SURGICAL TRAINING AND PERFORMANCE ASSESSMENT USING A MOTION TRACKING SYSTEM

Chuan Feng, Hanees Haniffa, Jerzy Rozenblit, PhD,
and Jianfeng Peng
Department of Electrical and Computer Engineering
The University of Arizona
Tucson, AZ 85721
jr@ece.arizona.edu

Allan Hamilton, MD, FACS
Mohamad Salkini, MD
Arizona Surgical Technology and Education Center
The University of Arizona
Tucson, AZ 85724
allan@surgery.arizona.edu

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ABSTRACT

Laparoscopic surgery is a newly developed surgical technology that can minimize recovery time. However, with this procedure surgeons lose many of the tactile and visual cues that they rely upon in conventional surgery. Current research and commercial products focus on virtual simulation of procedures, generation of haptic feedback for training, and automated control of the laparoscope in the operating room (OR). This paper discusses a surgical training and assessment system that provides unique sensing and reasoning capabilities for laparoscopic surgery. The system implements an inference module to process information acquired from sensors, and offers real-time guidance capability that will enhance sensory input for surgeons. A training device prototype has been developed. Future research work will focus on developing the technology as a surgical assistant system for use in the OR.

INTRODUCTION

Laparoscopic surgery, also called keyhole surgery or minimally invasive surgery (MIS) is a modern surgical technique. The first step in the procedure is to insufflate the abdomen, which provides the required space for instrument and telescope movements. Then a laparoscope is inserted into the abdomen through a small incision. The laparoscope system includes a telescope connected to a camera and a fiber optic cable with a cold light source. The surgeons can then insert surgical instruments through strategically placed trocars and perform the operation using the video monitor that displays the image captured by the laparoscope. Laparoscopic surgery, when performed by a well-trained surgeon, is a remarkably effective procedure that minimizes complications associated with large incisions, operative blood loss and post-operative pain, and speeds up recovery time. Unfortunately, from a surgeon's perspective, laparoscopic surgery is more challenging than conventional surgery because of the restricted vision, hand-eye coordination problems, limited working space and lack of tactile sensation. These issues also make laparoscopic surgery a more difficult skill for medical students to master.

In order to minimize the potential risks inherent in laparoscopic procedures, effective surgical training and guidance methods need to be developed. Laparoscopic training translates into approximately 30-35% more efficiency, as measured by operative time, and decreased error rate as compared to a similarly experienced control group of surgical residents who did not receive simulation training (Korndorffer, et al. 2005).

Traditional surgical training methods such as use of animals and cadavers have recently been supplemented by other modes of training. One method involves what is sometimes referred to as a pelvi-trainer (Shrivastava et al. 2003). Pelvi-trainers are usually enclosures that mimic the abdomen, with apertures for insertion of instruments and camera. Trainees use real instruments to practice basic skills by manipulating objects or interacting with artificial tissue and anatomical models, using a video display for visualization. The limitation of this approach is mainly in the absence of objective performance assessment, a feature available in some Virtual Reality (VR) systems.

VR systems represent another mode of training, where the training environment is simulated using computer models of objects or organs. Trainees interact with these models in real-time. Some VR systems provide virtually generated haptic feedback (Dankelman, 2004). Limitations of this approach include inadequate realism of the virtual environment, inaccurate haptic feedback and the exorbitantly high cost of these systems. The latest product available in the commercial market is the LAP Mentor from Simbionix, which claims to provide hands-on practice of some laparoscopic procedures as well as training in basic laparoscopic skills (Simbionix 2006).

Some auxiliary techniques have been developed to minimize the risks of laparoscopic procedures. EndoSista is a robotic system that controls the laparoscope during an operation following the surgeon's command (Finlay, Ornstein 1995). VR based human-machine interfaces to improve dexterity and sensation in minimally invasive surgery have also been developed (Tendick, Cavusogly 1997). These are devices that allow surgeons to remotely manipulate a robot through virtual reality controllers to perform surgery on a patient. The Da Vinci Surgical System, a commercial product, is a powerful robotic surgical system that allows a surgeon's hand movements to be scaled, filtered and translated into precise movements of micro-instruments within the operative site (Intuitive Surgical Inc. 2005). In our work, we propose a design that addresses many of the limitations of existing systems and advances the state of the art in surgical training, assessment and guidance in laparoscopic surgery.

