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COMPUTER INTEGRATED SURGICAL ROBOTS

R. Deepak[a*], S. Karthikeyan [b], C.Sunil Kumar[c]

Department of Mechatronics Engineering, Agni College of Technology, Chennai 600130, Tamilnadu, India
Department of Computer Science and Engineering, Agni College of Technology, Chennai 600130, Tamilnadu, India

[a] e-mail: deepak.mht@act.edu.in, [b] e-mail: karthikeyan.mht@act.edu.in

ABSTRACT
Two decades after the first reported robotic surgical procedure, surgical robots are just beginning to be widely used in the operating room or interventional suite. The da Vinci telerobotic system (Intuitive Surgical, Inc.), for example, has recently become more widely employed for minimally invasive surgery. This article, the first in a three-part series, examines the core concepts underlying surgical and interventional robots, including the potential benefits and technical approaches, followed by a summary of the technical challenges in sensing, manipulation, user interfaces, and system design. The article concludes with a review of key design aspects, particularly in the areas of risk analysis and safety design. Note that medical care can be delivered in a surgical suite (operating room) or an interventional suite, but for convenience, we will henceforth use the term surgical to refer to both the surgical and interventional domains.

POTENTIAL BENEFITS
The development of surgical robots is motivated primarily by the desire to enhance the effectiveness of a procedure by coupling information to action in the operating room or interventional suite. This is in contrast to industrial robots, which were developed primarily to automate dirty, dull, and dangerous tasks. There is an obvious reason for this dichotomy: medical care requires human judgment and reasoning to handle the variety and complexity of human anatomy and disease processes. Medical actions are chosen based on information from a number of sources, including patient-specific data (e.g., vital signs and images), general medical knowledge (e.g., atlases of human anatomy), and physician experience.
Computer-assisted interventional systems can gather and present information to the physician in a more meaningful way and, via the use of robots, enable this information to influence the performance of an intervention, thereby potentially improving the consistency and quality of the clinical result. It is, therefore, not surprising that surgical robots were introduced in the 1980s, after the dawn of the information age, whereas the first industrial robot was used in 1961. There are, however, cases where surgical robots share potential benefits with industrial robots and teleoperators.

First, a robot can usually perform a task more accurately than a human; this provides the primary motivation for surgical CAD/CAM systems, which are described later in the "Surgical CAD/CAM" section. Second, industrial robots and teleoperators can work in areas that are not human friendly (e.g., toxic fumes, radioactivity, or low-oxygen environments) or not easily accessible to humans (e.g., inside pipes, the surface of a distant planet, or the sea floor). In the medical domain, inhospitable environments include radiation (e.g., X-rays) and inaccessible environments include space-constrained areas such as the inside of a patient or imaging system. This also motivates the development of surgical CAD/CAM systems and is one of the primary motivations for surgical assistant systems, described in the "Surgical Assistance" section. In contrast to industrial robots, surgical robots are rarely designed to replace a member of the surgical or interventional team. Rather, they are intended to augment the medical staff by imparting superhuman capabilities, such as high motion accuracy, or to enable interventions that would otherwise be physically impossible. Therefore, methods for effective human-robot cooperation are one of the unique and central aspects of medical robotics.

TECHNICAL PARADIGMS

In our research, we find it useful to categorize surgical robots as surgical CAD/CAM or surgical assistance systems, based on their primary mode of operation [3]. Note, however, that these categories are not mutually exclusive and some surgical robots may exhibit characteristics from both categories. The following sections briefly describe these categories, with representative examples.

SURGICAL CAD/CAM

The basic tenet of CAD/CAM is that the use of a computer to design a part creates a digital blueprint of the part, and so it is natural to use a computer-controlled system to manufacture it, i.e., to translate the digital blueprint into physical reality. In the medical domain, the planning that is often performed prior to, or during, an intervention corresponds to CAD, whereas the intervention represents CAM. To take the analogy further, postoperative assessment corresponds to total quality management (TQM). We refer to the closed-loop process of

1) constructing a patient-specific model and interventional plan;
2) registering the model and plan to the patient;
3) using technology to assist in carrying out the plan; and
4) assessing the result, as surgical CAD/CAM, again emphasizing the analogy between computer-integrated medicine and computer-integrated manufacturing

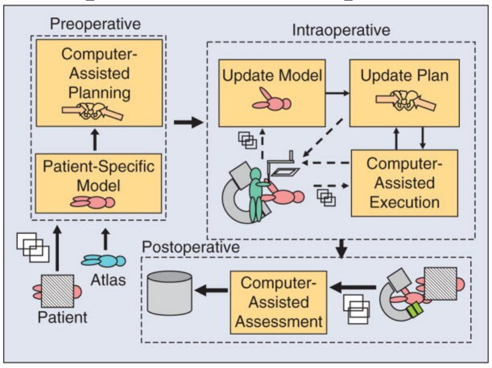

Fig. 1 Architecture of a Surgical CAD/CAM System

The most well-known example of a surgical CAD/CAM system is ROBODOC (ROBODOC, a Curexo Technology Company; formerly Integrated Surgical Systems, Inc.) [4], [5]. ROBODOC was developed for total hip and total knee replacement surgeries. In these surgeries, the patient's joint is replaced by artificial prostheses: for hip surgery, one prosthesis is installed in the femur and another in the acetabulum (pelvis) to create a ball and socket joint; for knee surgery, one prosthesis is installed in the femur and the other in the tibia to create a sliding hinge joint.

