

Tool Tracking in a Laparoscopic Virtual Reality Training System¹

Mohsen Zahiri

Department of Mechanical and Materials Engineering,
University of Nebraska-Lincoln,
Lincoln, NE 68588

Ryan Booton

College of Public Health,
University of Nebraska Medical Center,
Omaha, NE 68198

Carl A. Nelson

Department of Mechanical and Materials Engineering,
University of Nebraska-Lincoln,
Lincoln, NE 68588

Ka-Chun Siu

School of Allied Health Professions,
University of Nebraska Medical Center,
Omaha, NE 68198

1 Background

Minimally invasive surgery (MIS) is replacing the open surgical approach to reduce pain, expedite patient recovery, shorten hospital stays and improve cosmetic results for many abdominal procedures. It is widely accepted that the increased technical difficulty of MIS approaches (difficult visualization, tool fulcrum effect, etc.) requires specialized surgical training. The fundamentals of laparoscopic surgery (FLS) program has become a *de facto* standard to evaluate surgical skills for laparoscopic MIS [1].

Simulation-based surgical training has been growing not only as an innovative way to teach surgery [2] but also as a method to assess the skill of a surgeon in performing a procedure, without risk to patients [3]. However, cost and ease of access are two important limiting factors which make most surgical simulators ill suited for practical processing of high volumes of surgical trainees. We aim to develop a new simulation training device that enables surgeons to improve their skills in a flexible and accessible way.

We use cameras to track tool motion [4] and relay that information to a virtual reality environment. In Ref. [5], a general concept of the design and determination of appropriate workspace visualization were discussed. The fabrication process was explained and the first prototype was presented. In this paper, the computer vision and image processing aspects of the surgical simulator are described; these are used to detect the motion of the tool in the physical simulator and map these movements into a virtual surgical environment (Vizard, WorldViz, Santa Barbara, CA) for visualization. Pilot virtual simulation tasks are also described.

2 Methods

2.1 Image-Based Tracking. An image-based method is used to send grasper motion data into the simulator by using video from a pair of cameras, which are calibrated using toolboxes available with MATLAB software. A pose estimation algorithm [6] uses the planar homography matrix and four colored markers to



Fig. 1 Four colored markers mounted on the surgical tool

locate the cameras in our setup. The 3D position of the grasper is determined by the relations between the camera coordinate systems and the global coordinate system. This algorithm enables the user to change the cameras' positions for simulating various surgical tasks which may use different workspaces.

A four-colored marker is attached to the end of the grasper as shown in Fig. 1. The image processing algorithm is used to detect the positions of these markers in the two 2D camera images and combine these two datasets to map their locations in the 3D space.

The red-blue-green color space is used to find the position of the markers against a white background as frames are streamed from the cameras. The differently colored markers are arranged to minimize occluded views and detect rotation about the tool shaft. The color threshold module is used to segment the colored dots in the images by using the MATLAB image processing toolbox. The colored dots are extracted by subtracting the channel color of the image from the grayscale of the images and extracting the pixels whose value exceeds the threshold.

After calibrating the position of the cameras, the 3D positions of the markers are identified with respect to the 2D color-filtered images by applying a triangulation method. In this method, the nearest point from the projection line to the 3D position of the object is calculated, as illustrated in Fig. 2 [7].

In the first step, we determine the direction of the 3D rays by calculating the unit vector pointing from the camera center to the object.

$$V_j = \mathcal{N}(R_j^{-1}K_j^{-1}X_j)$$

The nearest point for each camera is calculated as follows:

$$q_j = c_j + v_j(v_j^T(P - C_j))$$

The square of the distance between P and q is

$$r_j^2 = \|P - (C_j + (v_j v_j^T)(P - C_j))\|^2$$

By taking the derivative with respect to P and setting it equal to zero, we will have

$$p = \left[\sum_j (I - v_j v_j^T) \right]^{-1} \left[\sum_j (I - v_j v_j^T) C_j \right]$$

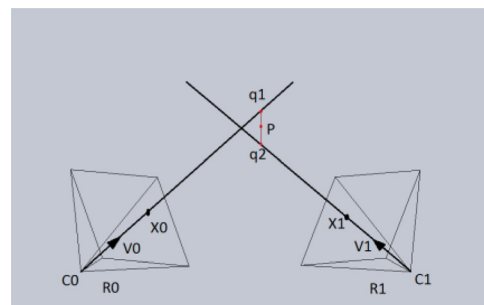


Fig. 2 The 3D position of the object

¹Accepted and presented at the Design of Medical Devices Conference (DMD2014), Minneapolis, MN, April 7–10, 2014.

DOI: [10.1115/1.4027051](https://doi.org/10.1115/1.4027051)

Manuscript received February 21, 2014; final manuscript received March 3, 2014; published online April 28, 2014. Editor: Arthur G. Erdman.

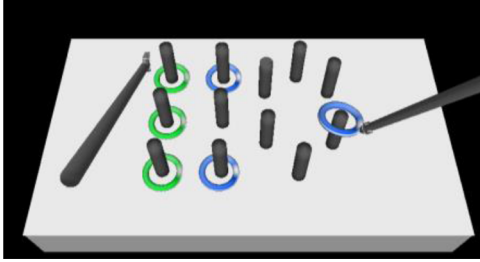


Fig. 3 Virtual training environment: peg transfer task

In this way, the surgical grasper has been localized in the 3D space. The grasper has three rotational degrees of freedom (DOF) and one translational motion along the tool axis. These motion parameters can be mapped from the tool position space using inverse kinematics [8] and then passed to the virtual environment.

