Integration and Preliminary Evaluation of an Insertable Robotic Effectors Platform for Single Port Access Surgery

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Abstract—In this paper, we present the integration and preliminary evaluation of a novel Insertable Robotic Effectors Platform (IREP) for Single Port Access Surgery (SPAS). The unique design of the IREP includes planar parallel mechanisms, continuum snake-like arms, wire-actuated wrists, and passive flexible components. While this design has advantages, it presents challenges in terms of modeling, control, and telemanipulation. The complete master-slave resolved-rates telemanipulation framework of the IREP along with its actuation compensation is presented. Experimental evaluation of the capabilities of this new surgical system include bi-manual exchange of rings, pick-and-place tasks, suture passing and knot tying. Results show that the IREP meets the minimal workspace and dexterity requirements specified for laparoscopic surgery, it allows for dual-arm operations such as tool exchange and knot tying in confined spaces. Although it was possible to tie a surgeon’s knot with minimal training, suture passing was difficult due to the limited axial rotation of the distal wrists.

I. INTRODUCTION

Robotic end-effectors reinstate dexterity [1], enhance accuracy, filter hand tremors [2], [3], and safeguard delicate anatomy by creating virtual fixtures [4], [5]. For these reasons, robotic-assisted Minimally Invasive Surgery (MIS) has been progressively accepted in many disciplines of surgery such as urologic, cardiothoracic, and gynecologic surgery. Although traditional MIS procedures reduce patient’s trauma, multiple (typically 3-5) access ports [6] are required for a minimal set of surgical instruments or approaches. Each incision increases the risk of infection, lengthen the patient’s convalescence, and increase post-operative pain. New surgical paradigms such as Single Port Access Surgery (SPAS) and Natural Orifice Trans-luminal Endoscopic Surgery (NOTES) aim to reduce or completely eliminate skin incisions. In SPAS procedures, the surgical site is reached through a single trocar while in NOTES procedures natural orifices are used. Both these surgical paradigms require a shift in the way robotic slaves are designed, built, and controlled.

In recent years, both industry [7] and academic groups [8]–[16] tried to further improve and expand the set of robotic-assisted procedures by proposing a variety of telesurgical systems for SPAS and NOTES. Designs vary from purely rigid-link effectors, wire-actuated rigid link effectors, and continuum arms [17].

Successful telemanipulation and control of hybrid platforms including continuum robots requires present additional challenges such as kinematic modeling, real-time implementation of direct and inverse kinematics, backlash compensation, friction estimation, and extensions of the actuation lines. Several approaches have been proposed to address these problems and limitations. The mathematical foundations for modeling and analysis of hyper-redundant robots were laid out in [18], [19] while subsequent works addressed practical implementation and specific modeling issues. For example, in [20], the authors presented a simplified kinematic model for multi-segment continuum robots suitable for real-time control. In [21], a recursive estimation framework for actuation compensation was proposed. In [22], intra-corporeal knot tying using a dual-arm continuum robot system for laryngeal surgery was demonstrated. In [14], the authors proposed a recursive method for overcoming coupling, backlash, and extension of multi-segment multi-backbone continuum robots while in [23], configuration tracking for tendon-driven catheters was presented. Other works such as [24], [25] focused on backlash and friction compensation for wire-actuated robots and tendon-driven catheters. In [17], [26], a modeling and control framework for concentric tube continuum robots was proposed. More recently, in [27], a mixed configuration and joint-space feedback for improving accuracy of multisegment continuum robots was proposed.

This paper presents the integration and the preliminary evaluation of the IREP system shown in Fig. 1. To the best of the authors’ knowledge the IREP is the smallest surgical robotic
platform for SPAS. We present the complete direct and inverse kinematics formulation, integration with a dual-arm master interface, resolved-rates telemanipulation control, redundancy resolution, workspace enlargement using an additional inser-
tion stage, and actuation compensation. Experimental results demonstrate that the IREP meets workspace and dexterity requirements for basic abdominal MIS procedures.

