The Red DRAGON: A Multi-Modality System for Simulation and Training in Minimally Invasive Surgery

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Abstract. With the development of new technologies in surgery, minimally invasive surgery (MIS) has drastically improved the way conventional medical procedures are performed. However, a new learning curve has resulted requiring an expertise in integrating visual information with the kinematics and dynamics of the surgical tools. The Red DRAGON is a multi-modal simulator for teaching and training MIS procedures allowing one to use it with several modalities including: simulator (physical objects and virtual objects) and an animal model. The Red DRAGON system is based on a serial spherical mechanism in which all the rotation axes intersect at a single point (remote center) allowing the endoscopic tools to pivot around the MIS port. The system includes two mechanisms that incorporate two interchangeable MIS tools. Sensors are incorporated into the mechanism and the tools measure the positions and orientations of the surgical tools as well as forces and torques applied on the tools by the surgeon. The design is based on a mechanism optimization to maximize the manipulability of the mechanism in the MIS workspace. As part of a preliminary experimental protocol, five expert level surgeons performed three laparoscopic tasks – a subset of the Fundamental Laparoscopic Skill (FLS) set as a baseline for skill assessment protocols. The results provide an insight into the kinematics and dynamics of the endoscopic tools, as the underlying measures for objectively assessing MIS skills.

Keywords. Minimally Invasive Surgery, Laparoscopy, Spherical Mechanism, Markov Models, Fundamental Laparoscopic Skills, Objective Skill Assessment

1. Introduction

Within the last two decades, minimally invasive surgery (MIS) has revolutionized the surgical field. Traditional surgical procedures utilize incisions designed to allow the maximum exposure of the operation location. In contrast, MIS procedures make use of small incisions, one centimeter or less, to allow cameras and surgical instruments to be inserted into the body cavity through air-tight ports. This significantly decreases the amount of tissue trauma for the patient as well as limiting the amount of pain,

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drastically improving the cosmetic effects of surgery, and allowing much shorter hospital stays.

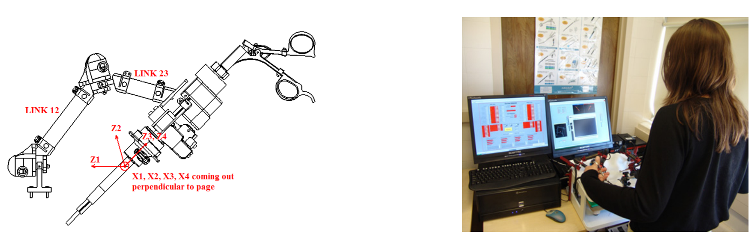
Unlike traditional surgeries, MIS does not allow the surgeons to directly see the operation; cameras inserted through the body cavity display the procedure on video monitors instead. Also, a new set of surgical tools are used that requires specific skills. As a result, a new set of skills are required to be known for an optimal usage of this technique.

The Blue DRAGON, which is based on a four bar mechanism, was the first generation of the system that was previously utilized to record the kinematics and the dynamics of MIS using an animal model [1]. Data acquired by the Blue DRAGON was used to develop and objectively assess surgeons' methodology for MIS using Markov models [2]. The data collected by the Blue DRAGON system also defined the workspace of the two endoscopic tools. Given a clear definition of the MIS tools' workspace, a new generation of the system known as the Red DRAGON was developed based on a spherical mechanism which was design and optimized in order to minimize the footprint of the system in the surgical site [3]. Both the four bar mechanism of the Blue DRAGON and the spherical mechanism of the Red DRAGON have a remote centers which are located at the intersection of the mechanisms' rotation axes. This characteristic allowed the incorporation of position sensors into the mechanism to track the rotation and the translation of the MIS tools with respect to their ports without creating interferences at the tool/port interface. The main objective of this paper is to describe the development of the Red DRAGON utilizing a spherical mechanism for tracking two tools in a MIS setup.

