2014 IEEE International Conference on Robotics & Automation (ICRA)
Hong Kong Convention and Exhibition Center
May 31 - June 7, 2014. Hong Kong, China

Kinematic Control of Redundant Arms based on the Virtual Incision Ports for Robotic Single-Port Access Surgery

Junwon Jang, Hyundo Choi, Hyungjoo Kim and Hoseong Kwak

***Abstract*— This paper presents a novel kinematic control scheme based on the Virtual Incision Ports (VIPs) for redundancy resolution of redundant robotic arms for single-port access (SPA) surgery. In general, manipulators have 6 DoFs except grippers to be able to reach the desired pose in 3D space. If a surgical robot for SPA surgery has only 6 DoFs, then its workspace could be restricted severely. Therefore most robots including our developed robot consist of more than 6 DoFs with an elbow to maintain triangulation. This means they have a redundancy resolution problem. One of the most popular methods for a redundancy resolution is a pseudo-inverse Jacobian method [1]. In case of robotic SPA surgery, however, this method intrinsically has a high possibility for hurting abdominal organs and muscles or conflicting with other instruments because of the unexpected elbow movements. Our control scheme can decrease the possibility of a collision with them and provide a more flexible working area for surgical tasks by reallocating the VIP. Results presented from simulation and experiment will demonstrate them.**

I. Introduction

Single-port access (SPA) surgery is a recently developed laparoscopic procedure that involves passing multiple instruments and an endoscope through a single incision [2][3]. It is a minimally invasive surgical procedure in which surgeon operates almost exclusively through a single entry point, typically the patients navel. When compared with traditional multi-port access (MPA) surgery techniques, the benefits of SPA techniques include less postoperative pain, reduction of the incidense of wound infections, and less cosmetic hurts [4].

Despite the potential advantages of SPA surgery techniques, there may also be limitations such as inadequate triangulation and an impaired view at positions in line with the instrument [5]. Additionally, the small operation space can make it difficult to manipulate surgical instruments and an endoscope because they are passed through a single incision. These problems can be solved by the improved ergonomic design, accuracy, and dexterity provided by teleoperated robotic surgery systems. Many researchers have attempted to apply robotics technologies to SPA surgery.

A number of manual single-site surgeries have been successfully performed by adopting an endoscopic robot [6][7]. The aim of these studies was to substitute a robotic manipulating system for the assistant surgeon tasked with manipulating the endoscope. These studies efficiently overcame space limitations of the operation site. Many other robotic devices are currently being developed to address the dexterity and visualization limitations for SPA surgery and to improve tissue manipulation capabilities as well as internal organ visualization.

In one approach, robotics technologies have been applied to instruments as well as endoscopes. In this approach, the surgery area is accessed by an overtube that includes the surgical instruments and an endoscope, and surgery is performed locally. Examples include a bimanual robotic system with two arms having six degrees of freedom (DoFs) for single-port laparoscopy [8], or that with a deployable mechanical structure and stereo vision [9][10]. Master-slave robotic systems that use long flexible instruments with multiple DoFs alongside existing flexible endoscopes are currently being developed [11][12]. These overtube-type surgery robots have a single robotic arm that manipulates an overtube outside the patient's body. A surgeon can efficiently perform small-part surgery because the surgical instruments and an endoscope are deployed from the same overtube, which can be flexible or rigid. However, view-independent instrument motion is limited by the overtube, and flexible overtubes can also degrade the stiffness of the instrument end. These problems can be more serious when multi-DoF motions of the instrument and an endoscope must be implemented inside the body.

Another approach for single-site surgery involves substituting the surgeon's hand with a robotic arm; articulated rigid instruments and an endoscope are connected to a robotic arm outside of the body and passed through the single incision. In particular, a remote center-of-motion (RCM) mechanism can be used to maintain the stationary point at the incision area. The *da Vinci* system from Intuitive Surgical, Inc. has been used to improve surgical dexterity for performing transumbilical single-port radical prostatectomy, dismembered pyeloplasty, and right-side radical nephrectomy procedures [13]. Instruments modified for triangulation are also used in single-incision surgery performed with the *da Vinci* system [14]. An instrument that possesses high stiffness can be applied with relatively high force to the tissue and manipulated in a large workspace. Recently, a more compact system to position and manipulate the surgical instruments has been proposed conceptually. The system is composed of two instruments and one endoscope attached to a common rotating base ring [15]. In this approach, the key requirement is to maintain triangulation of the instruments.

