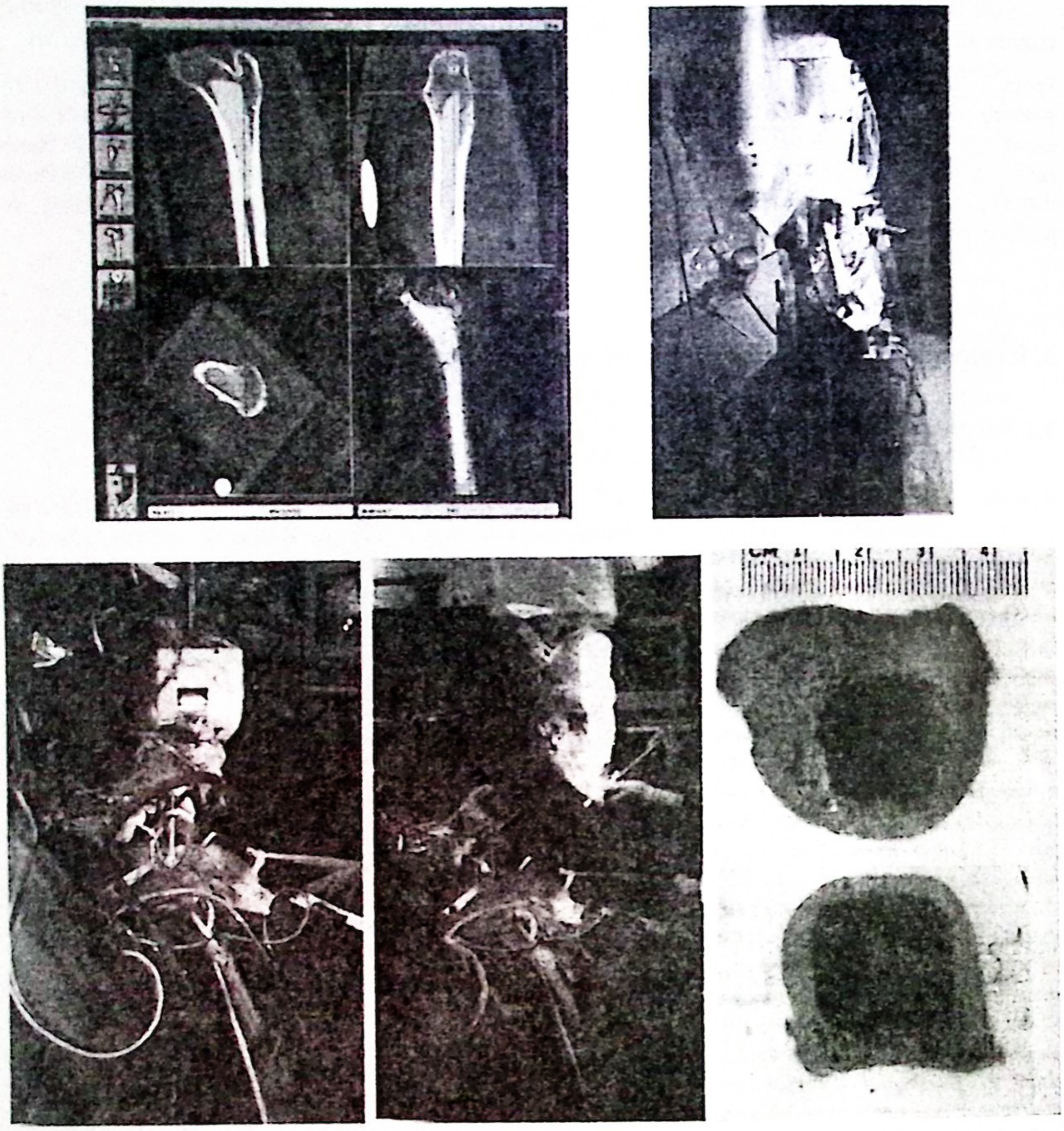

Figure 3: The ROBODOC system. The top left figure shows a screen of ORTHODOC, the preoperative planning module. Three windows show orthogonal cross sections of the CT and one shows a three-dimensional reconstruction of the femur. The yellow shape is the implant, which is chosen and positioned by the surgeon before the surgery. The top right figure shows the six-axis robot covered by a sterile protection drape. The machining tool (center) is inclined to provide better access to the patient trochanter. In the bottom left and center, the ROBODOC system in action: the surgeon attaching the milling tool to the robot after patient preparation (lleft), and in the robot milling the femoral canal (center). The bottom left image shows cross sections of a manually broached femur (top) and a robotically machined femur (bottom), which has superior surface finish and fit.