DESIGN OVERVIEW

We envision a platform where sensor based tracking permits information to be gathered about surgical instruments used in a procedure. Our design features the embedding of micro-sensors into the instruments employed for simulation training. The detection and recording of instrument movement would permit our system to not only measure a trainee's progress in acquiring psychomotor skills and compare these data to normative databases, but also to evaluate instrument effectiveness in reducing error. From a training perspective, the sensor based system shall track and return information on various performance metrics such as position and velocity of instruments, total path length of motion, erratic movements, time taken, number of attempts, dexterity, etc. From a surgical assistance perspective, the system shall be capable of providing surgeons with guidance and feedback during a surgical procedure.

Our vision is to bridge the gap between VR systems and pelvi-trainers and combine the advantages of both approaches to design a system that is simple, yet effective and efficient. We propose a knowledge-based sensor system, which can provide training prior to surgery and assistance during surgery. The design employs sensor technology, knowledge-based engines and robotics.

Framework

In Figure 1, the system on the left is a model of the traditional system, where the surgeon acts upon the patient or simulator through instruments and receives visual and force feedback. The system on the right is a model of the proposed design where the surgeon acts upon the patient or simulator through instruments and receives visual and force feedback, which is also supplemented by guidance feedback from the supervisor both in training and OR settings. The supervisor represents the sensing interface and the knowledge-based computer system.

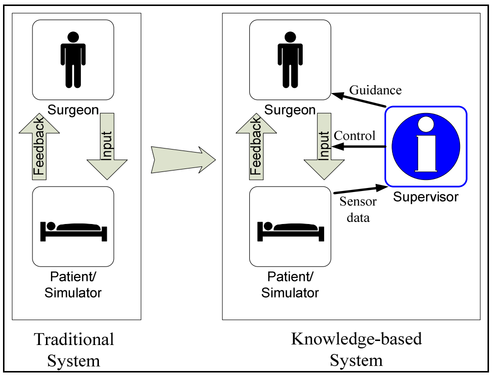

Figure 1: System Framework

Knowledge-based inference system

The supervisor is the kernel of the system. It consists of a sensor fusion engine at the front-end and a knowledge based inference system at the back-end. A senior surgeon or instructor, represented by 'Expert' in Figure 2, could optionally be present to provide additional guidance and feedback.

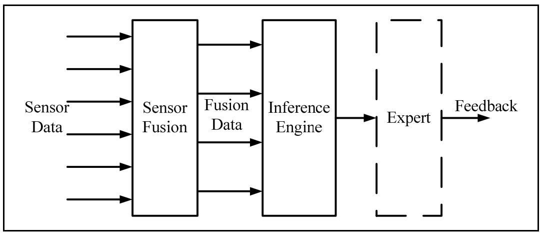

Figure 2: Supervisor Structure

The numerous sensing elements in the system call for a sensor fusion engine. The output of the fusion engine feeds into the knowledge-based inference engine, which processes the available information and makes decisions.

Surgeons maneuver instruments to perform a variety of functions. Through training, they need to gain a clear feel for what constitutes safe and correct movements. During a surgical procedure in the OR, potentially harmful movements must trigger an alarm or must be prevented altogether if possible, by the system.

In order to achieve this, we implement capabilities for motion rule checking and real-time feedback. The motion rules are a set of a priori knowledge regarding safe and correct moves for a specific training or surgical procedure. These rule sets define a safety envelope for instrument position, velocity, total path length of motion, sequence of operations, etc. We use configuration space based techniques to perform motion rule checking. We model the tips of the instruments as points in Configuration Space (C-space), analogous to robots in C-space. Potential field methods of motion planning are employed to help the system determine the ideal direction of motion based on current position. Potential field methods use an imaginary force field (U) to influence motion towards goal states and away from obstacles and other forbidden areas. We compute the artificial force (F) (attractive towards the goal state and repulsive towards obstacles and other forbidden regions of C) given by

$$\vec{F}(q) = -\nabla U(q) \tag{1}$$

We develop the knowledge-based inference system as a program that could utilize numerous rules in an attempt to model the decision-making processes of experts. This allows the system to determine whether a particular action is potentially harmful, the reason(s) why the action could be harmful, and present appropriate feedback to prevent injury and reinforce correct technique. The flow diagram of the inference system is illustrated in Figure 3.