In general, manipulators should have 6 DoFs except grippers to reach the desired pose in 3D space. If a surgical robot for SPA surgery has only 6 DoFs, then its workspace should

The authors are with the Samsung Advanced Institute of Technology, San 14, Nongseo-dong, Giheung-gu, Yongin-si, Gyeonggi-do,Korea (E-mail: {jw526.jang, hyundo.choi, hjuro.kim, hoseong.kwak}@samsung.com)

be limited so much. Therefore most robots including our robot consist of more than 6 DoFs with an elbow to maintain triangulation. These are required redundancy resolution methods. One of most popular methods for a redundancy resolution might be pseudo-inverse Jacobian method [1]. In robotic SPA surgery, however, this method intrinsically has high possibility for hurting abdominal organs because of unexpected elbow movements. In this paper, we present a novel kinematic control scheme based on the Virtual Incision Port (VIP) in robotic SPA surgery. This control scheme decreases collision possibility between the instrument and something, e.g organs and another instrument, through deterministic elbow movements. In some cases it may incur restriction of motion of instruments. Adjustment of working area with reallocation of the VIP can resolve this restriction so that provide sufficient working area for surgical task.

This paper is organized as follows. Surgical robotic arms for robotic SPA surgery developed by us recently will be presented in Section 2 in brief. Concept and properties of the proposed control scheme will be described in Section 3. Simulation results to evaluate validation of the proposed control scheme will be presented in Section 4. Experimental results will be presented in Section 5. Finally, conclusion will be presented in Section 6.

II. System Description

A. A Surgical Robotic Arm for SPA Surgery

We have developed a surgical robot system including a couple of articulated robotic arms and an endoscope for SPA surgery as seen in Fig. 1. A surgical robotic arm consists of a conically shaped RCM mechanism [16][17] and an articulated instrument with an elbow configuration to maintain triangulation. Each robotic arm has 9 DoFs including 3 DoFs, q_1 to q_3, for a conically shaped RCM mechanism and 6 DoFs for the instrument which consists of redundant 2 DoFs, q_4 and q_5, for wrist translation and 3 DoFs for wrist orientation, and 1 DoF for grippers. In this paper we will consider only 5 DoFs, q_1 to q_5, related to wrist translation as shown in Fig. 2. z_1 to z_5 represent rotation or translation axis for q_1 to q_5, respectively.