Other robotic systems have been proposed or (in a few cases) applied for hip or knee surgery include [15-21]. Navigation-assisted systems relying on surgeons' manual manipulation of surgical instruments have been applied extensively in the spine (e.g., [22-24]), pelvis (e.g., [25, 26], fractures (e.g., [27-31], hip (e.g., [32-34]), and knee (e.g., [35-38]).

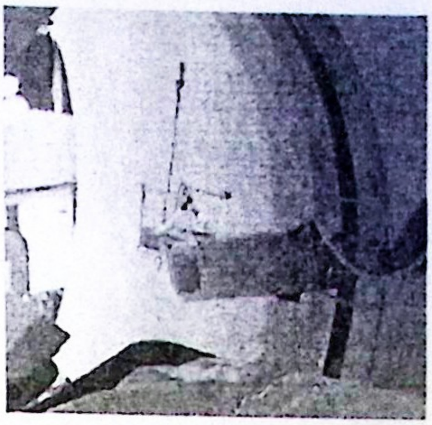
Figure 4: Remote-center-of-motion robot with in-CT injection system. Fiducial markers on the driver enable localization of the needle from a single CT image.

Percutaneous Therapy: One of the first uses of robots in surgery was positioning of needle guides in stereotactic neurosurgery [39-41]. This is a natural application, since the skull provides rigid frame-of-reference. However, the potential application of localized therapy is much broader, and a number of groups are pursuing efforts 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 [42, 43] was used to establish the feasibility of inserting radiation therapy seeds into the liver under biplane xray guidance. In this work, small pellets were implanted preoperatively and located in CT images used to plan the pattern of therapy seeds. After this experiment and related work directed at placing needles into the kidney [44, 45] established the basic feasibility of this approach, subsequent work focused on the development of a modular family of robots for use in a variety of imaging and surgical environments. Figure 4 shows an elegant compact remote-center-of-motion device (RCM) developed by Stoianovici *et al.*[46], together with a novel end-effector developed by Susil, Masamune *et al.* that permits the computer to determine the needle pose to be computed with respect to a CT or MRI scanner using a single image slice [47, 48]. This arrangement can have significant advantages in reducing set-up costs and time for in-scanner procedures and also eliminates many sources of geometric error.

3.2 Surgical Assistant Systems

Navigation Systems: Surgical navigation systems (e.g., [49, 50] and *supra*) may be thought of either as "surgical assistants" providing useful information to a surgeon or (as mentioned above) as instruments assisting in the execution of procedures planned from preoperative models. These systems are widely deployed and their use rapidly becoming the standard-of-care in brain surgery and certain spine procedures. Figure 5 shows a typical system, in this case the StealthStation® is [51] manufactured by Medtronic Surgical

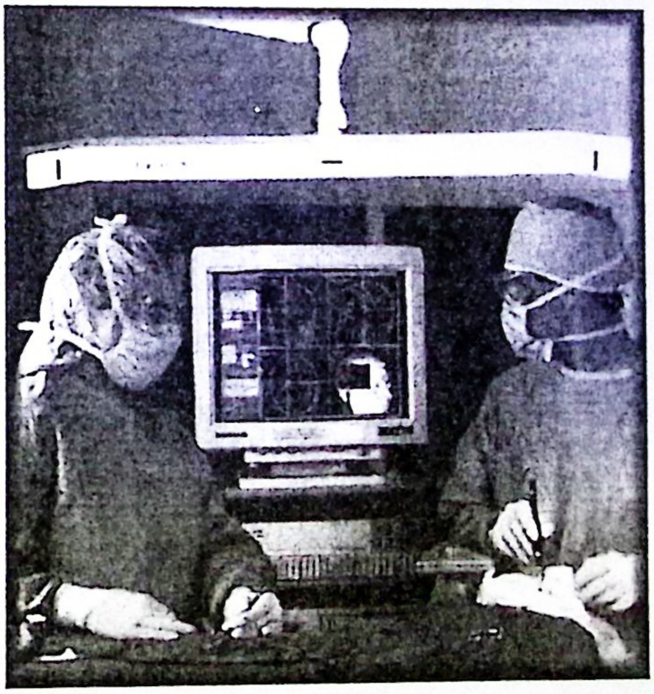
Figure 5: A CIS navigation system in action. (Photo courtesy Medronic Surgical Navication Technologies)

