Proceeding of the IEEE
International Conference on Robotics and Biomimetics
Dali, China, December 2019

Development of a Novel Hand-eye Coordination Algorithm for Robot Assisted Minimally Invasive Surgery*

Yanwen Sun, Bo Pan†, Yili Fu, Guojun Niu
State Key Laboratory of Robotics and System, Harbin Institute of Technology, Harbin, China

***Abstract* - The minimally invasive surgical robot greatly improved surgical OR efficiency, and surgeon manipulates the surgical instruments through master-slave control under the guidance of laparoscope vision. As a mapping of the surgeon's hand-eye coordination, the coordination between surgical instruments and laparoscope has an important impact on the surgical efficiency and the ergonomics. In this paper, a novel hand-eye coordination algorithm is proposed for the robot - assisted minimally invasive surgery (RMIS). Firstly, a novel cascade-calibration (CC) algorithm structure is proposed to determine the pose relationship between the robot laparoscope arm coordinate system and the robot instruments arm coordinate system. A hand-eye coordination algorithm is also proposed, which provides accurate master-slave control and improves the surgical operation room (OR) efficiency. We validate the proposed algorithm through two experiments with our minimally invasive surgical robot system. Our experiments demonstrate that the proposed method is competitively effective to induce the hand-eye coordination for the RMIS.**

Key Words–Surgical robot Hand-eye coordination Calibration

I. INTRODUCTION

Laparoscopic minimally invasive surgery requires surgeons to perform surgical task through the trocar in the abdominal cavity. In this case, surgeons and assistants must have high coordination, which greatly increases the fatigue. Based on the traditional minimally invasive laparoscopic surgery, the robot is introduced to improve the surgical efficiency and surgical quality, and Robot-assisted minimally invasive surgery (RMIS) has been extensively applied to the surgical task [1][2]. Further speaking, the configuration of minimally invasive surgical robot system can mainly be divided into separable structure and integral structure. For the integral structure [3][4], the commercial surgical robot products such as Da Vinci [5] use this configuration. The robot laparoscope holder arm and robot instrument holder arms are fixed on the same base, so they share the unified coordinate system to determine the kinematic relationship. However, this configuration has a complex mechanical structure, the preoperative placement of the slave arms is difficult, and they are easily collision with each other. The other configuration is separable structure, robot laparoscope holder arm and robot instrument holder arms are respectively located at different bases. the commercial surgical robot products such as DLR [6][7] and Sehance surgical robot system [8] use this configuration. This configuration has a higher flexibility mechanical structure and can be used for more preoperative placement position in different surgical scenarios. The surgeon can make more flexible surgery planning with the separate structure surgical robot system, they can decide when to use the surgical robot, even use only one slave arm to assist the surgical task. But for separate structure, determine the relationships of robot laparoscope holder arm and robot instrument holder arms between different base coordinate system has become an urgent problem. There are limited literatures aiming at solving this problem for surgical robot in detail [9-11], existing solutions including measure the relationship by optical measurement device, the external camera, the magnetic sensor measurements, but these methods are relatively complex, high cost, difficult to clinical application in surgery operation room.

In the minimally invasive surgical robot, the surgical instrument needs to enter the body through the trocar point. At the same time, the doctor needs to operate the surgical instrument through master-slave control. During the operation of the main hand, there is no direct connection between the movement of the hands and the movement of the surgical instruments shown on the monitor, so there are hand-eye coordination problems [5][12]. The current hand-eye coordination mostly based on the methods that terminal coordinate system of laparoscope is transferred to the monitor display coordinate system [13] [14]. But the actual display coordinate system should be the image coordinate system of laparoscope, so the errors of these two coordinate systems lead to the errors in the hand-eye coordination process. In this process, the hand-eye calibration method can be adopted to calibrate the robot. The image coordinate system of laparoscope is taken as the reference coordinate system, and the hand-eye coordination control method of the separate structure surgical robot system can be established based on the hand-eye coordination criteria.

Aiming at the above problems, this paper proposes a novel hand-eye coordination control algorithm for separate structure surgical robot system. First, for determining the relationships of robot laparoscope holder arm and robot instrument holder arms between different base coordinate system, this paper proposes a cascade-calibration (CC) algorithm structure, this

* This work is sponsored by State Key Laboratory of Robotics and Systems (Grant/Award Number: SKLRS201601C), and Heilongjiang Postdoctoral Scientific Research Foundation (LBH-Q17070, LBH-Q17068), National Science Foundation of China (Grant No.61803341).
† Corresponding author: Bo Pan. (e-mail: panbo4034@163.com).

