# The IntuitiveTM Telesurgery System: Overview and Application

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**Abstract**

*This paper briefly describes a surgical telerobot designed to provide enhanced dexterity to doctors performing minimally invasive surgical procedures. The rationale for a full 7-degree-of-freedom master-slave system is presented along with a discussion of the resulting computational architecture and recent clinical applications.*

## 1 Introduction

In the early 1980s, surgical technique experienced a revolution called Minimally Invasive Surgery (MIS). The goal of MIS is to reduce patients' pain and recovery time from surgical procedures by minimizing the trauma of the large incisions required by conventional open surgery. Surgeons pursuing MIS techniques use surgical endoscopes (cameras mounted on the end of long optical trains) to peer into the body through small puncture wounds. In addition, tool manufacturers build long tools adapted to working through ports in the body. Using endoscopes and modified tools, MIS methods have been rapidly applied to many procedures in several surgical fields, notably general surgery (laparoscopy), orthopedics (orthoscopy) and gynecology. Patients have realized the benefits of reduced pain and shorter recovery times from these procedures. However, the introduction of endoscopes and accompanying tools has brought with it increased technical complexity for the surgeon, making procedures that were simple as open procedures difficult as MIS procedures and making procedures that were complex as open procedures unapproachable as MIS procedures.

Complexity in MIS procedures using endoscopes originates in four sources. First, introduction of the endoscope forces the surgeon to work looking at a video instead of working looking at his own hands, breaking the surgeon's hand-eye coordination. Second, conventional endoscopes use two-dimensional vision, removing some depth cues of normal binocular vision. Some stereoscopic endoscopes exist, but their performance has been limited in resolution and contrast, both in the endoscope itself and in the display technology. Third, the tools used for manipulating tissue inside the body work through ports at the body's wall. A port acts as pivot, making the direction of the tool tip motion reversed from that of the tool's handle in side to side movements. Lastly, the port at the body wall constrains the motion of the tools in two directions, so that the tip of the tool has fewer degrees of freedom, typically reduced from the six degrees of freedom of unconstrained position and orientation to four degrees of freedom. All of these issues have limited the types of procedures that surgeons can perform confidently. Advances from robotics and virtual reality are now being applied to remove these limitations in surgical environments and to allow MIS concepts to be applied to procedures requiring a high degree of mobility in delicate and precise maneuvers.

**Figure 1**. Endoscopic EndoWrist™ Insturment

## 2 A Surgical Teleoperator System

Intuitive Surgical Inc. of Mountain View, CA has developed a surgical teleoperator, known as the daVinci™ System, to address the four main barriers to application of MIS techniques to complex procedures outlined above. Building upon and extending the efforts of previous research in the

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field [1-4], the daVinci™ System creates an immersive operating environment for the surgeon by providing both high quality stereo visualization and a man-machine interface that directly connects the surgeon's hands to the motion of his surgical tool tips inside the patient's body [5]. The registration, or alignment, of the surgeon's hand motions to the motion of the surgical tool tips is both visual and spatial. The system projects the image of the surgical site atop the surgeon's hands (via mirrored overlay optics), restoring hand-eye coordination and providing a natural correspondence in motions. Furthermore, the controller transforms the spatial motion of the tools into the camera frame of reference, so that the surgeon feels as if his hands are inside the patient's body. Lastly, the daVinci™ System restores the degrees of freedom lost in conventional laparoscopy by placing a 3 degree-of-freedom wrist (see Figure 1) inside the patient and controlling this wrist naturally, bringing a total of seven freedoms of motion to the control of the tool tip (3 orientation, 3 translation and grip). The system also uses its control system to filter out surgeon tremor, making the tool tips steadier than the unassisted hand. Also, the system allows for variable motion scaling from the masters to the slaves. For example, a 3:1 scale factor maps 3 cm of translation on the masters into 1 cm of translation at the slaves. In combination with image magnification, motion scaling makes delicate motions easier to perform [6].

Figure 2. daVinci™ System surgeon's console.

The daVinci™ System is made up of two major subsystems. One subsystem is the surgeon's console, housing the display system, the surgeon's handles, the surgeon's user interface and the electronic controller (Figure 2). The second subsystem is the patient side cart, consisting of fully sterilizable tools, the tool manipulators, the camera manipulator, the surgical endoscope and the assistant's user interface (Figure 3).