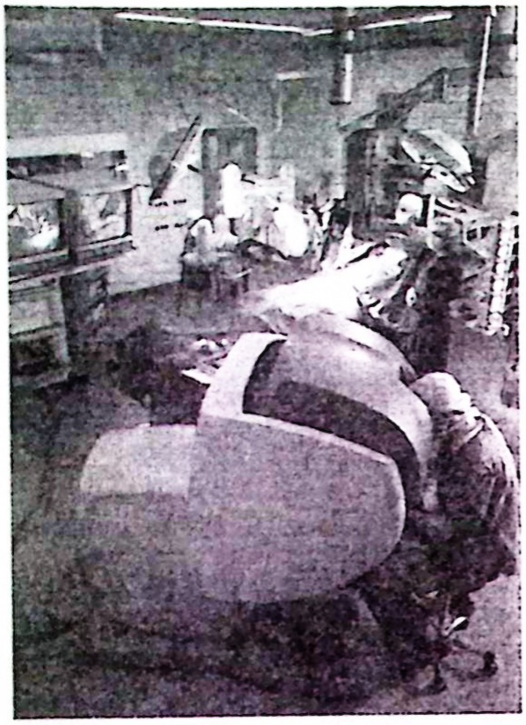

Figure 6: Telesurgical robot for laparoscopic surgery (Photo courtesy Intuitive Surgical).

Navigation Technologies. The system allows surgeons to intraoperatively visualize in real time the relative locations of surgical tools and anatomy and perform surgical actions accordingly. The anatomical model used for navigation is constructed from preoperative CT or MRI data. The instruments and rigid anatomy location is obtained in real time by attaching to them frames with light-emitting diodes that are accurately tracked with a stereoscopic optical tracking camera. The preoperative model is registered to the intraoperative situation by touching with a tracked proble predefined landmarks or points on the anatomy surface and matching them to their corresponding location on the model. Intraoperative navigation allows for less invasive surgery and more precise localization without the need of repeated intraoperative X-ray or ultrasound two-dimensional imaging. For example, to perform a biopsy of a tumor on the brain, the surgeon directs the instrumented drill on the patient's skull with the help of the images, and drills directly towards the tumor instead of making an incision on the skull and visually looking for the tumor.

Robotic assistants: Surgical assistant robots can be used to enhance human performance or efficiency in surgery. Much of the past and current work on assistants (e.g., [52-56]) has emphasized teleoperation. Figure 6 shows a typical telesurgical system, in this case the Intuitive Surgical DaVinci™ system.

Another approach which has been developed extensively by the CIS group at Johns Hopkins, and that has also been explored independently by Davies, et al. [17, 18, 60] emphasizes cooperative manipulation, in which the surgeon and robot both hold the surgical tool. The robot senses forces exerted on the tool by the surgeon and moves to comply. Initial experiences with this mode in Robodoc and subsequently with the IBM/JHU LARS system [61-65] indicated that it was very popular with surgeons and offered means to augment human performance while maximizing the surgeon's natural hand-eye coordination within a surgical task. Subsequent work at Johns Hopkins has focused on extending this work into microsurgery [57, 58, 66]. This work has included both extension of the basic cooperative control paradigm to close compliance loops on a scaled combination of forces exerted by the surgeon and tissue interaction forces [57, 59], as well as based on other sensors such as visual processing.

Other systems are commonly used for mundane tasks such as manipulating endoscopes [61, 67, 68] or surgical retraction [69]. More recently, there has been interest in developing similar systems for use with ultrasound [70-72]. Figure 8 shows one such example.