2. Method

2.1. Design

The port in MIS limits the six Degrees of Freedom (DOF) of any surgical tool to only five DOF including tool tip manipulation. The design of the Red DRAGON is based on a spherical mechanism with a remote center of rotation that is located at the midpoint of the abdominal wall cross-section or any other layer simulating it. The two DOF spherical linkage allows the attached tool to move its tip along a two-dimensional sphere with a center located at the port. Three more DOF were added to the system to allow linear translation along the tool's long shaft, rotational motion along the same axis, and opening and closing of the tool's handle.



(a) (b)

Figure 1. The Red DRAGON (a) the Left side mechanism and the associated coordinate system (b) A full assembly of the system with the endoscopic tools

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Position sensors were incorporated into the links of the mechanism along with a multi-axis force sensor located in the proximal end of the tool and a force sensor located at the handles of the MIS instruments. The sensors were connected to a PC utilizing USB-based data acquisition cards for acquiring the data. A graphical user interface (GUI) developed in Labview incorporated a graphical display of the data as well as a video stream of the endoscopic camera. The data along with the video screen were recorded for offline analysis. The software converts the signals received from the data acquisition cards back into either the tool's angular or linear displacement calculated from conversion factors found by testing performed on each of the sensors. The GUI also includes a virtual representation of the tools with an overlay of the velocity vectors as well as a three-dimensional representation of the force and the torque vectors.

2.2. Manipulator Kinematics

The Red DRAGON is a serial spherical mechanism comprised of five DOF defined by two joint rotations, the surgical tool translation and rotation, and the tool handle's opening/closing. The system geometry was defined as three joints and two links (Figure 1a). To specify the position and orientation of the tool, Denavit-Hartenberg (D-H) parameters [3] were assigned to the mechanism joints. The z-axis of each frame was aligned with the axis of rotation or the direction of linear translation, pointing out from the sphere, and positioned at the center of the mechanism. From this parameter setup, Eq. (1) was used to calculate the transformation matrices between each of the frames where the angular motions of the joints were denoted as θ_i, the relative position as p_x, p_y, and p_z, the link angles as α_{i-1}, and the sine and cosine functions as 'S' and 'C', respectively.

$$ {}^{i-1}_{i}T = \begin{bmatrix} C\theta_i & -S\theta_i & 0 & p_x \\ S\theta_i C\alpha_{i-1} & C\theta_i C\alpha_{i-1} & -S\alpha_{i-1} & p_y \\ S\theta_i S\alpha_{i-1} & C\theta_i S\alpha_{i-1} & C\alpha_{i-1} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1} $$

The forward kinematics maps the mechanism joint configuration defined by its DOF (θ_1, θ_2, θ_3, d_4), to the position of the tool tip and the orientation of the tool. The forward kinematics enables the surgical tool tip tracking that is the key to the data acquisition and later on to the objective skill assessment algorithms. Using the joint parameters and transformation matrices, the coordinate transformations from the base of the tool to each joint and tool tip were calculated. The transformation from the base frame to the tool tip frame was calculated using Eq. (2).

$$ {}^{0}_{4}T = {}^{0}_{1}T\,{}^{1}_{2}T\,{}^{2}_{3}T\,{}^{0}_{4}T \tag{2} $$

This matrix can be dissembled into a rotation and position denoted in Eqs. (3) and (4), respectively.