II. INTEGRATED SYSTEM FOR SPAS

Figure 1 shows the integrated surgical system for SPAS. The system is composed of 24 controlled axes: 18 for the IREP’s hybrid arms, 3 for the stereo camera system, and 3 for the Cartesian stage. The Cartesian robot provides additional motion along the insertion axis for gross manipulation.

Each arm is composed of 9 axes \((q_1...q_9)\): an insertion linear stage \(q_1\), a planar 2 DoF parallel mechanism \((q_2, q_3)\), two continuum arms \((q_4, q_5, q_6\) and \(q_7)\), a 1 DoF wrist \(q_8\), and a gripper jaw \(q_9\). The role of the parallel linkage is to increase the lateral movement of the arm and to improve dual-arm triangulation. The insertion stage \(q_1\) coordinates the insertion of the passively bending stem when the parallel linkage deploys. Each continuum segment is composed of four circumferentially located super elastic NiTi secondary backbones and 1 centrally located super elastic NiTi primary backbone. The particular design of the actuation unit couples opposing secondary backbones; thus, reducing the controlled axes from four to two for each continuum segment \([28]\).

By controlling the length of the secondary backbones, each segment may be actively bent in 2 DoF.

Four coordinate systems are defined as shown in Fig. 2. Frame \(\{0\}\) is the fixed base frame attached to the end of long insertion stem. Frame \(\{1\}\) is attached to the moving ring of the parallelogram and always maintains the same orientation of frame \(\{0\}\). Frames \(\{2\}\) and \(\{3\}\) are attached at the end disk of the first and second continuum arm respectively. Frame \(\{4\}\) captures the additional wrist rotation.

A. IREP Direct Kinematics

The direct kinematics of each arm may be described by the following augmented configuration space vector:

\[
\Psi = \begin{bmatrix} b_x & b_z & \psi_1^T & \psi_2^T & \gamma \end{bmatrix}^T
\]

where \(b_x\) and \(b_z\) (Fig. 2) denote the \(x\) and \(z\) coordinates of frame \(\{1\}\) with respect to base frame \(\{0\}\), \(\psi_1 = \begin{bmatrix} \theta_1 & \delta_1 \end{bmatrix}^T\) and \(\psi_2 = \begin{bmatrix} \theta_2 & \delta_2 \end{bmatrix}^T\) define the shape of the first and second continuum segments and, therefore, the position and the orientation of frame \(\{2\}\) with respect to frame \(\{1\}\) and frame \(\{3\}\) with respect to frame \(\{2\}\) respectively. Angle \(\theta_k\) is the bending angle of segment \(k = 1, 2, \delta_k\) is the angle defining the plane in which segment \(k\) bends, and \(\gamma\) (Fig. 2) is the roll angle about axis \(\hat{z}_3\) that defines frame \(\{4\}\).

The position and orientation of the end-effector is given by:

\[
^0p_4 = ^0p_1 + ^0R_1 \begin{bmatrix} 1 & -1 & 0 & 2 \end{bmatrix} + ^1R_2^2R_3^3R_4 p_4 \quad (2)
\]

\[
^0R_4 = ^0R_1^1R_2^2R_3^3R_4 \quad (3)
\]

where \(^0p_1 = \begin{bmatrix} b_x & 0 & 0 & b_z \end{bmatrix}^T\), \(^3p_4 = \begin{bmatrix} 0 & 0 & z_0 \end{bmatrix}^T\), \(^0R_1 = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix}\), \(^3R_4 = \text{Rot}(\gamma, \hat{z})\), and the remaining offsets and orientations due to the two continuum segments \((k = 1, 2)\) are given by:

\[
^kP_{k+1} = \frac{L_k}{\Theta_k} \begin{bmatrix} \cos(\delta_k) (\sin \theta_k - 1) \\ -\sin(\delta_k) (\sin \theta_k - 1) \\ -\cos \theta_k \end{bmatrix}
\]

\[
^kR_{k+1} = \text{Rot}(-\delta, \hat{z})\text{Rot}(-\Theta_k, \hat{y})\text{Rot}(\delta, \hat{z})
\]

where \(\Theta_k = \theta_k - \frac{\pi}{2}\) and the operator \(\text{Rot}(a,b)\) defines the rotation matrix about axis \(b\) by angle \(a\).

