

Defining spatial regions in computer-assisted laparoscopic surgical training

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Abstract

To provide appropriate guidance in minimally invasive surgical training (and potentially an additional safety measure in the operating room), we propose a model called a “No-Fly Zone” based on the situational awareness enhancing system. By defining the configuration space of the instrument, a collision free region is defined. If an intrusion occurs into the no-fly region space, the system provides audio, visual, and haptic feedback to reinforce an appropriate maneuver. The proposed method is intended to refine surgical skills and to improve the patient safety. Usability experiment will be performed to test the system.

1. 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 by CO₂, 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 surgeon then inserts surgical instruments through strategically placed trocars, which are tubes with cutting capability, and performs the operation while viewing the operating site on a 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, this procedure 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.

Moreover, many complications specific to MIS can result in major morbidity or potential mortality. To minimize the disadvantages of the technology, research has focused on the development of methods for training both students and practicing surgeons effectively.

According to Gallagher [3], the goal of any surgical training program is to help surgeons automate their basic psychomotor skills before they operate on a patient (“the more innate visuospatial, perceptual, and psychomotor ability the surgeon has, the faster he or she will automate the surgical skills” [3]).

One representative simulation training tool-set is called the virtual reality simulators (VRS) [4]. VRS systems use a computer to simulate the entire training procedure. Trainees interact with the simulator through a specially designed interface. Hamilton [13] reports that the VRS simulator has the capability to report minor errors for each task performance. Due to the current technical constraints, VRS simulations provide inadequate perception of reality and inaccurate haptic feedback [11]. Those limitations make the performance of a VRS simulator as a training tool questionable [16] [17]. Therefore, a number of physicians prefer to use another kind of simulation tool-set called the pelvic trainer [12]. Different from the exorbitantly costly VRS systems, a pelvic trainer is just a simple box with apertures that simulates the abdomen [12]. Trainees use real instruments to practice basic skills and observe the operating scene through a video display. The pelvic trainer provides higher degree of realism and haptic feedback. The main limitation of this approach is the absence of objective performance assessment. The only quantitative measurement device used in most of

the educational and clinical research is the stopwatch [14], [15].

Therefore, our goal is to bridge the gap between VR simulators and pelvic trainers and to develop a fully integrated training system for MIS. By utilizing multiple sensors and computerized processing technology on real surgical instruments, we developed a Situational Awareness Enhancing System (SAES) [5]. The SAES provides a high fidelity training environment as well as objective performance assessment capabilities. Since we implement the SAES using real instruments, it can be used to support real operating room procedures, including real time sensor fusion, run-time surgery guidance, and emergency safety reinforcement.

In this paper, we focus on the safety movement detection, working space boundary checks, and feedback problems. We call this the “No-Fly Zone” component.

The computer generated “No-Fly Zone” provides additional safety checking when training and has a strong potential for guidance in the operating room setting. In training, the trainee would be required to repeat the motion within the safety bounds until a motion rule check is passed. In a real operating procedure, the instrument movements could be restricted only to specific areas to enhance surgical safety.

In the reminder of this paper, we discuss our proposed approach in detail. In section 2, the SAES system is introduced briefly. In section 3, the No-Fly Zone is described; in section 4, the prototype system is presented. Section 5 summarizes and concludes the paper.

2. Situational Awareness Enhancing System (SAES) Introduction

The ultimate goal of our system is to offer another dimension of sensing, data processing, and feedback capabilities that can not be achieved by human being.

The SAES features embedding of micro-sensors into the surgical instruments. By detecting and recording instrument movements, the system can measure a trainee’s progress in acquiring psychomotor skills.

To our knowledge, this SAES is the first approach to embed micro-sensors into the instruments employed for traditional pelvic-trainers. The system model structure is shown in Figure 1. The perception layer provides the awareness of objects and their states. This layer comprises sensors and tracking mechanisms. The comprehension layer is used to understand the state of

the system. It consists of the assessment engine and sensor fusion engine. The projection layer evaluates the situation and its possible further states. This design layer focuses on a high level reasoning system. It is achieved by a knowledge-based inference engine, optimal path generator, and the No-Fly Zone generator.