2.2 Virtual Reality Environment. Virtual reality environments are created with the Vizard Software Toolkit (WorldViz, Santa Barbara, CA). Tool position information from MATLAB image analysis is delivered to these virtual environments using the user data protocol (UDP) communications protocol at a refresh rate of 10 fps. This information is used to link the movements of simulated surgical instruments that exist in the virtual environments with the movements of physical tools in the hands of a trainee.

The virtual environments offer realistic simulations through physics-based interactions including gravity and detection of object collisions. When the jaws of a virtual surgical grasper open, anything in the grasper's jaws will fall and collide with the surface below. Surgical graspers can "pick up" an object when jaw closure coincides with a detected collision between the grasped object and a hidden marker object located between the jaws.

Two virtual training tasks are selected based on information from the FLS protocols and our physician recommendations. These include a peg transfer task (Fig. 3) and a moving ring task (Fig. 4). The objective of the peg transfer task is to move rings lying around a set of six pegs to an adjacent set of pegs without dropping the rings. This task helps a trainee develop depth perception and bimanual coordination. The metrics used to evaluate the progress of a trainee include the total path traveled and the task completion time.

The goal of the moving ring task is to move a ring along a coiled wire with minimal collisions between the ring and the wire. This task helps a trainee develop depth perception, precision and fine control of movement. The metrics used for trainee evaluation

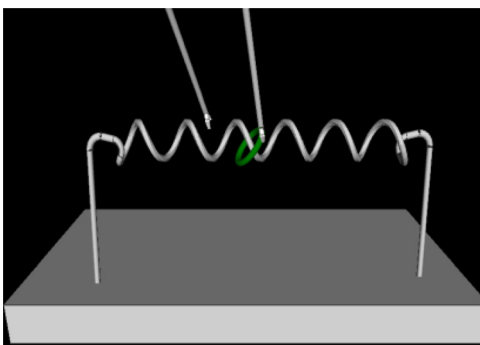


Fig. 4 Virtual training environment: hoop/coil task



Fig. 5 Prototype of laparoscopic training system with cameras

include the task completion time and the number of collisions between the hoop and the wire. When a collision is detected, feedback is given to trainees by flashing the wire red.

3 Results

A box-like structure is used to simulate the abdominal work environment in the physical simulator. A pair of cameras is mounted on the box and 4-DOF gimbal joints constrain the grasper motion. LED lighting is installed in the box to enable robust marker detection (Fig. 5).

Pilot testing of the system was carried out with five novice volunteers on the peg transfer task. Questionnaire-based feedback (using a 5-point Likert scale) indicated, among other results, that the participants achieved a sense of accomplishing the task (2.8 ± 0.4), and that the system provided a relatively realistic training experience (2.8 ± 1.1).

4 Interpretation

A laparoscopic training device was designed and fabricated based on image processing and computer vision to make virtual surgical training portable and cost effective. Pilot testing of the system indicated promise for its practical application in surgical training.

Acknowledgment

The authors gratefully acknowledge support from Nebraska Research Initiative and NASA Nebraska Space Grant.

References

- [1] Rattner, D. W., Apelgren, K. N., and Eubanks, W. S., 2001, "The Need for Training Opportunities in Advanced Laparoscopic Surgery," *Surg. Endoscopy*, **15**(10), pp. 1066–1070.
- [2] Kimura, T., Kawabe, A., Suzuki, K., and Wada, H., 2006, "Usefulness of a Virtual Reality Simulator or Training Box for Endoscopic Surgery Training," *Surg. Endoscopy*, **20**(4), pp. 656–659.
- [3] Munz, Y., Almoudaris, A. M., Moorthy, K., Dosis, A., Liddle, A., D., and Darzi, A. W., 2007, "Curriculum-Based Solo Virtual Reality Training for Laparoscopic Intracorporeal Knot Tying: Objective Assessment of the Transfer of Skill From Virtual Reality to Reality," *Am. J. Surg.*, **193**(6), pp. 774–783.
- [4] Yang, S. F., Shiu, M. F., Shiu, B. K., and Lin, Y. H., 2012, "3D Position Tracking of Instruments in Laparoscopic Surgery Training," 1st Asia-Pacific Workshop on FPGA Applications, Xiamen, China, December 8–9, pp. 50–55.
- [5] Zahiri, M., Nelson, C. A., and Siu, K. C., 2013, "Portable Laparoscopic Training System Using Virtual Reality," Design of Medical Devices Conference (DMD 2013), Minneapolis, MN, April 8–11, Paper No. DMD2013-1760.
- [6] Yang, Y., Cao, Q., Lo, C., and Zhang, Z., 2009, "Pose Estimation Based on Four Coplanar Point Correspondences," Sixth International Conference on Fuzzy Systems and Knowledge Discovery (FSKD '09), Tianjin, China, August 14–16.
- [7] Hartley, R., and Zisserman, A., 2004, *Multiple View Geometry in Computer Vision*, 2nd ed., Cambridge University, Cambridge, UK.
- [8] Hartenberg, R. S., and Denavit, J., 1995, *Kinematic Synthesis of Linkages*, McGraw-Hill, New York.