By taking the time derivative of (2) and (3) one obtains the \(6 \times 7\) Jacobian matrix that relates the rate of change of the augmented configuration space vector \(\dot{\Psi}\) and the linear and angular velocities of the end-effector:

\[
J_{\text{arm}} = \begin{bmatrix} e_1 & e_3 & S_1J_1 & S_2J_2 & S_3e_6 \end{bmatrix}
\]
where \( e_i \in \mathbb{R}^6 \) is the \( i \)-th canonical basis vector, \( J_1 \) and \( J_2 \) are the Jacobian matrices of the first and second continuum segment respectively. These Jacobians \((k = 1, 2)\) are given by [14]

\[
J_{c,k} = \begin{bmatrix}
L_k c_{\delta_k} \Theta_k c_{\delta_k} - s_{\delta_k} + 1 & -L_k s_j (s_{\delta_k} - 1)
\end{bmatrix}
\]

where \( c_y = \cos(y) \), \( s_y = \sin(y) \), and matrix \( S_k \) \((k = 1, 2)\) transforms the local Jacobians into base frame \( \{0\} \):

\[
S_1 = \begin{bmatrix}
I & 0
\end{bmatrix}
\]

\[
S_2 = \begin{bmatrix}
0 R_2 & -[0 R_3^3 p_4]
\end{bmatrix}
\]

\[
S_3 = \begin{bmatrix}
0 & 0
\end{bmatrix}
\]

where \( I \in \mathbb{R}^{3 \times 3} \) is the identity matrix, \( 0 \in \mathbb{R}^{3 \times 3} \) is a matrix of zeros, and operator \([u] \times \) constructs a \( 3 \times 3 \) skew-symmetric matrix from vector \( u \).

### B. Joint-Space Kinematics

The augmented configuration space vector \( \Psi \in \mathbb{R}^7 \) is related to the joint space vector \( \mathbf{q} = [q_1 \ldots q_8]^T \) as following:

\[
q_1 = L (b_z, b_z) - L_0
\]

\[
q_2 = b_z - d_z \cos(\alpha) - d_5 - q_1
\]

\[
q_3 = q_2 - d_6 + d_4 \cos(\xi) - d_4 \cos(\beta) - q_1
\]

\[
q_4 = r \Theta_1 \cos(\delta_1)
\]

\[
q_5 = -r \Theta_1 \sin(\delta_1)
\]

\[
q_6 = r (\Theta_1 \sin(\delta_1) + \Theta_2 \cos(\delta_2))
\]

\[
q_7 = -r (\Theta_1 \sin(\delta_1) + \Theta_2 \sin(\delta_2))
\]

\[
q_8 = q_4 - q_5 + q_6 - q_7 + \gamma_r
\]

where \( L (b_z, b_z) \) and \( L_0 \) are respectively the arc-length of the passive stem when the parallelogram is open and when it is closed at a home position \((\alpha = 0, q_2 = 0)\), \( r \) and \( r_w \) are the kinematic radii of the continuum segments (Fig. 2) and the wrist mechanism respectively. Kinematic parameters \( \alpha, \beta, \xi, d_1, d_4, d_5, \) and \( d_8 \) are shown in Fig. 2. Arc-length \( L (b_z, b_z) \) of the passive stem depends on the position of the moving base ring and can be obtained using the pseudo-rigid body method proposed in [29]. The derivative of (14), (15), (16), (17), and (18) yields the instantaneous inverse kinematics Jacobian matrix that relates configuration space velocities \( \dot{\psi}_1, \dot{\psi}_2, \dot{\gamma} \) and joint space velocities \( \dot{\mathbf{q}}_8 = [\dot{q}_4 \ldots \dot{q}_8]^T \) such that:

\[
\dot{\mathbf{q}}_8 = J_{w_k} \mathbf{r}_w \dot{\psi}_1 \dot{\psi}_2 \dot{\gamma}
\]

where, for \( k = 1, 2 \),

\[
J_{w_k} = \begin{bmatrix}
J_{w_1} & 0 & 0
\end{bmatrix}
\]

\[
\mathbf{r}_w \dot{\psi}_1 \dot{\psi}_2 \dot{\gamma}
\]