978-1-7281-6321-5/19//$31.00 ©2019 IEEE

method does not require the external sensors, laparoscope information is acquired as exclusive source to determine the relationships of robot laparoscope holder arm and robot instrument holder arms. On this basis, take the image coordinate system of laparoscope as reference coordinate system, and based on the hand-eye coordination criteria, a hand-eye coordination control method of separate structure surgical robot system is established. Compared with traditional hand-eye coordinate methods, the method can improve control accuracy and operation efficiency.

II. METHODS

A. calibration of minimally invasive surgical robot

Consider the RMIS scenario that the surgeon manipulates the robot instrument slave arm and robot laparoscope slave arm through master-slave control, the robot instrument arm (RIA) and robot laparoscope arm (RLA) have the independent base coordinates. To calibrate the position and pose relation between the RIA and RLA, we set the T_I^L as the relationship between two coordinate systems, and the T_I^L contains rotation and homogeneous transformation matrixes. In this paper, a novel cascade-calibration (CC) algorithm structure is proposed. The method incorporates the hand-in-eye and the hand-to-eye calibration, impending the hand-in-to-eye calibration to realize the calibration of surgical robot.

For the specific configuration of RLA, we can't get the accurate coordinate relationship between the laparoscope frame to the RLA end frame. Most of hand-eye coordination algorithm and the master-slave control algorithm use the kinematic chains based on the laparoscope frame which is located as the end position of the laparoscope. But the actual laparoscope frame and the display frame is the image frame of the laparoscope. As shown in Fig. 1, we set the ${}^{RL}_{L}T$ as the translation and rotation from the *laparoscope image frame* to the *RLA end frame*. The ${}^{RI}_{L}T$ is the translation and rotation from the *laparoscope image frame* to the *RIA end frame*.

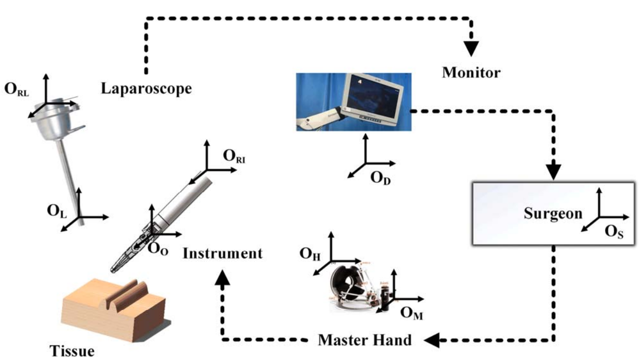

Fig. 1 The relationship among different frames

For the two motion of RLA, according to the kinematics chain and the relationship AX=XB [15-17], we could get:

$$ {}^{BL}_{RL}T_i\,{}^{RL}_{L}T\,{}^{L}_{O}T_i = {}^{BL}_{RL}T_{i+1}\,{}^{RL}_{L}T\,{}^{L}_{O}T_{i+1} \tag{1} $$

In Eq. 1, the ${}^{BI}_{RL}T$ represent the translation and rotation from the *RLA end frame* to *RLA base frame*. ${}^{L}_{O}T$ represent the translation and rotation from the *object calibration board frame* to *laparoscope image frame*. The ${}^{RI}_{L}T$ is the main value to calibration in this phrase. In the calibration progress, the object calibration board keep stable, and RLA change the pose of laparoscope for *i* times.

Then we keep the RLA stable, in the calibration progress, the RIA holds the object calibration board, and the relationship between object calibration board and the RIA keep stable, and RIA change the pose of object calibration board for *i* times. The laparoscope captures the object and according to the kinematics chain and the relationship AX=XB, we could get:

$$ {}^{RI}_{BI}T_i\,{}^{BI}_{L}T\,{}^{L}_{O}T_i = {}^{RI}_{BI}T_{i+1}\,{}^{BI}_{L}T\,{}^{L}_{O}T_{i+1} \tag{2} $$

In Eq. 2, the ${}^{RI}_{BI}T$ represent the translation and rotation from the *RIA end frame* to *RIA base frame*. the ${}^{BI}_{L}T$ represent the translation and rotation from the *RIA base frame* to *laparoscope image frame*, the relationship is the main value to calibration in this phrase. ${}^{L}_{O}T$ represent the translation and rotation from the *object calibration board frame* to *laparoscope image frame*.