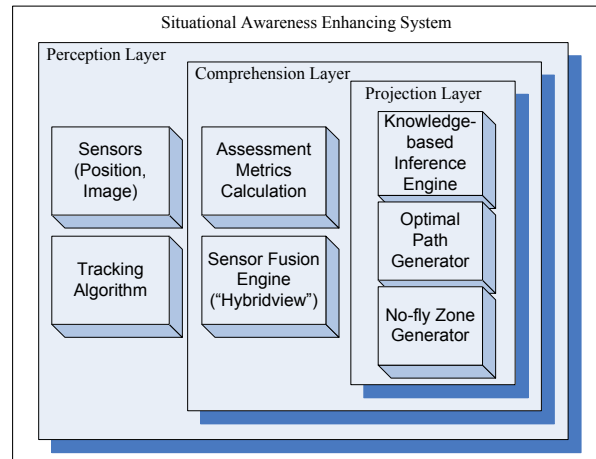


Figure 1 System model structure

Sensors are a key element of the system. From the data obtained from the position and image sensors, the inference engine calculates key instrument motion metrics. Sensor fusion technology is used to combine sensory data from disparate sources. These sources of information include the 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 engine to provide effective information representation while reduce cognitive overhead of the users [20].

To evaluate the situation within both training and operating room settings, we implement capabilities for objective performance assessment. Context rules are constructed based on empirical expert knowledge about laparoscopic surgical processes. A fuzzy inference engine uses these rules to assess the performance in real time and to provide appropriate feedback [21]. Because the knowledge-based inference engine is developed as a program that models the decision making processes of experts, it allows the SAES system to determine whether a particular action is potentially harmful, the reason(s) why the action could be harmful, and present appropriate action to reinforce correct skill or prevent injury.

The inference engine can then calculate a virtual bound for instrument motion and manipulation to assist surgeons during a procedure. By overlapping the optimal path with the virtual bound, a computer

generated “No-Fly Zone” is introduced to provide additional safety checking for both training and operating processes.

3. No-Fly Zone Design

Analogously to the concept borrowed from aviation, our No-Fly Zone has a clear boundary between safe and un-safe regions. Any intrusion into the un-safe zone will trigger an alert. Thereafter appropriate feedback methods will be selected and used to give the user either a warning or stop the maneuver.

3.1. Working space definition

We use configuration space-based techniques [1] to define the working space of the instruments.

The first step is to model the instruments in their configuration space. To do so, we consider the problem of a rigid instrument A moving in a Euclidean space $W = R^3$, equipped with a fixed Cartesian coordinate system, denoted by F_W . We also represent a moving coordinate system F_A attached to A so that each point in the instrument has consistent coordinates in F_A (Figure 2).

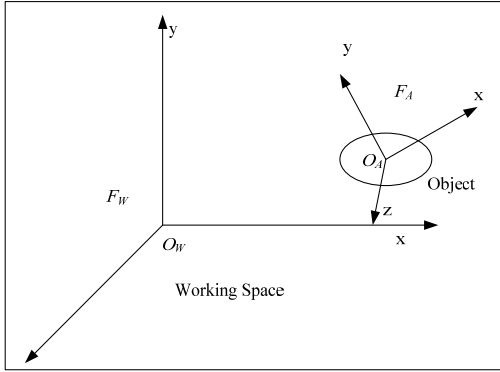


Figure 2 Working space and object coordinates

The origin of F_W is O_W , and the origin of F_A is O_A . O_A is the reference point of A .

The configuration space of A is the space C of all the possible positions of A , subject to external constraints. Now, suppose W contains a series of physical obstacles B_i , $i = 1, 2, \dots, q$. Each obstacle B_i in W maps in C space to the region CB_i , which is called a C-obstacle.

$$CB_i = \{q \in C \mid A(q) \cap B_i \neq \emptyset\} \quad (1)$$

In our application, the main task is to define the C-obstacles. There are several different kinds of C-obstacles in the current SAES application. The first one is the safety space boundary; the second one is the objects within the safety boundary; the third one is the opposite instrument; and the fourth one is the additional constraints. In the following, they will be introduced in detail.

3.1.1 C-obstacles with safety space boundary

Safety space boundary, we call it CBs_i , is the most important C-obstacles in our application. Usually, the safety space boundary consists of the working space boundary and the boundary of the sensing space. Working space is the internal of a convex polyhedron; the sensing space is related to the features of the sensing devices. The sensing space of the widely applied endoscope is a cone. The safety region is defined as the combination of these two spaces. As the example in Figure 3 shows, the left figure indicates the safety space. The sensing space is the cone area indicated by the transverse lines determined by the endoscope. The working space is the rectangle area indicated by the horizontal lines. The intersection set of both spaces, gray area indicated by the cross line, is the safety space. The boundary of the safety space is a closed polygon, we call it obstacle Bs_i . In order to provide some kind of "safety-zone" around the instrument such that feedback about a collision is given before the actual instrument-tip intersects the no-fly zone, the instrument tip is modeled as a sphere. The size of the sphere is determined based on the possible maximum speed of the instrument.