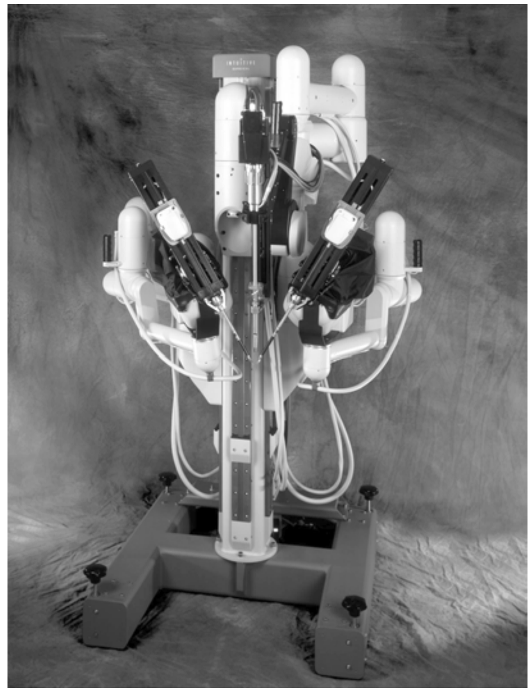

Figure 3. daVinci™ System patient side cart.

Turning first to the surgeon's console, the surgeon's tool handles are serial link manipulators designated the masters. The masters act both as high resolution input devices, reading the position, orientation and grip commands from the surgeon and as haptic displays, transmitting forces and torques to the surgeon in response to various measured and synthetic force cues. The image of the surgical site is transmitted to the surgeon through a high-resolution stereo display, which uses two medical grade CRT monitors to display one image to each of the surgeon's eyes. The virtual image plane of the stereo viewer is placed atop the range of motion of the masters. The user interface at the surgeon's console consists of foot switches and buttons that allow the surgeon to control the system throughout the surgical procedure as well as a variety of other mode selection and initialization switches. This interface allows the surgeon to control the endoscope naturally from the surgeon's console, to re-position the masters in their workspace, to focus the endoscope and so on. The last major component of the surgeon's console is the electronic controller.

Speed, reliability and fail-safe system operation drove the design of the electronic controller. It is a custom designed control computer capable of fully interconnected control of forty-eight degrees of freedom at update rates exceeding one thousand cycles per second. It can read up to 48 encoders and 96 analog input channels in real time while driving output through up to 48 DACs. The heart of the controller is a parallel floating point DSP architecture with a peak computational power of 384 Mflops and a sustained processing power of between 128 and 256 Mflops. Surrounding the compute engine of the controller is a network of 24 micro-controllers and integer DSPs performing data transfer and health watchdog functions. Redundant sensors, hardware watchdogs and real-time error detection ensures fail-safe operation of the controller in all its states (Figure 4).

The patient side system is designed to accurately deliver tools with 7 degrees of freedom (including grip actuation) into the body. Tools are the most distal components of the patient side system. They are four degree-of-freedom, fully sterilizable instruments, ranging from graspers to scalpels, which attach interchangeably to the two tool manipulators. Sterilization is accomplished using standard procedures that have been reviewed and approved by the FDA and European regulatory bodies. Visualization is provided by a high-resolution stereo endoscope that uses two independent optical channels sampled by two independent three-chip CCD cameras. Three slave manipulators drive the two tools and the endoscope. In turn, these manipulators are positioned around the body by three passive multi-link arms mounted to a fixed base. Setup of the patient-side system, from power-up to tool use inside the body, takes approximately fifteen minutes. Removal of the slaves from the patient takes only seconds.