After cascade-calibration, we could get kinematics chain :

$$ {}^{RI}_{L}T = {}^{RI}_{BI}T\,{}^{BI}_{L}T \tag{3} $$

$$ {}^{BI}_{BL}T = {}^{BI}_{L}T\,{}^{L}_{RL}T\,{}^{RL}_{BL}T \tag{4} $$

The ${}^{BI}_{L}T$ represent the translation and rotation from the *RIA end frame* to *RIA base frame*.

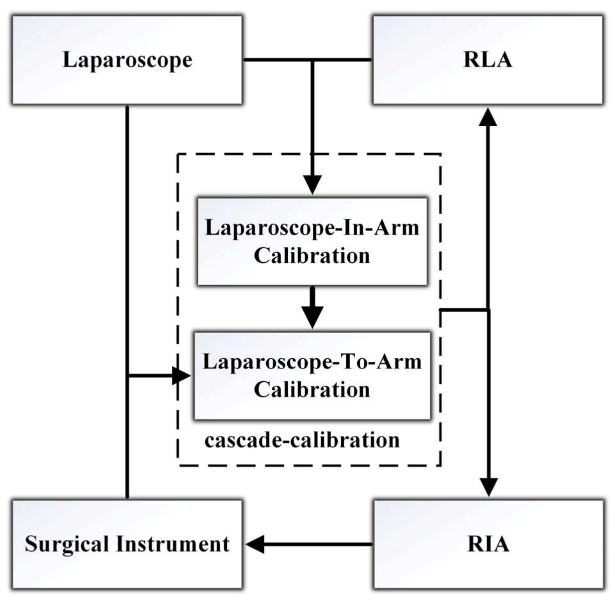

Fig. 2 The framework of the overall CC calibration algorithm

B. Model of hand-eye coordination of minimally invasive surgical robot

The Hand-eye coordination criteria refers to the ability of the human brain to control hand movements based on the visual information acquired by the eyes and its own intuitive feelings, so as to realize the corresponding movement and object manipulation. For RMIS, according to the hand-eye coordination criteria, the motion of the surgical instrument end point in monitor screen should be consistent with the movement of the haptic system. In the process, the haptic system operated and the display observed by surgeon need to meet the hand-eye coordination. Surgical instrument attitude and position need to be moved according to the expectations of the surgeon, and the doctor watching the movement of surgical instrument provided by laparoscopic surgical field is in line with intuitive natural feeling. This process is consistent with the scenario that the surgeons control the movement of the hand to perform specific action through the observation of the eyes. The intuitive operation and hand-eye coordination of surgical robot system can ensure surgeon operation comfortable, and significantly reduce fatigue, improve the quality of surgical task. In this paper, the display coordinate system is set as the image coordinate system of the laparoscope. Based on the coordinate relationship and hand-eye calibration of the separate structure surgical robot system established in the section A, we can design a novel hand-eye coordination control block diagram for separate structure surgical robot system. As shown in Fig. 3. The motion information of the haptic system is obtained from consecutive sampling, and then the surgeon's hands motions are accurately transmitted to the robot slave arms' movements. The surgical robot system could perform the surgical operation according to the surgeon's wishes. The surgeon can adjust the operation in real time through the image feedback of the laparoscope.

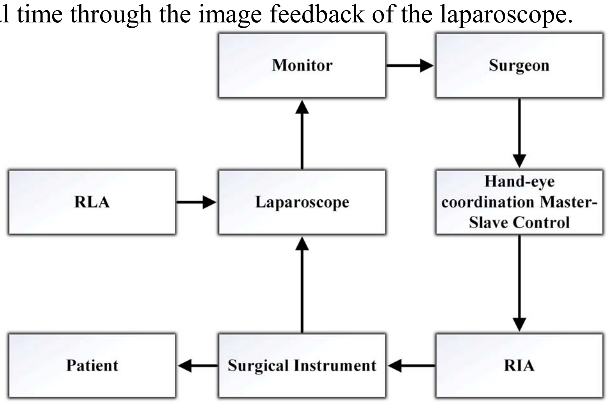

Fig. 3 Procedure of the hand-eye coordination master-slave control

Based on the laparoscope image frame, we could get the kinematics chain from the surgical instrument end point to the laparoscope image frame, equivalent to the surgical instrument end point to the display frame, the relationship represents the movement of surgical instruments observed by the surgeon from the monitor. The kinematics chain from the haptics system to the laparoscope image frame, equivalent to the haptic system to the monitor, the relationship represents the mapping of doctor's hand movements relative to the movement of surgical instruments in the monitor. Based on the kinematics chain, we could get the relationship between the haptic system to the surgical instrument endpoint. The master-slave motion alignment could be established for the surgical robot system, in which the robot laparoscope holder arm and robot instrument holder arms are respectively located at different bases. We only deduce the hand-eye coordination relationship of one robot slave arm. In practice, surgeon control two robot slave arms with two haptic systems, and the hand-eye coordination relationship of the two arms is same. In order to simplify the derivation process, this paper only deduces the hand-eye coordination relationship of one robot slave arm. The following conditions should be met when the laparoscopic image coordinate system is used as the reference coordinate system.