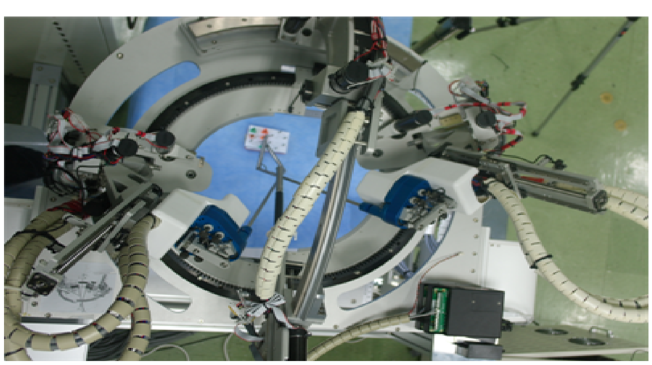


Fig. 1. Surgical robotic arms and an endoscope

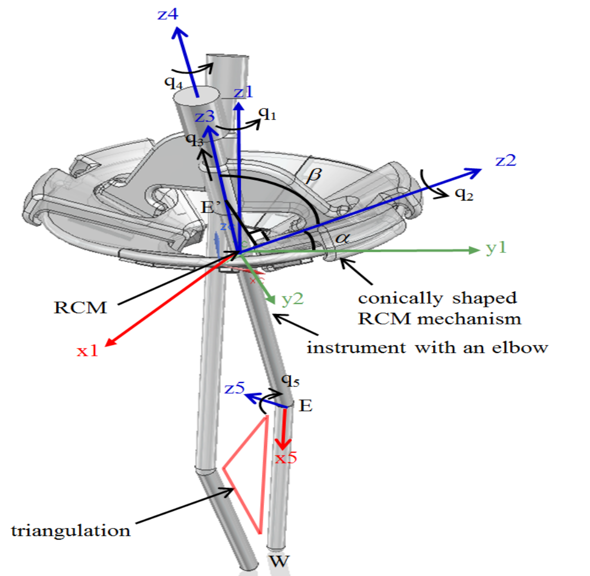


Fig. 2. Surgical robotic arms maintaining triangulation for SPA surgery.

B. Inverse Kinematics Analysis

As shown in Fig. 2, RCM (R) is an intersection point of each axis for q_1, q_2 and q_3 and is set to the origin in base coordinates. E(x_e,y_e,z_e) and W(x_w,y_w,z_w) are set to the elbow and wrist position, respectively. α between z_2 and $x_1 - y_1$ plane and β between z_3 and $y_2 - z_2$ plane, are design parameters.

We assume that

$$0 < \alpha < \frac{\pi}{2}, 0 < \beta < \frac{\pi}{2} \tag{1}$$

$$x_e \neq 0 \quad or \quad y_e \neq 0. \tag{2}$$

If E is given, then inverse kinematics solutions for the elbow position are solved as follows: For solving q_1, firstly let us define $E^{'}(a, b, c)$, minus normal vector of E,

$$E^{'}(a, b, c) = -\frac{E(x_e, y_e, z_e)}{n} \tag{3}$$

where

$$n = |E(x_e, y_e, z_e)|. \tag{4}$$

Secondly, let us define $T(x_p, y_p, z_p)$, projection point of $E^{'}$ on q_2 axis. Then x and y are presented as follows:

$$x_p = \frac{DB \pm \sqrt{-B^2 + (1 + D^2)A}}{1 + D^2} \tag{5}$$

$$y_p = -Dx_p + B \tag{6}$$

where

$$A = \frac{\cos^2\beta \sin^2\alpha}{\tan^2\alpha}, \tag{7}$$

$$D = \frac{a}{b}, \tag{8}$$

$$k = A^2 + a^2 + b^2 + (\cos\beta \sin\alpha - c)^2 - \sin^2\beta, \tag{9}$$

$$B = \frac{k}{2A}. \tag{10}$$

Then q_1 can be computed as follows:

$$q_1 = \arctan 2(y_p, x_p). \tag{11}$$

q_2 can be computed as follows:

$$q_2 = \arctan 2(b^{'}, a^{'}) \tag{12}$$

where

$$a^{'} = a \sin q_1 - b \cos q_1, \tag{13}$$

$$b^{'} = -a \cos(\frac{\pi}{2} - \alpha) \cos q_1 -$$

$$b \cos(\frac{\pi}{2} - \alpha) \sin q_1 + c \sin(\frac{\pi}{2} - \alpha). \tag{14}$$

q_3 can be computed as follows:

$$q_3 = -|E|. \tag{15}$$

If W is given, then inverse kinematics solutions, q_4 and q_5, can be computed as follows:

$$q_4 = \arctan 2(y^{'}, x^{'}). \tag{16}$$

where

$$(x^{'}, y^{'}, z^{'}) = \frac{W^{'}}{|W^{'}|} \tag{17}$$

and $W^{'}$ is W transformed to q_4 coordinates.