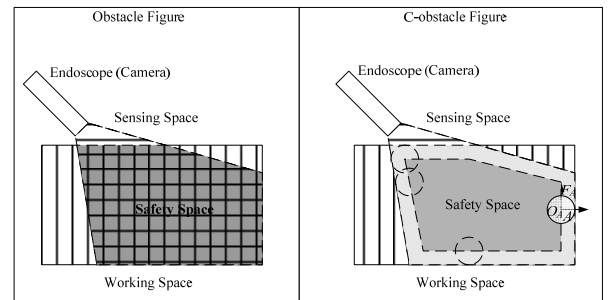


Figure 3 Safety boundary illustrations

In the right picture of Figure 3, let the tip of the instrument be a sphere A , with O_A at the center of the sphere, then the C-obstacle CBs_i is obtained by “shrinking” Bs_i isotropically by the radius of A . The CBs_i is the curve following by O_A as A rolling over

the boundary of Bs_i . In the right picture of Figure 3, the boundary of the darker gray area is the C-obstacle, which is everything outside the boundary.

3.1.2 C-obstacles with the objects within the safety boundary

Objects within the safety boundary are also considered as C-obstacles. We call them CBt_i . The objects can be targets or obstacles within the safety zone. To obtain the CBt_i , we used a two step method. In step one, we obtain a C-obstacle CBt'_i by “enlarging” the obstacle Bt_i isotropically by the radius of A (Figure 4).

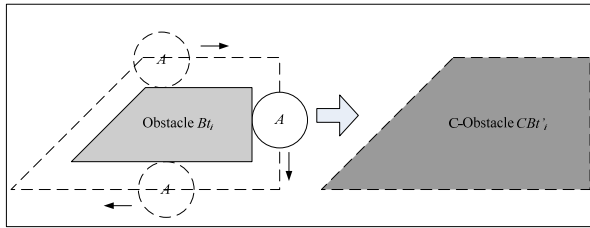


Figure 4 Objects' C-obstacle

For each instrument, there is a unique insertion point in MIS, this insertion point limits the degree of freedom of the instrument from 6 to only 4 (depth I , pitch α , yaw β , and roll γ). This means some places within the working space that are blocked by Obstacle Bt_i are inaccessible by the rigid instrument. Therefore, the second step is to get another C-obstacle CBt''_i by calculating the shadow of the C-obstacle CBt'_i according to the insertion point. An example is shown in Figure 5. Suppose we have a plane P , which is bottom of the safety boundary, and a rectangle block C-obstacle $abcd-efgh$ is standing on the plane. In actual operation, P can be a plane, or curve, or some irregular edge. If a point light source is placed at the insertion point o , there will be a shadow cast by the rectangle block on plane P . The projection is done by drawing a straight ray from the insertion point to the obstacle, and the extension line from the vertex of the obstacle to the plane P is the edge of the shadow. By connecting the edge of the shadow, we can get a polyhedron indicated by gray color in the figure. This polyhedron is the C-obstacle CBt''_i . And the C-obstacle CBt_i is obtained by

$$CBt_i = CBt'_i \cup CBt''_i \quad (2)$$

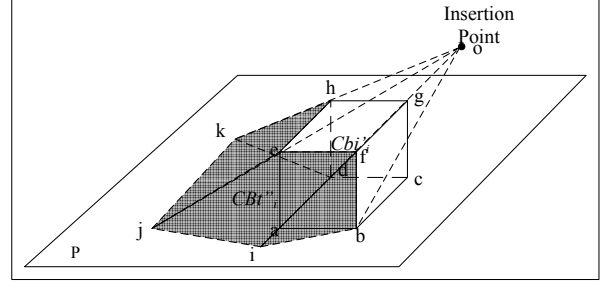


Figure 5 Shadow area of the C-Obstacle

3.1.3 C-obstacles with the opposite instrument

In general, there are more than one instrument within the operating area. The opposite instrument may become an obstacle, too. We call it the C-obstacle CBi_i . The method to get CBi_i is the same as the two step method used to calculate CBt_i from objects within the safety area. The only difference is that the object is the opposite instrument. Therefore, the object changes its position in real time.