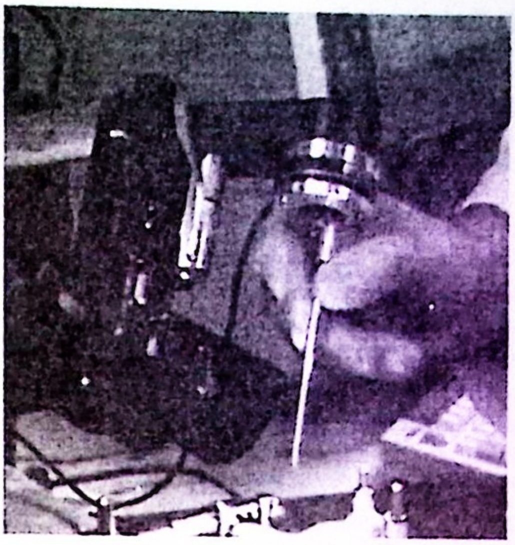

Figure 7: JHU "Steady Hand" microsurgical assistant robot [57-59]

4. The future of computer-integrated surgery

The development of innovative CIS systems has seen a boom in the last ten years, and we expect this to continue in the future. Together with the technological advancements, we see more short and mid-term clinical studies that evaluate the clinical benefits and cost-effectiveness of the methods. We believe that this new paradigm is here to stay.

We predict that computer-integrated surgery 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. Computer-integrated manufacturing 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. We see this happening

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 in improved and more cost-effective health care. Quantifying these advantages in practice can be problematic, and sometimes the final answer may take years to be demonstrated. The consistency, enhanced data logging, and analysis made possible by CIS systems may help in this process. It will not be easy to figure out how to apply these capabilities.

There is a need for novel algorithms and representational methods for modeling the patient and surgical environment and for using this information in the planning and execution of surgical procedures. Issues of image processing, modeling and analysis are ubiquitous in computer-integrated surgical systems. Advances are needed in each of the topics (registration, segmentation, etc.) enumerated there. Fundamental themes underlying this research include: 1) extracting and combining information from multiple sources and sensors; 2) combining functional and geometric information; 3) representing and reasoning about uncertainty; and 4) managing complexity. Further, it is necessary to develop methods that are computationally effective, i.e., that enable our 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 and/or anatomical atlases.

5. Acknowledgments

Any survey or critical summary must necessarily draw upon the work of many people. We would like especially to acknowledge the contributions of many colleagues over the past decade who have helped develop an evolving shared understanding of medical robotics and computer-integrated surgery. We are especially grateful to those individuals who generously provided photographs and other information about the specific systems that we have used as examples. In some cases, these colleagues have also worked with us in developing some of these systems.

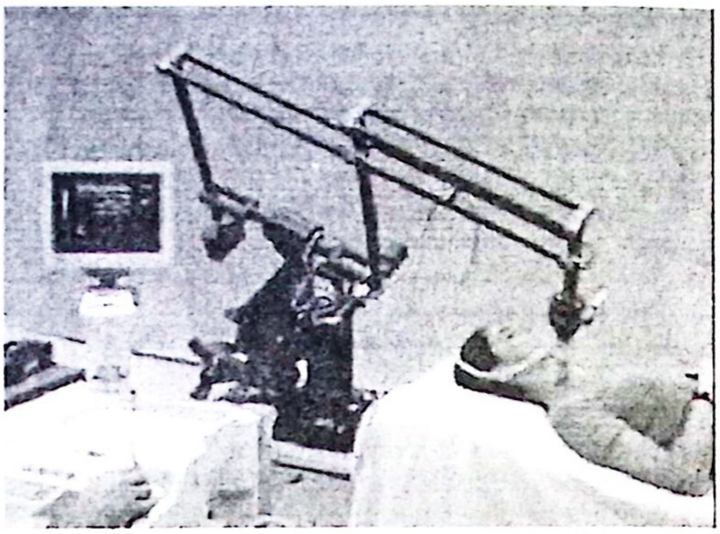

Figure 8: Ultrasound probe manipulation robot [70]

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