Finally,

$$q_5 = \arccos(\overrightarrow{u}, \overrightarrow{v}). \tag{18}$$

where

$$\overrightarrow{u} = \frac{\overrightarrow{RW} - \overrightarrow{RE}}{|\overrightarrow{RW} - \overrightarrow{RE}|}, \overrightarrow{v} = \frac{\overrightarrow{RE}}{|\overrightarrow{RE}|}. \tag{19}$$

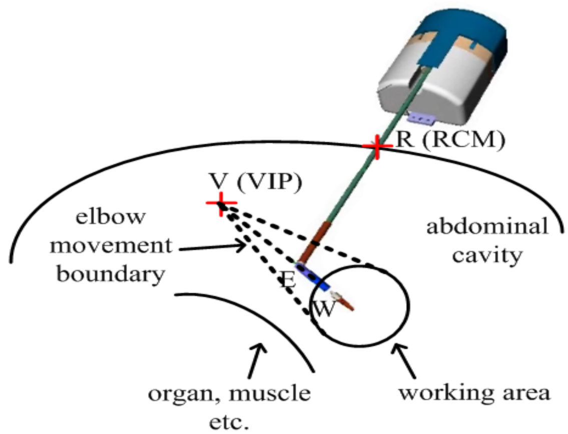
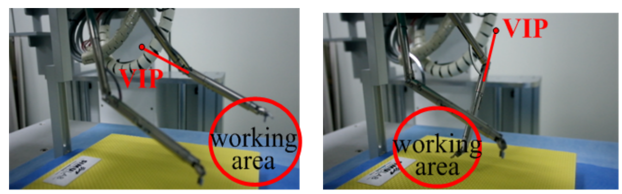


Fig. 3. Conceptual description of the Virtual Incision Ports



(a) (b)

Fig. 4. Adjustable working area by the change of the VIP

III. Kinematic Control Scheme based on the Virtual Incision Port (VIP)

A. Concept

We present a novel kinematic control scheme based on the Virtual Incision Port (VIP). At first we introduce the VIP (V). It is a virtual incision port and acts as a virtual RCM. The position of the VIP can be chosen anywhere in 3D space conceptually. In the proposed control scheme, the VIP, elbow (E), and wrist (W) exist in the same straight line as described in Fig. 3. In other words, the VIP is exploited in order to select the elbow position when the reference wrist position is commanded. Actually this means a redundancy resolution for a redundant manipulator with an elbow configuration. If the VIP, $\overrightarrow{RV}$, and the reference wrist position, $\overrightarrow{RW}$, are given, then the elbow position , $\overrightarrow{RE}$, are computed as followings:

$$\overrightarrow{RE} = \overrightarrow{RW} + \overrightarrow{WE} \tag{20}$$

where

$$\overrightarrow{WE} = \frac{\overrightarrow{RV} - \overrightarrow{RW}}{|\overrightarrow{RV} - \overrightarrow{RW}|} |\overrightarrow{WE}|. \tag{21}$$

When $\overrightarrow{RE}$ is fixed, inverse kinematics solutions, (11), (12), and (15) derived from Section 2, are applied to compute q_1, q_2, and q_3, respectively. Then q_4 and q_5 can be also computed by (16) and (18).

B. Properties

As shown in Fig. 3, the proposed control scheme provides elbow movement boundaries for the specified working area.

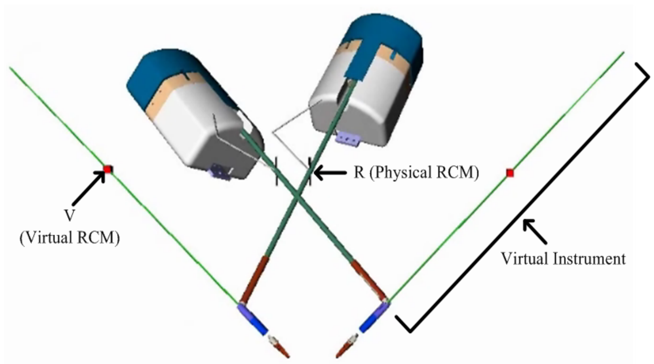


Fig. 5. Virtual Instruments and Virtual RCMs

This could improve surgery safety through deterministic elbow movements. Fig. 4 shows that the working area can be moved to somewhere according to the VIP position modification. Adjusting the VIP position provides surgeons with a large working area. The VIPs act as virtual RCMs for pivoting the virtual instruments as shown in Fig. 5. Through the virtual instrument, a surgeon is able to manipulate the curved instruments as if she does straight things in robotic MPA surgery. Therefore surgeons accustomed to robotic MPA surgery widely used will be able to operate robotic SPA surgery more easily. According to selection of the VIPs the working area of the instruments can be affected. In some cases the static VIPs may not give enough working area to operate, so proper selection of the VIPs should be considered.