3.1.4 C-obstacles with additional constraints

Besides all the C-obstacles introduced above, some other C-obstacles may exist. We call these C-obstacles CBo_i . These C-obstacles are generated according to additional constraints. For instance, during the hand-eye coordination training, giving the trainees some guidance about the correct movement is very important. An optimal path will then be calculated in advance. There are various methods to generate an optimal path based on different requirements.

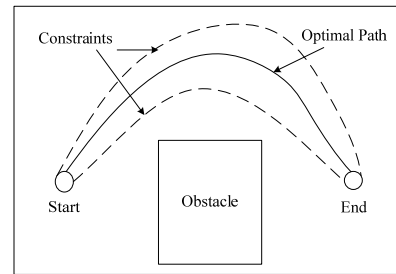


Figure 6 Additional constraints

As shown in Figure 6, the trainee needs to move the instrument from the start point to the end point, avoiding the obstacle in between. In order to enforce the trainee to follow the optimal path we generated, additional constraints are applied. Therefore, the trainee will get a warning and a corresponding

“penalty” if he or she collides with the constraints. Similarly as for the safety space boundary, the additional constraint CB_{o_i} is the internal edge of a closed polygon.

The universal set of the C-obstacle is the union of all the C-obstacles we introduced above.

$$CB = CB_s \cup CB_t \cup CB_i \cup CB_o \quad (3)$$

Where $CB_x = \bigcup_{i=1}^{n_x} CB_{x_i}$, here $x \in \{s, t, i, o\}$, n_x is the number of individual obstacles. During the training or operating room applications, the free working space of the instrument will be defined by:

$$C_{free} = C \setminus CB \quad (4)$$

where C is the configuration space and CB is the union of all the C-obstacles. C_{free} is the free configuration. Any collision free path within the configuration space is a continuous map $\tau: [0, 1] \rightarrow C_{free}$, with the start point $\tau(0) = p_{init}$ and end point $\tau(1) = p_{end}$.

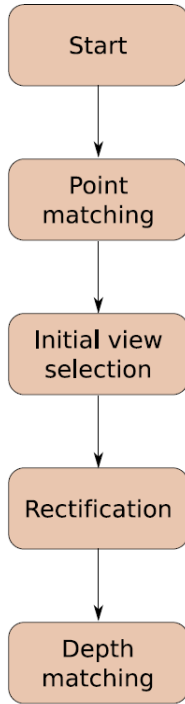


Figure 7 Outline of the 3D reconstruction processing pipeline

For the purpose of defining the initial geometry of the working space and the positions of C-obstacles a

structure-from-motion approach is used. The 2D images from the laparoscopic camera are processed through a series of algorithms to obtain a rough 3D structure of the working space and the C-obstacles [23] [24] [25]. The input images can be obtained in a natural manner during the initial phase of an exercise (or surgical procedure), when the trainee performs a series of camera movements to see the whole operating field.

3.2. Dynamic Adjustment

During the training or operating procedures, the C-obstacles we defined above may change. Therefore, we need to adjust the C-obstacles in real time.

The first changeable C-obstacle is the opposite instrument CB_i . Because the user needs to move the instrument most of the time, we need to sense the latest position of the instrument and update its CB_i for the free space calculation.

The endoscope is a rigid body. Thus, the direction and position of the camera need to be adjusted so that the user can observe the operating area clearly. When the camera moves, the world coordinates will not move, so there exists a transform matrix M that indicates the position and orientation of the camera's movement. In other words, this transform matrix maps the relative movement between the world coordinates and the camera coordinates. The mapping function is:

$$P'_c = M \cdot P_c \quad (5)$$

where $P_c = (x_c, y_c, z_c)$ represents the position vector before the camera moves, and $P'_c = (x'_c, y'_c, z'_c)$ is the new position vector after the camera moves. For a simplified linear camera model, direct linear transformation (DLT) can be used to extract pixel coordinates from the 3D coordinates [18]. After a careful calibration, an isomorphic mapping function can be built as below:

$$\lambda \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = f(X_c) = f\left(\begin{bmatrix} x_c \\ y_c \\ z_c \\ 1 \end{bmatrix}\right) \quad (6)$$

where u, v are the pixel coordinates in image plane and x_c, y_c, z_c are the 3D point coordinates relative to the camera. Thus, if we have the camera movement matrix M , it is easy to determine whether a point is in the sensing space (camera field of view) by calculating whether the pixel coordinates u, v are in a reasonable position of the image plane. Through this method, we can update the safety space boundary CB_s in real time.