$$ {}^{0}_{4}R = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \tag{3} $$

where

$$ \begin{aligned}
r_{11} &= -C\alpha_{12} S\theta_1 (C\theta_3 S\theta_2 + C\theta_2 C\alpha_{23} S\theta_3) + C\theta_1 (C\theta_2 C\theta_3 - C\alpha_{23} S\theta_2 S\theta_3) \\
&\quad + S\theta_1 S\theta_3 S\alpha_{12} S\alpha_{23} \\
r_{12} &= -C\theta_1 C\theta_3 C\alpha_{23} S\theta_2 + C\alpha_{12} S\theta_1 S\theta_2 S\theta_3 - C\theta_2 (C\theta_3 C\alpha_{12} C\alpha_{23} S\theta_1 + C\theta_1 S\theta_3) \\
&\quad + C\theta_3 S\theta_1 S\alpha_{12} S\alpha_{23} \\
r_{13} &= -C\alpha_{23} S\theta_1 S\alpha_{12} - C\theta_2 C\alpha_{12} S\theta_1 S\alpha_{23} - C\theta_1 S\theta_2 S\alpha_{23} \\
r_{21} &= C\theta_2 C\theta_3 S\theta_1 + C\theta_1 C\theta_3 C\alpha_{12} S\theta_2 + C\theta_1 C\theta_2 C\alpha_{12} C\alpha_{23} S\theta_3 - C\alpha_{23} S\theta_1 S\theta_2 S\theta_3 \\
&\quad - C\theta_1 S\theta_3 S\alpha_{12} S\alpha_{23} \\
r_{22} &= C\theta_1 C\theta_2 C\theta_3 C\alpha_{12} C\alpha_{23} - C\theta_3 C\alpha_{23} S\theta_1 S\theta_2 - C\theta_2 S\theta_1 S\theta_3 - C\theta_1 C\theta_3 S\alpha_{12} S\alpha_{23} \\
r_{23} &= C\theta_1 C\alpha_{23} S\alpha_{12} + C\theta_1 C\theta_2 C\alpha_{12} S\alpha_{23} - S\theta_1 S\theta_2 S\alpha_{23} \\
r_{31} &= C\theta_3 S\theta_2 S\alpha_{12} - C\theta_2 C\alpha_{23} S\theta_3 S\alpha_{12} - C\alpha_{12} S\theta_3 S\alpha_{23} \\
r_{32} &= -C\theta_2 C\theta_3 C\alpha_{23} S\alpha_{12} + S\theta_2 S\theta_3 S\alpha_{12} - C\theta_3 C\alpha_{12} S\alpha_{23} \\
r_{33} &= C\alpha_{12} C\alpha_{23} - C\theta_2 S\alpha_{12} S\alpha_{23}
\end{aligned} $$

and

$$ P = \begin{bmatrix} P_x \\ P_y \\ P_z \end{bmatrix} = \begin{bmatrix} d_4 (C\alpha_{23} S\theta_1 S\alpha_{12} + C\theta_2 C\alpha_{12} S\theta_1 S\alpha_{23} + C\theta_1 S\theta_2 S\alpha_{23}) \\ -d_4 (-S\theta_1 S\theta_2 S\alpha_{23} + C\theta_1 C\alpha_{23} S\alpha_{12} + C\theta_1 C\theta_2 C\alpha_{12} S\alpha_{23}) \\ d_4 (C\theta_2 S\alpha_{12} S\alpha_{23} - C\alpha_{12} C\alpha_{23}) \end{bmatrix} \tag{4} $$

The Jacobian Matrix was determined for the Red DRAGON mechanism as a way to map the angular and linear velocities measured by the sensors incorporated into the Red DRAGON mechanism to the angular and linear velocities of the surgical tool, most notably the tool tip. By expressing the end-effector angular and linear velocities with respect to the tool frame (${}^{4}\omega_4$ and ${}^{4}v_4$) in terms of the system's Jacobian matrix, a closed form solution, Eq. (5), was found in terms of the input joint velocities ($\dot{\theta}_1, \dot{\theta}_2, \dot{d}_4$).

$$ \begin{bmatrix} {}^{4}\omega_{4x} \\ {}^{4}\omega_{4y} \\ {}^{4}v_{4z} \end{bmatrix} = \begin{bmatrix} -S\alpha_{12} S\theta_3 & 0 & 0 \\ S\alpha_{12} C\alpha_{23} C\theta_3 + C\alpha_{12} S\alpha_{23} & S\alpha_{23} & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{d}_4 \end{bmatrix} \tag{5} $$