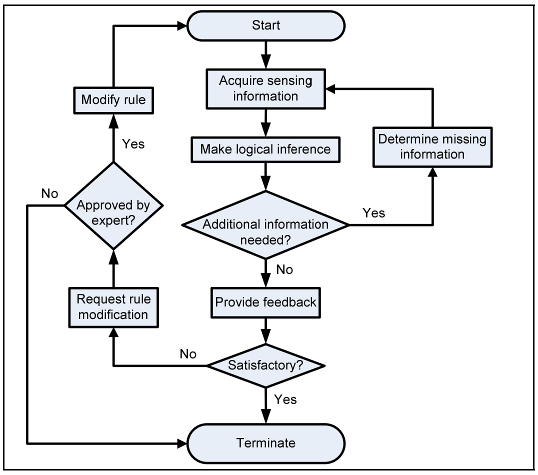

Figure 3: Process Flow of Inference System

The decision step following the feedback step, enables the user to request a modification of the rule base if the inference system provides inaccurate or unsatisfactory feedback. An expert can review the request and make modifications as appropriate to the rule base.

Unlike the general clinical diagnosis system MYCIN (Ledley 1969), our system focuses on the area of minimally invasive surgery, which means the knowledge space is finite and complete profile information is available. As a result, we are able to implement certainty factors for symbolic reasoning approaches within the knowledge-based system.

The supervisor will also be capable of selecting and displaying helpful tutorials, video clips and anatomical drawings during a training session to address the various levels of learning, ranging from basic psychomotor skills to procedural and anatomical knowledge.

Sensor technology

Sensors are a key element of the system. Figure 1 illustrates how sensors can enhance traditional modes of training. The additional feature of embedding micro-sensors into the actual instruments employed during simulation training not only permits us to establish normative data for training protocols but also allows us to quantitatively compare instruments and even individual manufacturers. Furthermore, as additional ergonomic designs appear, they could be quantitatively assessed to accelerate development and proliferation of instrumentation that demonstrate significant improvement over existing designs. Finally, the ability to link VR-based anatomic fields with the actual movement of individual instruments during a simulated procedure could assist in the development of so-called “smart” instruments. “Smart” instruments could not only teach surgeons during training sessions by actually mimicking the movements of expert surgeons but could also be programmed to restrict instrument movements only in specific areas (“fly-zones” versus “no fly-zones”) to enhance surgical safety.

There are two types of sensor data that can be used, one is medical data, such as electrocardiogram (ECG), blood pressure (BP), etc. The other kind of data is those gathered from the instruments being used in the procedure. For example, visual data obtained from the laparoscope, and instrument motion information obtained from mounted micro-sensors. We use sensor fusion to combine sensory data from disparate sources. The source of information includes sensors such as laparoscopic camera, 6 degrees-of-freedom (DOF) magnetic kinematics sensors and reference information such as the safety operational area. Different data processing levels are involved within the sensor fusion module. The first level is source preprocessing, which can distribute data to appropriate process and synchronize the other processes to the current situation. At this level, the data that come from different sensors will be normalized for further operation. The second level is the object refinement level, which is the most important part in our approach. It can estimate the position and kinematics of the objects and apply statistical measurements. It also transforms sensor data into a consistent coordinate.

An example is the hybrid view, shown in Figure 4, indicating the movement of the instruments in the surgical space. It fuses information from the video image of laparoscope and motion data of the instruments. This view can help confirm the erroneous movements made by overlaying positions of organs and objects with the path history of the instruments.

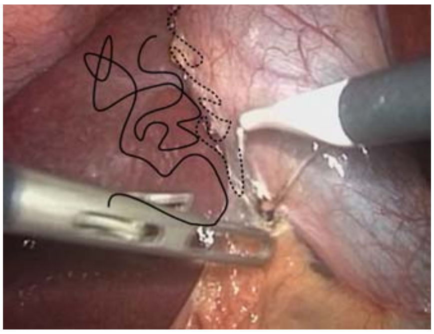

Figure 4: Hybrid View

Guidance feedback

In the OR setting, the system could provide real-time feedback to assist surgeons during a procedure. The inference engine could process motion data from the micro-sensors embedded in the surgical instruments and provide the surgeon with a virtual bound for instrument motion and manipulation. Intrusion into "no fly-zones" would trigger an audio-visual alert. In a training setting, the trainee would be required to repeat the motion within the safety bounds until motion rule check passes. This enforced learning process should help the trainee master necessary basic skills.

TRAINING SYSTEM PROTOTYPE

The first phase in our vision is developing a system that can provide a platform for medical students to master some of the many skills required in laparoscopic surgery. We have developed a system prototype that provides tracking, performance assessment and feedback. The training system consists of a pelvi-trainer, a pair of motion micro-sensors capable of tracking movement of the instruments with 6-DOF and a computer to process data and provides feedback.