C. Selection of the VIP

Selecting the VIP should be considered in both engineering and medical aspects. For exmaple, in engineering aspect it would be considered to provide large working area as possible, and in medical aspect it would be considered to provide effective and safe poses of the instruments for surgery. Its optimal selection to satisfy both sides, however, is a very challenging problem. Until now it has not been resolved clearly. At current status we introduce a heuristic method to determine the VIP position. This has been applied to our experiments successfully.

Procedure of the VIP selection

Refer to Fig. 3.
Step 1. Determine working area (e.g. organ).
Step 2. Adjust manually elbow (E) and wrist (W) of the instrument considering organs and muscles which should be avoided.
Step 3. Compute $\overrightarrow{RE}$ and $\overrightarrow{RW}$ via forward kinematics using each joint angle which is read from sensors, e.g. encoder.
Step 4. Draw a virtual line, $\overrightarrow{EV}$, extending $\overrightarrow{WE}$.
Step 5. Set $|\overrightarrow{EV}|$. We usually set it 0.02∼0.05 m.
Step 6. Finally the VIP, $\overrightarrow{RV}$, is computed as followings:

$$\overrightarrow{RV} = \overrightarrow{RW} + \overrightarrow{WV} \tag{22}$$

where

$$\overrightarrow{WV} = \frac{\overrightarrow{RE} - \overrightarrow{RW}}{|\overrightarrow{RE} - \overrightarrow{RW}|}(|\overrightarrow{WE}| + |\overrightarrow{EV}|) \tag{23}$$

IV. Simulation

We have evaluated the proposed control scheme through simulation. For convenience we have assumed that there is no limitation of range of motion of each joint in the robotic arms. In Fig. 6, the black line is the reference wrist trajectory and the computed wrist trajectory by the proposed control scheme. The blue line is the computed elbow trajectory, and a red $*$ is the VIP(0.0420,-0.0554,-0.0803) used in this simulation. Given every reference wrist position, firstly each joint angle, q_1 to q_5, is computed by inverse kinematics solution described in Section II in real time. Then these are sent to each joint as control inputs. Through simulation we have shown that the reference wrist and the computed wrist trajectory are equivalent. This means the control scheme is working exactly. Additionally as shown in Fig. 6 we can see the elbow trajectory is similar to the wrist trajectory, which demonstrates that elbow movement can be deterministic.

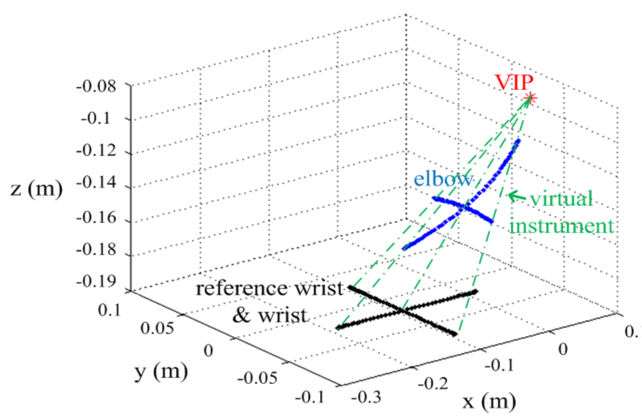


Fig. 6. The trajectory of wrist and elbow by inverse kinematics from given reference wrist [m] (R is origin. VIP (0.0420,-0.0554,-0.0803))

Graphically to demonstrate movement of the arms controlled by the proposed scheme, we have introduced an open source simulator OpenRAVE [18]. Instrument movements with the VIP based control scheme are superimposed in Fig. 7. The VIPs are fixed during operation and the straight virtual instruments (green lines) are operated as our expectation.