### III. TELEMANIPULATION

#### A. Telemanipulation Architecture

Figure 3 shows the 1-arm telemanipulation architecture of the IREP. Two computers labeled as Host and Target are used for querying the master device and controlling the IREP. The two machines exchange information over a Local Area Network (LAN) via User Datagram Protocol (UDP).

The telemanipulation framework (Fig. 3) is subdivided as follows: master-slave tracking error, redundancy resolution, configuration-to-joint space mapping, and direct kinematics. The master-slave tracking error subsystem receives data from the master manipulator and computes the desired twist of the end-effector. The redundancy resolution subsystem inverts the kinematics avoiding joint-limits and Jacobian singularities. The third subsystem provides the desired joint-space values that achieve the desired motion as described in the InvPos solution of (11), (12), (13), and InvKin solution of (19).

#### B. Master-Slave Tracking Error

The telemanipulation is initiated by pressing one of the buttons on the master stylus as shown in Fig. 4. At this time (denoted by subscript 0) the following entities are stored: gripper’s position and orientation \( \mathbf{p}_{m_0}, \mathbf{R}_{m_0} \) and the master’s stylus position and orientation \( \mathbf{p}_{m_0} \mathbf{R}_{m_0} \). Note that, in the remainder of this section subscript \( c \) denotes the values of these entities at current time.

During operation (stylus button pressed) the change in the current stylus orientation \( \mathbf{p}_{m_0} \mathbf{R}_{m_0} \) in its local base frame \( \{m\} \) is mapped to correspond to the change in gripper orientation \( \mathbf{p}_{m_0} \mathbf{R}_{m_0} \) in frame \( \{0\} \). This correspondence is shown in Fig. 4 where these two frames are related by a fixed rotation \( \mathbf{R}_t = \text{Rot}(x, \pi) \). Using similarity transformations, the change in the stylus orientation is given by:

\[
\Delta (\mathbf{m} \mathbf{R}_{m_0}) = \mathbf{R}^T (\mathbf{m} \mathbf{R}_{m_0}) \mathbf{R}_t
\]

where \( \mathbf{m} \mathbf{R}_{m_0} \) and \( \mathbf{m} \mathbf{R}_{s_0} \) designate the stylus orientation in current time and at button-press event. These frames are reported by the Phantom Omni software.

The desired gripper position \( \mathbf{p}_{d_{4..8}} \) and orientation \( \mathbf{R}_{d_{4..8}} \) are specified by the following:

\[
\mathbf{p}_{d_{4..8}} = \mathbf{p}_4 + \mathbf{v}_4 \mathbf{R}_{m_b} \mathbf{p}_{m_0} - \mathbf{m} \mathbf{p}_{m_0}
\]

\[
\mathbf{R}_{d_{4..8}} = \mathbf{R}_4 \mathbf{R}_{m_b}
\]
where $^0R_{mb}$ is the rotation between the master interface base frame and the snake stem frame $\{0\}$ and the scalar $\nu$ is the telemanipulation scaling factor between stylus movement and gripper movement.

The slave robot position tracking error $p_e$ and orientation tracking error $\zeta$ are given by

$$p_e = 0\ 4_{des}x - 0\ 4_x$$

$$\zeta = \cos^{-1}(e_{1c} \cdot e_{1d} + e_{2c} \cdot e_{2d} + e_{3c} \cdot e_{3d})$$

where $e_{ic}$ and $e_{id}$ are the $i^{th}$ column of the current and desired rotation matrix respectively.