Sensor setup

Position sensors mounted on the tip of each instrument gather data in real-time. We use the microBIRD 3D sensing system developed by Ascension Technology Corporation for this purpose (Ascension Technology Co. 2006). The sensing system includes a magnetic field transmitter, two position sensors (1.3mm in diameter) and a PCI interface data processing card. The measurement rate is 68.3 Hz with linear accuracy of ±1.4mm and rotational accuracy of ±0.5 degrees. The transmitter remains fixed to provide a Cartesian frame of reference for position tracking.

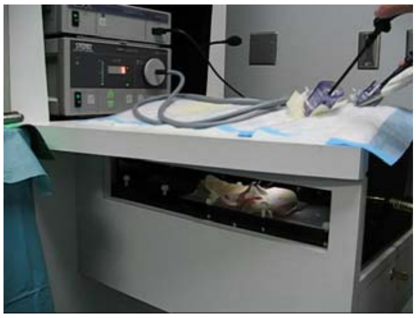

Figure 5: Pelvi-trainer equipped with MicroBIRD sensors

Tracking and performance assessment

The position data obtained from the microBIRD sensors is written to a linked-list data structure with a time stamp for tracking and recording movements. From this data, the inference engine calculates key instrument motion metrics. Some of these metrics include total path length, average speed, instantaneous speed, average radius of motion and number of times "no-fly zones" were breached. Table 1 lists equations for some of the performance metrics measured. In Table 1, t_{P_i} is the time stamp of point i, whose position vector is P_i. Performance assessment will be based against the "steepest descent" path in the C-space. Movement towards the steepest descent path will earn credit and movement towards obstacles will impose penalties. An overall score will be computed upon completion of the procedure. The score will also be affected by the time taken to complete the procedure successfully, the number of collisions with obstacles or other instruments, dexterity and intrusions outside the C-space region.

Table 1: Performance metric equations

Metric	Equation
Total time T (s)	$T = t_{P_{i+1}} - t_{P_0}$
Total path length L (cm)	$L = \sum_{i=0}^{n-1} \lvert P_{i+1} - P_i \rvert$
Average speed S(cm/s)	$S = L / T$
Instant speed s(cm/s)	$s = \lvert P_{i+1} - P_i \rvert / (t_{P_{i+1}} - t_{P_i})$
Motion area radius R(cm)	$R = \left(\sum_{i=0}^{n-1} \left\lvert P_i - \left(\sum_{i=0}^{n-1} P_i \right) / n \right\rvert \right) / n$

Context rules are constructed based on empirical expert knowledge about laparoscopic surgical processes. A forward chaining process, using real-time data searches the inference rules to assess performance. An inference engine using forward chaining methods of reasoning operates by searching the inference rules until it finds one where an *"If"* clause is determined to be true. When found it can conclude, or infer, the *"Then"* clause, resulting in the addition of new information to its dataset. The inference module can use these rules to assess the trainee's performance in real-time and provide appropriate feedback. The system displays instrument position and orientation in 3D using OpenGL 3D software libraries. Figure 6 illustrates one of the views available on the system showing instrument tracks, and "no-fly zone" breaches.

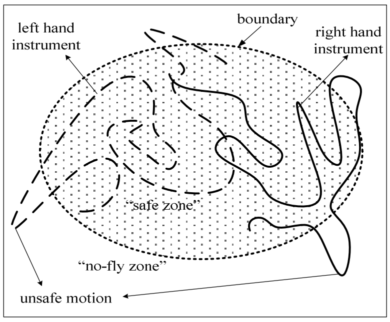

Figure 6: Tracking diagram

APPLICATION AND RESULTS

The prototype developed is capable of acquiring data from the microBIRD sensors, and using this information to track and record instrument motion during training. Figure 7 displays a screenshot of the tracking view of the program, where the curve represents the path track of the instrument and the cones represent orientation. The 3D tracking view is overlaid with the laparoscope image to create the hybrid view discussed earlier. "No-fly zones" can be optionally viewed if necessary.

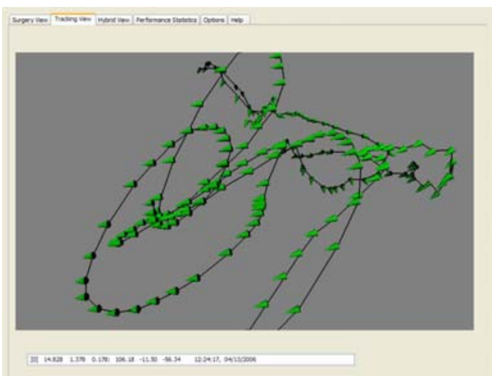

Figure 7: Tracking view screenshot

The optimization of three-dimensional tracking and linkage to the deployment of instruments within a VR-based anatomical landscape would establish a powerful platform whereby both ergonomic, optical, and image-guidance technologies could all be quantitatively assessed to determine cost-benefit ratios. Obviously, innovations that produce statistically significant reductions in unnecessary, redundant, or even dangerous movements could be embraced more readily than designs that do not affect tangible results.