V. Experiment

A. Setup

Our robotic SPA surgery system is composed of a master system, a slave system, and a control system as shown in

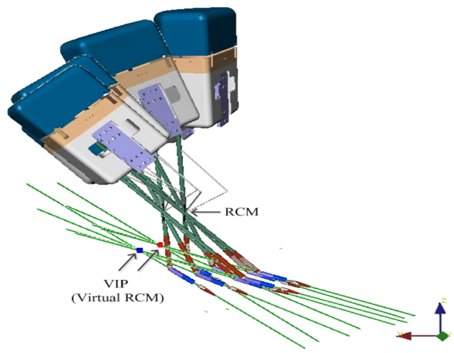


Fig. 7. Superimposing of the instrument movements with the VIP based control scheme: The VIPs are fixed during operation and the wrist position tracks given reference position exactly. Trajectory of elbow and wrist are represented in Fig. 6.

Fig. 8. A couple of omega7 haptic devices by Force Dimension [19] have been used for a master system to generate surgeon's command input for operating the robotic arms. We have developed a slave system which consists of both robotic arms, an endoscope with a stereo camera for 3D display, and a gantry for supporting them. For the control system, we have developed a PC based controller using off-the-shelf motion controllers, NI-7350 from National Instruments Corp. [20]. The PC based controller also provides interface to omega7 for surgeon's command input. Control periods for each axis in motion controllers have been set to 4KHz. Surgeon's command input via omega.7 is transmitted to a slave system every 40ms.

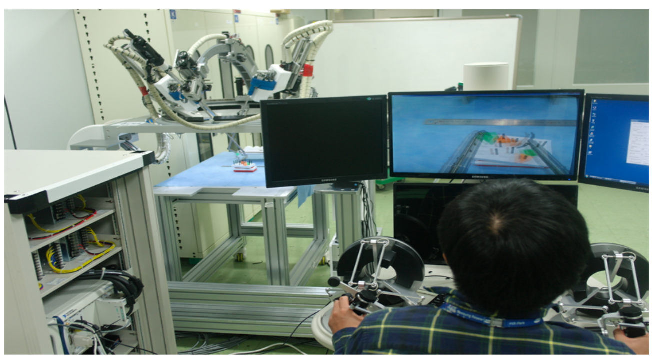


Fig. 8. The surgical robot system for SPA surgery

B. Practical Consideration: Selection of the VIP

In practical selection of the VIP is necessary to be considered with respect to range of motion of each joint. Empirically initial joint angles are recommended to be in the middle of range of motion as possible after completing Step 2 in procedure of the VIP selection. Table I shows angle limits applied in our experiment. We also have set $|\overrightarrow{EV}|$ to 0.05m.

C. Results

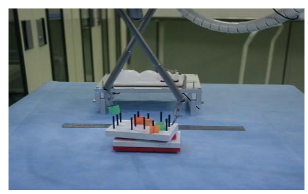
Fig. 9 demonstrates that working area can be adjustable with reallocation of the VIPs when a surgeon needs to change

TABLE I
RANGE OF MOTION AND INITIAL ANGLE OF EACH JOINT

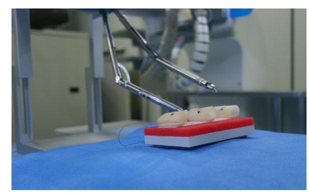
joint	min.	max.	initial
q_1 (degree)	-20	60	20
q_2 (degree)	5	50	30
q_3 (m)	-0.195	-0.02	-0.14
q_4 (degree)	-90	90	30
q_5 (degree)	0	90	45

surgical sites. In Fig. 9 (a) the instrument can move around right site. When it moves to left site, inverse kinematics solution could fail because of limitation of range of motion of some joints. This can be resolved by modification of the VIP like Fig. 9 (b). In current status this task should be performed by a surgeon, but in the future automatic and dynamic reallocation of the VIPs on operation would be necessary.

We have investigated the feasibility of the proposed control scheme based on the VIP through the peg transfer and suturing using Fundamentals of Laparoscopic Surgery (FLS) trainer system [21] as shown in Fig. 10. As a result of 7 trials of the peg transfer and 8 trials of suturing , each elapsed time has decreased by 40.6% and 49.1% in Fig. 11, respectively.