Next, the desired end-effector twist can be computed as follows:

$$t_{des} = \begin{bmatrix} V \dot{m} \\ \Omega \dot{r} \end{bmatrix}$$

where

$$\dot{m} = \frac{p_e}{\|p_e\|}$$

$$\dot{r} = \frac{e_{1c} \times e_{1d} + e_{2c} \cdot e_{2d} + e_{3c} \cdot e_{3d}}{\|e_{1c} \times e_{1d} + e_{2c} \cdot e_{2d} + e_{3c} \cdot e_{3d}\|}$$

$$V = \begin{cases} \frac{V_{max}}{\eta(V_{max} - V_{min})} + V_{min} & \text{if } \frac{\|p_e\|}{\epsilon_p} > \lambda_p \\
\frac{V_{max}}{\eta(\lambda_p - 1)} & \text{if } \frac{\|p_e\|}{\epsilon_p} \leq \lambda_p 
\end{cases}$$

$\epsilon_p$ is the smallest allowable position error, $\lambda_p$ is a scaling factor that defines the radius of position error beyond which the end-effector moves at maximal linear velocity $V_{max}$, $\eta = \|p_e\| - \epsilon_p$, $\epsilon_o$ and $\lambda_o$ are defined similarly to $\epsilon_p$ and $\lambda_p$ respectively, and $\mu = \zeta - \epsilon_o$.

### C. Redundancy Resolution

Once the desired twist of the end-effector is obtained as in (27), the configuration space velocities and then the joint space velocities are computed.

The configuration space velocities are given by:

$$\dot{\Psi} = J_{arm}^\dagger t_{des} + (I - J_{arm}^\dagger J_{arm}) \dot{\Psi}_0$$

where $\dot{\Psi}_0$ is a configuration space vector of velocities that can be used to accomplish a secondary task, $I \in \mathbb{R}^{7 \times 7}$ is the identity matrix and

$$J_{arm}^\dagger = W^{-1}J_{arm}^T (J_{arm}W^{-1}J_{arm}^T + \epsilon I)^{-1},$$

matrix $W \in \mathbb{R}^{7 \times 7}$ is a diagonal positive-definite matrix of weights, and $\epsilon(\Psi)$ avoids robot’s singularities [30]. In the case of the IREP, the primary goal of the weighted inverse is to prevent the continuum segments from reaching the minimum ($\theta_k = 0$) and maximum ($\theta_k = \theta_0 = \pi/2$) bending angles by exploiting redundancy as in [31]. Additionally, matrix $W$ can be used to guide the inversion of the Jacobian in order to favor the movement of the parallel mechanism or the insertion stage for some Cartesian directions.

Once the configuration space velocities are obtained, a resolved-rate approach [32] is used for both the parallel mechanism and the continuum arm. The position of frame $\{1\}$ is obtained as

$$b_x(t_{k+1}) = b_x(t_k) + b_x(t_k) \Delta t$$

$$b_z(t_{k+1}) = b_z(t_k) + b_z(t_k) \Delta t$$

while, using (20) and (21), the rest of the configuration space vector is obtained as

$$q_{48}(t_{k+1}) = q_{48}(t_k) + \dot{q}_{48}(t_k) \Delta t$$

where $q_{48}$ denotes $[q_4, ..., q_8]$. 

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**Fig. 3.** Telemanipulation integration architecture of the IREP. The notation $q_{ij}$ is used as shorthand notation to vector $q_1...q_j$. 

**Fig. 4.** Definition of end-effector coordinate system of the continuum arm (left) and the Phantom Omni (right).
IV. COMPENSATION

Equations (11), (12), (13), and (36) provide the theoretical joint values that accomplish the commanded motion of the end-effector. However, because of backlash, friction, coupling between subsequent continuum segments, and extension of the actuation lines, the responsiveness of the IREP system is degraded. In particular, the main deficit of the parallel mechanism is backlash while the extension of the long actuation lines affects the continuum segments.