2.3. Testing Protocol

The Fundamentals of Laparoscopic Surgery (FLS) education module created by the Society of American Gastrointestinal and Endoscopic Surgeons (SAGES) is used for testing the Red Dragon. Three tasks are currently being studied including object manipulation, suturing, and dissecting. Out of a thirty subject protocol including surgical residents at different levels of their five training stages (R1-R5), data was collected from five expert level surgeons from the University of Washington Medical

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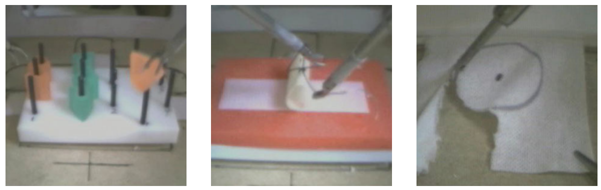
Center. Markov Modeling analysis will be further applied to objectively assess surgical skills [4].

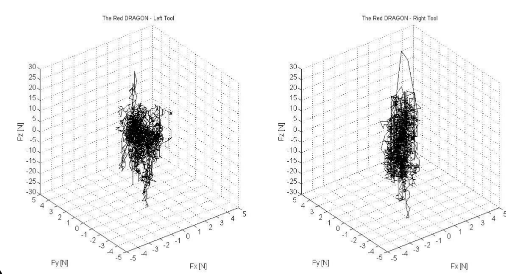


(a) (b) (c)

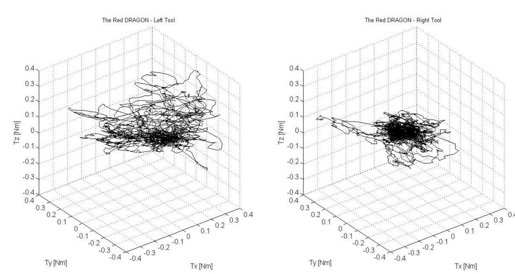
Figure 2. Subtasks of the FLS system used skill testing with the Red DRAGON: (a) object manipulation, (b) suturing, and (c) dissecting

3. Results

Typical raw data of forces torques and tool tip position was plotted in 3D graphs showing the kinematics and the dynamics of the left and the right endoscopic tools measured by the Red DRAGON while performing the FLS tasks (Figure 3). The forces and torques (F/T) can be described as vectors with an origin at the center of the sensor and a coordinate system aligned with the tool coordinate system. These vectors are constantly changing both their magnitudes and orientations as a result of the F/T applied by the surgeon's hand on the tool while interacting with the models. The F/T displayed as vectors can be depicted as arrows attached to the origin that are changing their lengths and orientations as a function of time. Figures 3a and 3b describe the traces of the tips of these vectors as they were changing during the surgical procedure. In a similar fashion the traces of the tool tips positions were plotted in Figure 3c.



(a)



(b)

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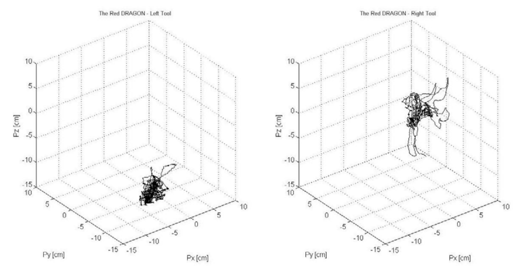

(c)

Figure 3. The kinematics and dynamics data of the left and the right endoscopic tools measured by the Red DRAGON during a suturing procedure (For coordinate system definition see Fig. 1) - (a) forces; (b) torques (c), and tool tip position.

4. Discussion

The Red Dragon provides a multi-modal training system for MIS. Physical models, virtual models, and real animal models, can all with the same system. Using the system with these various modalities provides a means to study translation of skill from a simulation environment to a real animal model. Further analysis using Markov model will allow objective assessment of MIS skills [2] and the ability to use the system for credentialing and continuing education programs in MIS.

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