Because tissue is elastic, it may be compressed or stretched observably under exogenous processes. Sometimes, the topology of the tissue can be changed due to cutting. Therefore, the formations of the objects within the safety space boundary change in real time. The C-obstacles CB_t must respond rapidly to interactive manipulation. It should closely approximate the behavior of tissues as they are being stretched or cut. Currently, physically-based models can incorporate material properties. Mass-spring and finite-element models are by far the most common methods used in surgical simulation [22].

3.3. Feedback Mechanism

The interaction between surgical tools, tissues, and organs requires collision detection. Currently, most techniques adopt a two-level approach [2]. First, a computationally inexpensive method bounds the region of intersection, and then a slower method determines the exact collision location. The most natural measure of proximity is the Euclidean distance between the objects, the length of a shortest line segment joining the two objects. The key element of this approach is an algorithm for computing the distance between convex bounding sets in a 3-dimensional space. Objects that can potentially collide are bounded by spheres. Unless bounding spheres intersect, collision is not possible between the objects. For long, thin objects such as surgical instruments, bounding boxes have been used instead of a sphere. One example is axis-aligned bounding boxes (AABB) [2]. The intersection of AABBs occurs if their projections onto all coordinate axes overlap (Figure 8).

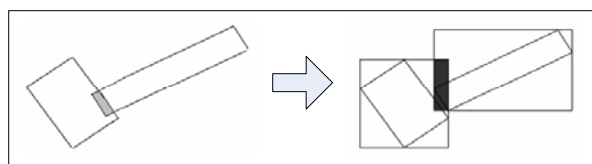


Figure 8 Collision detection

In Figure 7, when the two bounding boxes overlap, we can determine if a collision occurs. If we detect any collision between the instrument and C-obstacles, feedback will be given.

In general, the computer can display feedback information through three channels: audio, visual, and haptic display. Displaying the information visually on the video monitor used for observing the operation is the most straightforward technique. The current position of the instrument, where the collision point occurs, how serious the violation is, and how to avoid

the violation can be displayed on the monitor as well. Guidance information can also be displayed visually.

In addition to the visual display, audio warning sound, verbal guidance, and alert information can be given at the same time.

Besides the conventional multimedia feedback information, force feedback will be implemented to give the user additional guidance and security guarantee. The ability to link haptic devices with the SAES will assist in the development of the so-called “smart” instruments.

When the system detects a mistake made by the trainee, a “smart” instrument provides “resistance” to prevent further error. This approach gives students enhanced training ability. It also provides a new type of safety guarantee capability for the future use during the real operating procedure.

4. Prototype System

Currently, we are developing the prototype SAES system with the proposed No-Fly Zone technique. The prototype training system is illustrated in Figure 8. Users employ real surgical instruments. As shown in the figure, the targets were embedded into LEGO® bricks for easy reconfiguration. The computer selects a target randomly and sends commands to the target control board. Multiple LEDs with different colors were applied to give a user an indication as to which target to reach. When a target is touched by the tip of a right-hand or left-hand instrument, information is transmitted to the computer. The trajectories of the movements are recorded by 6-DOF kinematics sensors mounted on the instruments.



Figure 9 Prototype system

Our experiment features various metrics for the assessment of hand-eye coordination tasks: dominant hand vs. non-dominant hand, speed of movement, movement economy ratio, and movement proficiency.

The analysis also considers how many years of medical experience the participant has and if he or she has received MIS training before.

The No-Fly Zone will be introduced into the system and a series usability experiments will be conducted in the Arizona Simulation Technology and Education Center (ASTEC) at the University of Arizona Medical Center.

5. Conclusion

In this paper, we have introduced the design concept of the situational awareness enhancing system for minimally invasive surgery. The training and operating safety enhancing guidance model – “No-Fly Zone” has been presented. By defining the configuration space of the instrument, we can provide a collision free working space for users. If any intrusion into the unsafe region occurs, the system will provide audio, visual, and haptic feedback to give users assistance and to reinforce training. A usability experiment will be performed to test the system.

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