$$ {}^{L}_{H}T\left({}^{H}_{M}T_{t+1} - {}^{H}_{M}T_{t}\right) = \left({}^{BL}_{RL}T\,{}^{RL}_{L}T\right)^{-1}\,{}^{BL}_{BI}R\left({}^{BI}_{RI}T_{t+1} - {}^{BI}_{RI}T_{t}\right) \tag{5} $$

In the Eq. 5the ${}^{L}_{H}T$ represent the translation and rotation from the *laparoscope image frame* to *haptic system base frame*, the *laparoscope image frame* represent the monitor display to the surgeon. ${}^{H}_{M}T$ represent the translation and rotation from the *haptic system base frame* to *haptic system operation frame*, the coordinate system reflects the motion of the surgeon's hand.

In the Eq. 6, the ${}^{BI}_{RI}T$ represent the matrix to be calculated, from this matrix, we can get the control value to move the surgical instrument based on forward kinematics and inverse kinematics of robot instrument holder arm. We set the ${}^{BI}_{RI}T$ as:

$$ {}^{BI}_{RI}T = \begin{bmatrix} {}^{BI}_{RI}R & {}^{BI}_{RI}P \\ 0 & 1 \end{bmatrix},\ {}^{L}_{M}T = {}^{L}_{H}T\,{}^{H}_{M}T = \begin{bmatrix} {}^{L}_{M}\mathrm{R} & {}^{L}_{M}P \\ 0 & 1 \end{bmatrix} \tag{6} $$

Hand-eye coordination control of surgical robot is mainly divided into absolute position control and relative position control. Among them, the hand-eye coordination method of absolute position requires the working space of the master hand and slave hand to be consistent, Moreover, and most of the existing surgical robot systems are designed with heterogeneous haptic system and robot slave arm, for the master-slave heterogeneous robots, one-to-one correspondence often causes some gestures to be difficult to reach, making the surgeons operate not flexible enough, or in a tired position, not ergonomic requirements. This hand-eye coordination control scheme cannot well complete the master-slave consistency control of the surgical robot. The other method is relative position control, normally incremental master-slave control. When this method is used for master-slave control, the control signal received by the slave hand is the increment value of the master-slave system, so the master-slave consistent control of the surgical robot can be well completed. In this paper, incremental master-slave hand-eye coordinated control scheme is adopted, and the position and pose are separated for master-slave mapping. With incremental control, the consistency of movement tendency between the haptic system and the robot slave arm can be guaranteed. From the surgeons' point of view, consistent movement can meet the requirements of the surgical operation.

The position information is linear in cartesian space, position increment of the haptic system can be directly mapped to the position increment of the surgical instrument. The actual position of the surgical instrument can be calculated from the actual position at the current moment plus the position increment. As shown in Eq. 7, The ${}^{BI}_{RI}P_{i+1}$ and ${}^{BI}_{RI}P_i$ are the position of surgical instrument in the RIA base frame, ${}^{L}_{M}P_{i+1}$ and ${}^{L}_{M}P_i$ are the position of haptic system. The λ is the Master-slave mapping magnification, to meet the needs of different surgical scenarios and environments. When performing vascular knotting operations, a large ratio can be applied to narrow down the movement from the haptic system to improve operating accuracy. Some nonessential adipose tissue cuts may be performed to reach the lesion site to use the small radio to improve the surgical efficiency.

$$ {}^{BI}_{RI}P_{i+1} - {}^{BI}_{RI}P_i = \lambda\, {}^{BI}_{BL}R\, {}^{BL}_{RL}R\, {}^{RL}_{L}R({}^{L}_{M}P_{i+1} - {}^{L}_{M}P_i) \tag{7} $$

In this paper, the attitude information is nonlinear in cartesian space, the relative master-slave control scheme can only be used for position control, but not for attitude control of the robot slave arm. Therefore, the attitude of the haptic system should be consistent with the surgical instrument in this process. The attitude angle increment of the haptic system should be transformed into attitude matrix and then mapped into attitude matrix of the surgical instrument.