Research on ROBODOC began in the mid-1980s as a joint project between IBM and the University of California, Davis. At that time, the conventional technique for hip and knee replacement surgery consisted of two-dimensional (2-D) planning (using X-rays) and manual methods (handheld reamers and broaches) for preparing the bone. The motivation for introducing a robot was to improve the accuracy of this procedure—both the placement accuracy (to put the prostheses in the correct places) and the dimensional accuracy (to get a good fit to the bones). The technical approach of the system is to use computed tomography (CT) for three-dimensional (3-D) planning and a robot for automated bone milling. The planning (surgical CAD) is performed on the ORTHODOC workstation, which enables the surgeon to graphically position a 3-D model of the prosthesis (or prostheses) with respect to the CT image, thereby creating a surgical plan. In the operating room (Surgical CAM), the robot is registered to the CT image so that the surgical plan can be transformed from the CT coordinate system to the robot coordinate system. The robot then machines the bone according to the plan, using a high-speed milling tool.

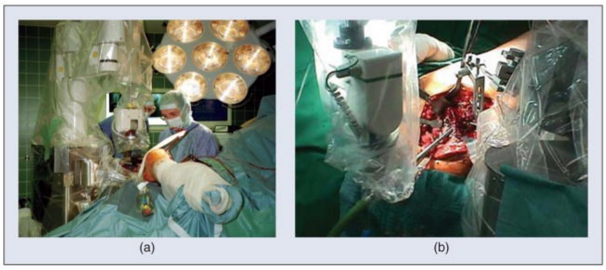

Fig. 2. ROBODOC System

Medical interventions are highly interactive processes, and many critical decisions are made in the operating room and executed immediately. The goal of computer-assisted medical systems, including surgical robots, is not to replace the physician with a machine but, rather, to provide intelligent, versatile tools that augment the physician's ability to treat patients. There are many forms of technological assistance.

There are two basic augmentation strategies: 1) improving the physician's existing sensing and/or manipulation, and 2) increasing the number of sensors and manipulators available to the physician (e.g., more eyes and hands). In the first case, the system can give even average physicians superhuman capabilities such as X-ray vision, elimination of hand tremor, or the ability to perform dexterous operations inside the patient's body. A special subclass is remote telesurgery systems, which permit the physician to operate on patients at distances ranging from a few meters to several thousand kilometers. In the second case, the robot operates side by side with the physician and performs functions such as endoscope holding, tissue retraction, or limb positioning. These systems typically provide one or more direct control interfaces such as joysticks, head trackers, or voice control but could also include intelligence to demand less of the physician's attention during use.

The da Vinci system (Intuitive Surgical, Inc.) is a telesurgery system that demonstrates both of these augmentation approaches [2]. As shown in Figure 3, the system consists of a patient-side slave robot and a master control console. The slave robot has three or four robotic arms that manipulate a stereo endoscope and dexterous surgical instruments such as scissors, grippers, and needle holders. The surgeon sits at the master control console and grasps handles attached to two dexterous master manipulator arms, which are capable of exerting limited amounts of force feedback to the surgeon.

The surgeon's hand motions are sensed by the master manipulators, and these motions are replicated by the slave manipulators. A variety of control modes may be selected via foot pedals on the master console and used for such purposes as determining which slave arms are associated with the hand controllers. Stereo video is transmitted from the endoscope to a pair of high-quality video monitors in the master control console, thus providing high-fidelity stereo visualization of the surgical site. The display and master manipulators are arranged so that it appears to the surgeon that the surgical instruments (inside the patient) are in the same position as his or her hands inside the master control console.

Thus, the da Vinci system improves the surgeon's eyes and hands by enabling them to (remotely) see and manipulate tissue inside the patient through incisions that are too small for direct visualization and manipulation. By providing three or four slave robot arms, the da Vinci system also endows the surgeon with more than two hands.

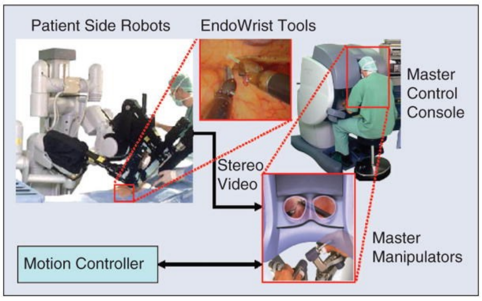

Fig. 3. Davinci Surgical System

OTHER TECHNOLOGIES

Robotics is not the only manner in which computers can be used to assist medical procedures. One important, and widely used, alternative is a navigation system, which consists of a sensor (tracker) that can measure the position and orientation of instruments in 3-D space (typically, the instruments contain special tracker targets). If the tracker coordinate system is registered to a preoperative or intraoperative image (see the "Registration" section), the navigation system can display the position and orientation of the instrument with respect to the image. This improves the physician's visualization by enabling him or her to see the internal structure, molecular information, and/or functional data, depending on the type of image. This can also enable the physician to execute a preoperative plan (surgical CAD/CAM), e.g., by aligning an instrument with respect to a target defined in the preoperative image. Currently, the most widely used tracking technology is optical because of its relatively high accuracy, predictable performance, and insensitivity to environmental variations. The primary limitation of optical trackers is that they require a clear line of sight between the camera and the instruments being tracked. This precludes their use for instruments inside the body. Electromagnetic tracking systems are free from line-of-sight constraints but are generally less accurate, especially due to field distortions caused by metallic objects.

CONCLUSION

This article presents the first of a three-part tutorial on surgical and interventional robotics. The core concept is that a surgical robot couples information to action in the operating room or interventional suite. This leads to several potential benefits, including increased accuracy and the ability to intervene in areas that are not accessible with conventional instrumentation. We defined the categories of surgical CAD/CAM and surgical assistance. The former is intended to accurately execute a defined plan. The latter is focused on providing augmented capabilities to the physician, such as superhuman or auxiliary (additional) eyes and hands. Surgical robotics is a challenging field, but it is rewarding because the ultimate goal is to improve the health and quality of human life.

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