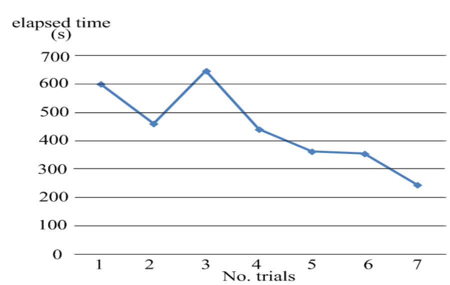


(a)

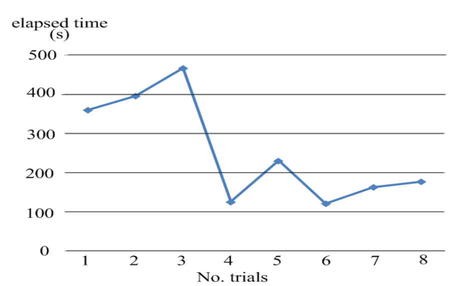


(b)

Fig. 10. Snapshot of the surgical task:(a) Peg transfer (b) Suturing

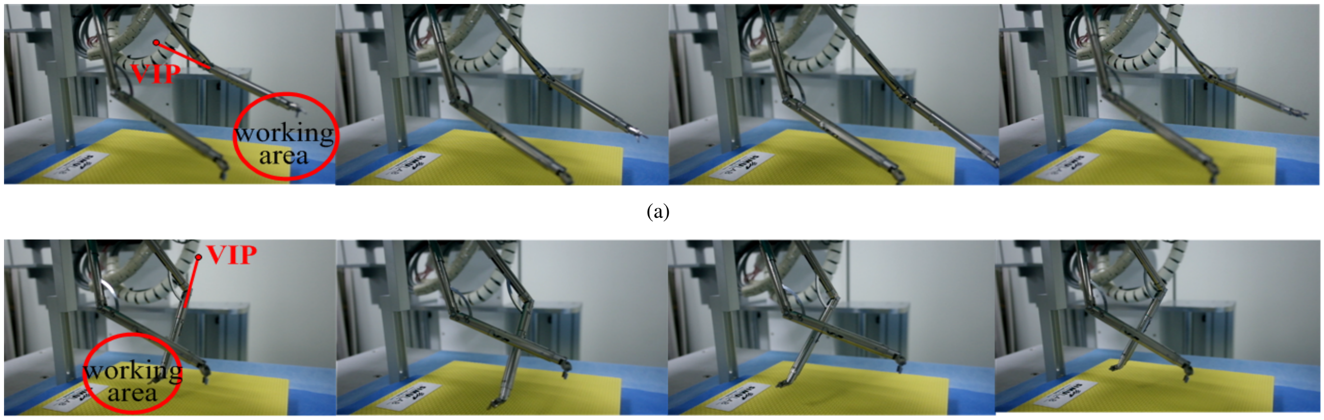


(a)



(b)

Fig. 11. Learning Curves: (a) Peg transfer (b) Suturing



(a)

(b)

Fig. 9. Experiments of adjustable working area by the change of the VIP

VI. Conclusions

We have presented the kinematic control scheme via the VIP for redundant robotic arms for SPA surgery. The scheme introduces the virtual incision ports which robotic instruments with the elbows can be manipulated as straight things. This can improve surgery safety because each elbow of instruments moves deterministic and within boundary. In some cases it may incur restriction of motion of instruments. However adjustment of working area through reallocation of the VIP can resolve this problem as described in experiment. In simulation we have presented the proposed scheme works correctly. It has proven inverse kinematics solution is accurate that the reference wrist positions and the computed wrist positions are equivalent. Curved instruments have been operated like straight things with the VIPs. In experiment we have demonstrated the proposed scheme can be applied to robotic SPA surgery through performing the peg transfer and suturing.

In future work, we will investigate methods to determine the optimal VIPs dynamically on operation. This will be considered to maximize working area and avoid undesirable obstacles automatically.

References

[1] Yoshihiko Nakamura. ”Advanced Robotics Redundancy and Optimization”. Addison-Wesley Publishing Company, 1991.