Specifically speaking, the current attitude matrix of the surgical instrument is mapped to the attitude matrix of the haptic system, and then the haptic system attitude angle corresponding to the current surgical instrument attitude can be obtained from the inverse kinematics of haptic system. The attitude angle increment recorded by the haptic system is added to this attitude angle, and then the sum attitude angle value is transformed into attitude matrix ${}^{L}_{M}R_{i+1}$ through the forward kinematics of the haptic system. Finally, the attitude matrix ${}^{L}_{M}R_{i+1}$ is mapped to the attitude matrix of the surgical instrument ${}^{BI}_{RI}R_{i+1}$. The resultant position and attitude components are synthesized to obtain the pose matrix of the surgical instrument ${}^{BI}_{RI}T$. The displacement of each joint is solved with the inverse kinematics of robot slave arm, and sent to GMAS for master- slave control of one control loop. The model of this hand-eye coordination master-slave control could be shown as:

$$ {}^{BI}_{RI}R_{i+1} = {}^{BI}_{BL}R\, {}^{BL}_{RL}R\, {}^{RL}_{L}R\, {}^{L}_{M}R_{i+1} \tag{8} $$

So that, the surgeons manipulate the master system to control the surgical instruments in coordinate with the display, the surgical instrument move according the hand-eye coordination rule.

III. Experiments and Results

A. *Experimental setup*

The experimental setup is shown in Fig. 4. which is shown in [21]. The haptic system is Omega.7 (Force Dimension, Switzerland), The laparoscopic system is 3D laparoscope system (Einstein Vision, AESCULAP, Germany). The robot system contains three slave arms, one RLA is used to hold the laparoscope, two RIAs are used to hold the surgical instruments. Each slave arm consists passive and active joints. During the experiment, the passive joint is used to adjust the appropriate preoperative placement. The active joint is used for RCM constraint and performing intraoperative changes in the position and posture of surgical instruments and laparoscope. In this paper, to simplify the experiment, we only one RIA slave arm and RLA slave arm, another RIA slave arm is same as the procedure.

Fig. 4 Configuration of the surgical robot system, the RIA and RLA are the robot instrument slave arm and robot laparoscope arm.

B. *calibration results*

We validate the CC calibration algorithm with the surgical robot system, the experiment scenario is shown in Fig.5. The calibration board is held on the surgical instrument, and the RIA is moved to several poses to obtain calibration board images from different perspectives, the pose of the RIA can be obtained from its joint encoder. In the experiment, we conducted the CC calibration by varying the number of motions. For the first phrase of CC calibration, the number of motions is the laparoscope motions, and the number of motions is the surgical instrument motions in the second phrase. We repeat the 30 trials for each number of motions.

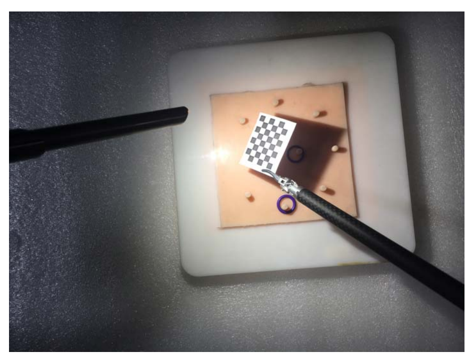
Fig. 5 Scenario of the CC calibration experiment

During the experiment, the calibration results are compared with the ground truth, the ground truth of the calibration results is obtained from the optical measuring instrument (Optotrak Certus, NDI, Canada). we adopt the indirect measurement method to measure the position of the three slave arms' coordinate systems. The marker is placed at the upper end face of the slave arm column. In this case, the geometric relationship between this marker and the RIA and RLA base coordinate systems is known, the position of markers in the NDI global coordinate system is measured by NDI Optotrak Certus. The translation and rotation relationship from the *RIA base frame* to *RLA base frame* ${}^{BI}_{BL}T$ can be obtained. We repeat the measurement three times to calculate the average value and get the ground truth for every trail.

The translation error and rotation error of CC calibration results are shown in Fig. 6 and 7. From the results we could conclude that the proposed methods could efficiently calibrate the transformation and rotation relation between the RLA and RIA base frame. The number of motions has a strong impact on the performance of CC calibration, and we should try to avoid small number of motions in the process of CC calibration. From the analysis, the errors mainly come from the inaccurate kinematics of the surgical robot system, the accumulate error of the mechanical structure cause the kinematics chain error. In addition, the laparoscope intrinsic calibration also contributes to the error of our proposed calibration algorithm. Furthermore, the optical measurement device may get error caused by the manually located mark points.