## 3 Clinical Application

In the past year, the daVinci™ System has entered consistent use in numerous hospitals performing a wide variety of procedures. In general surgery, the system has been used to perform over 500 procedures spanning a wide variety of surgeries including, as of October 1999; nissen fundoplication, cholecystectomy, hernia repair, tubal reanastomosis, gastroplasty, appendectomy, arteriovenous fistula, intra-rectal surgery, lysis of adhesions, hysterectomy, lumbar sympathectomy, toupet surgery, and colorectal surgery. In an equivalency study performed for the FDA in 1998, the system completed over 200 combined cholecystectomy and nissen fundoplication procedures and demonstrated equivalent surgical outcomes when compared to conventional

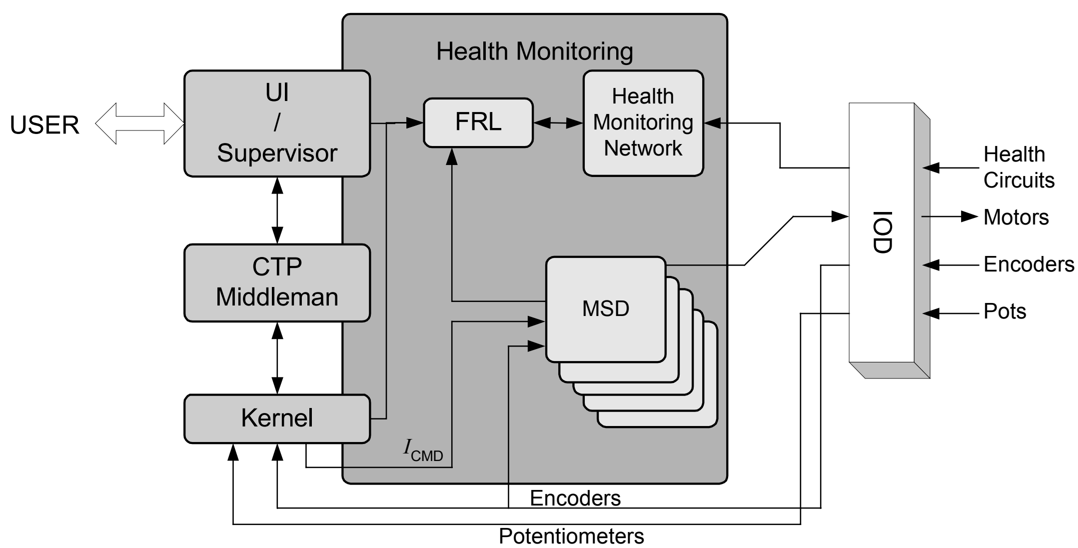


Figure 4. System Architecture. Illustrated are the principal components of the system's control architecture. These include a hierarchically organized user interface/supervisor system (UI, a finite state machine) which handles user input events, a "middleman" process which handles the principal mathematical calculations to support and enable smooth transitions in servo modes, and the kernel which implements servo loop closure. The MSD (multiple servo drive) boards control and monitor the servo amplifiers while the health monitoring network logs errors and controls amplifiers via fault reaction logic function (FRL).

laparoscopic technique. MIS cardiac surgery has been an area of particular interest for users of surgical teleoperators because of the relative complexity of the procedures and the potential benefit to the patient of minimal access to the heart. In cardiac surgery, the daVinci™ System has been used to perform fully endoscopic coronary artery bypass grafts (CABG) in dozens of patients [7]. In addition, the system has been used in many open heart procedures, including mitral valve repairs and replacements, repairs of atrial septal defects and tri-cuspid valve repairs. In 1999 alone, the daVinci™ System was used in hundreds of human cases, with many sites moving to daily use of the system.

## 4 Conclusions

As surgical teleoperators and other surgical robots move into the OR, surgeons, scientists and engineers are presented with novel challenges and opportunities. The use of computers and robotics in the complex and dynamic environment of the operating room stresses the need for creative and seamless man-machine interfaces by changing the traditional roles of surgeons and assistants. At the same time, inserting a computer into the surgical field allows the surgeon access to information intra-operatively that was difficult to use in the past. For example, teleoperators may provide the surgeon with a platform on which to train prior to surgery, while using the same platform to conduct the surgery. Likewise, image guided surgery and other intra-operative surgical assistance is possible when a computer-enhanced environment provides the physical and informational interface between the surgeon and the surgical field. The building blocks for fully integrated surgical simulation and training, planning and execution are well on the way; 3D image re-construction and segmentation, tissue dynamic modeling, haptic interfaces and the like will form the technical foundation for the development of the next generation surgical systems and computer aided procedures. Combined with surgical procedure development and training strategies, computer aided surgery can benefit both the patient and the surgeon by giving the surgeon integrated access to tools and information.

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