1) Backlash Compensation: Experiments using a stereo vision tracking system were conducted to characterize the backlash affecting the parallel mechanism. Figure 5 shows a graph of the actual vs. the commanded x position of the moving ring of the parallelogram while opening the mechanism. The figure shows a deadband between $x = 3.8 \text{ mm (five-bar closed)}$ and $x = 15 \text{ mm}$. A reverse spline was numerically evaluated and its coefficients used during operation.

2) Actuation Compensation: Actuation compensation for multi-backbone continuum robots was presented in [14], [21], [27]. Xu and Simaan [21] proposed the following compensation law:

$$\vec{q}_{d7} = \vec{q}_{d7} + K^{-1} \vec{\tau} \tag{37}$$

where

$$K = \begin{bmatrix} E_{ys}A/L_a & 0 \\ 0 & E_{ys}A/L_a \end{bmatrix}, \tag{38}$$

$$\vec{\tau} = \begin{bmatrix} J_{q_5} & J_{q_6} & J_{q_7} \end{bmatrix}^T \nabla U, \tag{39}$$

$E_{ys}$ is the Young’s modulus of the secondary backbones, $A$ is the cross-sectional area of the backbones, $L_a$ is the length of the actuation lines, and $\nabla U$ is the gradient of the elastic energy $U = U_1 + U_2$ of a two segment continuum robot [14] with respect to $\psi_1$, and $\psi_2$.

V. AUGMENTING THE WORKSPACE

The robotic system presented in Section II was augmented with two additional Cartesian axes as shown in Fig. 1. Coordinated motion of the $x$ and $z$ axes allows the IREP to translate along the central stem axis. This additional DoF turned out to be essential for increasing the reachable workspace of the dual-arm system. The configuration space vector of the leading arm in (1) is then augmented as the following

$$\vec{\Psi} = [ \vec{b}_z \hspace{1cm} \vec{\Psi}^T ]. \tag{40}$$

The inversion of the kinematics presented throughout Section III-C is modified as follows. The augmented arm Jacobian $J_{arm}$ is given by

$$J_{arm} = \begin{bmatrix} J_{xz} \\ J_{arm} \end{bmatrix} \tag{41}$$

where $J_{arm}$ is given in (6) while

$$J_{xz} = [ -\sin(\varphi) \hspace{1cm} 0 \hspace{1cm} \cos(\varphi) \hspace{1cm} 0 \hspace{1cm} 0 \hspace{1cm} 0 ]^T \tag{42}$$

In order to use the Cartesian manipulator when the IREP reaches upper and lower limits of its workspace, the following weight $w_{ins}$ is associated with the insertion stage:

$$w_{ins} = w_{min} + \frac{w_{max}}{2} \left( 1 - \left( \frac{b_z - b_{z,mid}}{b_{z,amp}} \right)^n \right) \tag{43}$$

where $b_{z,mid}$ is the middle of the range in the $z$ direction and $b_{z,amp}$ is the mechanical travel of the insertion stage. Weight $w_{ins}$ depends on the $z$-component of the position of the tip of the parallelogram. By choosing exponent $n$, it is possible to guide the inversion of the kinematics in (33) and use the insertion stage only when $b_z$ approaches the upper and lower joint limits of the five-bar linkage.

VI. EXPERIMENTS AND DISCUSSIONS

The integrated telemanipulation system of Fig. 1 was qualitatively evaluated for ability to complete key surgical tasks. The capabilities of this system were evaluated in stringent conditions that do not rely on using the standard four DoFs of laparoscopic surgery (translation along the insertion axis and three tilting angles). We evaluated the system with only one additional translational DoF provided by the coordinated motion of the Cartesian robot. The insertion DoF allowed for sufficient workspace reachability to complete some of the surgical tasks described by the Fundamentals of Laparoscopic Surgery (FLS) [33]. The addition of the insertion DoF was crucial to place the IREP near the target surgical zone and successfully complete the tasks.