[2] K.Ahmed, T.T.Wang, V.M. Patel, K. Nagpal, J. Clark, M. Ali, S. Deeba, H. Ashrafian, A. Darzi, and T. Athanasiou, ”The role of single-incision laparoscopic surgery in abdominal and pelvic surgery: a systematic review”, Surgical Endoscopy, pp1-19, July, 2010.

[3] Tracy CR, Raman JD, Cadeddu JA, Rane A , ”Laparoendoscopic single-site surgery in urology: where have we been and where are we heading?”, Nat Clin Pract Urol, vol 5, pp 561-568 , 2008.

[4] Jackson T, Einarsson J, ”Single-port gynecologic surgery”, Rev Obstet Gynecol 3:133139, 2010.

[5] Romanelli JR, Mark L, Omotosho PA, ”Single port laparoscopic cholecystectomy with the TriPort System: a case report”, Surg Innov, Vol 15, pp223-228, 2008.

[6] A. A. Gumbs, L. Milone, P. Sinha, and M. Bessler, ”Totally transumbilical laparoscopic cholecystectomy”, J Gastrointest Surg, vol. 13, pp. 533-534, 2009.

[7] S. Kane and K. J. Stepp, ”Laparo-endoscopic single-site surgery hysterectomy using robotic lightweight endoscope assistants”, J Robotic Surg, vol. 3, pp. 253-255, 2010.

[8] M. Piccigallo, U. Scarfogliero, C. Quaglia, G. Petroni, P. Valdastri, A. Menciassi, and P. Dario, ”Design of a novel bimanual robotic system for single-port laparoscopy”, IEEE/ASME Transactions on Mechatronics, vol 15, no. 6, pp. 871-878, 2010.

[9] J. Ding, K. Xu, R. Goldman, P. Allen, D. Fowler, and N. Simaan, ”Design, simulation and evaluation of kinematic alternatives for insertable robotic effectors platforms in single port access surgery”, in IEEE International Conference on Robotics and Automation, pp.1053-1058, 2010.

[10] N. Simaan, X. Kai, W. Wei, A. Kapoor, P. Kazanzides, R. Taylor, and P. Flint, ”Design and integration of a telerobotic system for minimally invasive surgery of the throat”, The International Journal of Robotics Research, vol. 28, pp. 1134-1153, 2009.

[11] D. Abbott, C. Beck, R. Rothstein, W. Peine, ”Design of an endolumenal NOTES robotic system”, in Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, pp 410-416, 2007.

[12] L. Phee, S. Low S, Z. Thant Z, K. Ho, S. Chung, ”Robotic system for no-scar gastrointestinal surgery”, Int J Med Robotics Comput Assist Surg, vol 4, pp15-22, 2008.

[13] Kaouk JH, Goel RK, Haber GP, Crouzet S, Stein RJ, ”Robotic single-port transumbilical surgery in humans: initial report”, BJU Int, vol 103, pp366-369, 2009.

[14] G.-P. Haber, M. A. White, R. Autorino, P. F. Escobar, M. D. Kroh, S. Chalikonda, R. Khanna, S. Forest, B. Yang, F. Altunrende, R. J. Stein, and J. H. Kaouk, ”Novel robotic da vinci instruments for laparoendoscopic single-site surgery”, Urology, vol. 76, no. 6, pp. 1279- 1282, 2010.

[15] P. Berkelman and S. Okamoto, ”Compact modular system design for teleoperated laparoendoscopic single site surgery”, in The Fourth IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechatronics, Roma, Italy. June, pp24-27, 2012.

[16] Hyundo Choi, Hyung Joo Kim, Yo-An Lim, Ho-Seong Kwak, Jun-Won Jang, Jonghwa Won, ”Conically Shaped Remote Center-of-Motion Mechanism for Single-Incision Surgery”, in Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, 2013.

[17] H. Kim, et al ”A novel compact single incision surgical robot with conical remote center-of-motion mechanism and rod elbow joint,” in EUS Annual Meeting, San Diego, USA, May, p 25, 2013.

[18] Rosen Diankov, ”Automated Construction of Robotic Manipulation Programs”, Ph.D Thesis, Carnegie Mellon Univ. , August, 2010.

[19] http://www.forcedimension.com

[20] http://www.ni.com

[21] http://www.flsprogram.org