CONCLUSION

The aim of our work here has been to address the difficulties involved in laparoscopic surgical training. We use sensors and model based system design techniques in order to overcome the limitations of existing solutions such as pelvi-trainers and virtual reality systems. The knowledge-based assistant described here offers a new approach for mitigating the complications of laparoscopic surgery by providing an additional dimension of input to surgeons. The prototype discussed will continue to undergo further software and hardware development to meet the specifications for use as a standard assessment tool. The field of simulation in medicine is expected to closely parallel many of the paradigms that exist in other industrial and military situations where VR-based training has now become a standard part of training, accreditation, and maintenance of skills. The diffuse nature of medical intervention – from first responders at the scene to the most advanced operative interventions – will require reliable, robust, and flexible instrumentation assessment. We believe that the model proposed is an important step in the design of a new generation of VR-based trainers whose application will be initially assessed specifically in minimally-invasive surgery and tested against current, commercially available trainers.

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AUTHOR BIOGRAPHIES

CHUAN FENG is currently pursuing his Ph. D. in Electrical and Computer Engineering at The University of Arizona. He holds an M.Sc degree in Computer Science and Technology and a B.Sc degree in Electrical Engineering from Tsinghua University, China. His research interests are in the areas of model based systems design, applications of wireless sensor network, network security and virtual reality simulation.

HANEES HANIFFA is currently pursuing his M.Sc degree in Electrical and Computer Engineering at The University of Arizona. He received his B.Sc degree in Computer Engineering from The University of Arizona. His research interests are in the areas of system design, modeling, simulation and bioengineering.

DR. JERZY ROZENBLIT is Professor and Head of Electrical and Computer Engineering at The University of Arizona. His research and teaching interests are in the areas of complex system design, AI and simulation modeling. His research in design has been supported by the National Science Foundation, Siemens AG, Semiconductor Research Corporation, McDonnell Douglas, NASA, and the US Army Research Laboratories. Dr. Rozenblit serves as Associate Editor of ACM Transactions on Modeling and Computer Simulation, Associate Editor of IEEE Transactions on Systems, Man and Cybernetics, and Executive Board Member of IEEE Technical Committee on Engineering of Computer Based Systems. He was Fulbright Senior Scholar and Visiting Professor at the Institute of Systems Science, Johannes Kepler University, Austria and has held visiting professorship appointments at the Technical University of Munich, Central Research Laboratories of Siemens AG, and Infineon Technologies AG, in Munich.

JIANFENG PENG is currently pursuing his Ph. D. in Electrical and Computer Engineering at The University of Arizona. He holds an M.Sc degree in Electrical and Computer Engineering from the University of Arizona and a B.Sc degree in Electronic Engineering from Tsinghua University, China. He is currently a research engineer working on decision support and visualization systems, parallel computing, wireless sensor networks, and network security.

DR. ALLAN HAMILTON, MD is Professor of Surgery and Executive Director of Arizona Surgical Technology and Education Center (ASTEC). He is also Professor of Psychology-Surgery and Clinical Professor of Radiation/Oncology. He received his MD from Harvard Medical School and served his internship and residencies at Massachusetts General Hospital in Boston. The recipient of several international awards for his groundbreaking work in the area of minimally invasive stereotactic neurosurgery of the spine, Dr. Hamilton treated the first spinal radiosurgery patient in the world. Among many innovations, he developed techniques for shielding the spinal cord from excessive radiation during stereotactic radiosurgery. He also invented a device for using laser guidance systems to aim beams of radiation at spinal cord tumors without damaging the spinal cord.

DR. MOHAMAD W. SALKINI, MD, Urologist, and Minimal Invasive Surgery (Laparoscopy and Endourology) specialist. He attended medical school at Damascus University Medical School (1992-1998). He attended urology residency at Damascus University Urology Residency Program between 1998 and 2002, and received his training in Minimal Invasive Surgery from the University of Heidelberg (Germany) 2003-2004. In 2004 Dr. Salkini joined ASTEC as a surgical instructor where he develops curriculum and teaches laparascopic simulation to attending physicians, surgical residents and medical students.