We set forth to evaluate the ability of the IREP to complete the following tasks: 1) pick and place, 2) hand exchange of rings, 3) passing circular needles, 4) completing knot tying. To achieve these goals we used the dexterity peg board provided by FLS, the Robotic Sea Spikes Pod training model available from The Chamberlain Group, a suturing goretex model by FLS, and standard circular needles used in abdominal surgery.

A. Pick and place and hand exchange

Experiments for pick and place included manipulation of plastic triangular-shaped objects as shown in Figs. 6 and 7. Multimedia extension I shows experiments carried out to demonstrate successful exchange of these small rings between the left and right hands and also successful tagging of different spikes. The experiments show that the tasks were completed successfully with minimal experience by novice users (all

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users in these experiments with the exception of the lead author had no experience with the telemanipulation system and had only minimal familiarization periods totalling less than 30 minutes of continuous test driving of the system. The experiments for FLS required the users to manipulate size large objects by picking them from the left 6 pegs and then placing them on the right 6 pegs. The peg diameters in the FLS training model is 3.2 mm, the diameter of hole in the manipulated triangular cross section objects is 6.34 mm. Part 2 of Multimedia Extension I shows these experiments. We found out that 1) exchange of objects between hands was possible despite the small side of the IREP gripper; 2) some difficulties were observed due to limited depth perception when trying to guide the objects to slide on the pegs. This stemmed from the fact that we were unable to use real 3D stereo vision but instead, the user observed the robot while standing as shown in Fig. 1; 3) the accuracy of the IREP was suitable for successful completion of the experiments by both the surgeon author and the non-surgeon authors; 4) the reach of the IREP arms allowed it to cover the entire workspace of 64 mm × 103 mm of the FLS board without exchange of the manipulated object between hands.

B. Passing surgical needles and knot tying

In addition we evaluated the ability of the IREP to pass circular sutures and tie surgeon’s knots. We used standard V-shaped 26 mm needle and a 2-0 size suture. The passage of circular needles was not easy due to the limited rotation range of the distal wrist of ±60 degrees. Though it was possible to pass a circular suture using a long series of needle re-grasping, we deem the performance of the IREP for this task as deficient and new designs to allow full turn rotation in each direction will be considered. Knot tying was completed after manually placing the circular needle in a goretex tube. The third part of multimedia extension I shows the first attempt of the surgeon author to tie a double throw (double loop) surgeon’s knot. The IREP was able to easily triangulate to its target zone and the knot tying was achieved easily. The grippers were also able to exchange the needle successfully despite the limited rotation of the wrist. In addition to multimedia extension I, Figures 6, 7, and 8 show sequences of images depicting the experiments.

VII. CONCLUSIONS

SPAS presents challenges that require unique designs of surgical devices with large workspace and enhanced dexterity in small and confined spaces. The IREP system meets these requirements and, to the best of authors’ knowledge is the smallest existing robotic system for SPAS that requires a single incision of ⊘15 mm. The IREP’s 24 controlled axes are able to deploy two 7 DoF continuum manipulators equipped with wrists and grippers and a 3 DoF stereo vision module.

This paper presented the telemanipulation framework, kinematic modeling, and redundancy resolution of the IREP system. The qualitative evaluation and demonstration revealed that the current integrated system is capable of completing key laparoscopic tasks. Because the IREP is compact, it can be locked to the surgical bed facilitating quick reorientation of the patient during surgery. This capability eludes existing commercial systems, which use stand-alone slave robots next to the surgical bed. The IREP thus offers key advantages in terms of setup time, dexterity, reduced operating room footprint and ease of changing the patient’s surgical pose. Because it requires only one small ⊘15mm incision, the IREP is expected to minimize patient trauma, pain, recovery time and complications such as wound infection and incisional hernia. These benefits remain to be validated in future clinical evaluations.

Experiments demonstrated successful completion of knot tying, exchange of small and large objects between hands, and delicate pick and place tasks. The experiments revealed that the limited axial rotation of the wrists ±60° hindered successful completion of circular suture passing. In future designs, the wrists will allow for full rotation of the grippers.

REFERENCES

Fig. 8. Sequence of knot tying under bimanual telemanipulation