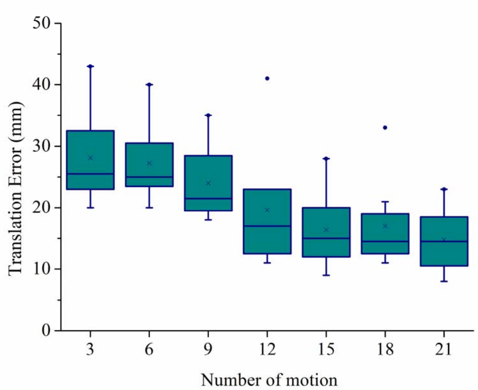

Fig. 6 Translation error of CC calibration results

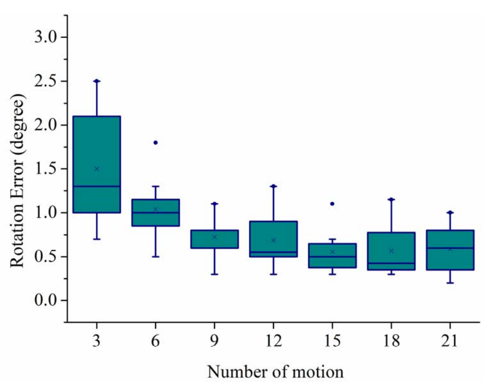

Fig. 7 Rotation error of CC calibration results

C. Hand-eye coordination experiment

To evaluate the ability of our proposed hand-eye coordination and master-slave control algorithm, we manipulated the master hand, and the trajectories of the master hand and the robot slave arm can be obtained by calculating the forward kinematics with the joint encoder value. As shown in Fig. 8 and 9. The Master-slave mapping magnification is set as $\lambda = 1$. From the results, we could conclude that the hand-eye coordination algorithm can realize master-slave control following the motion of master hand with monitor feedback.

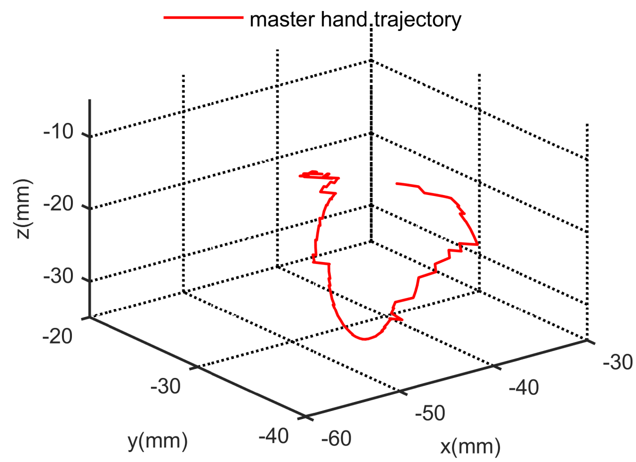

Fig. 8 Trajectory of the master hand

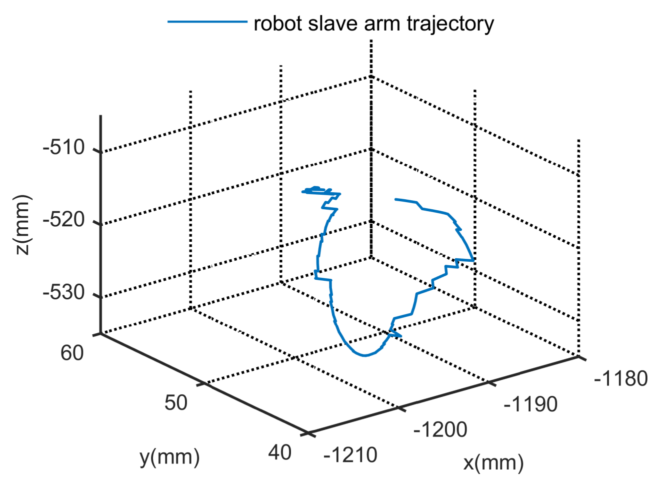

Fig. 9 Trajectory of the robot slave arm

We also conduct the pick and place experiments to validate the hand-eye coordination. The Master-slave mapping magnification is set as $\lambda = 1$. We set the surgical task that surgeon pick two rings and fold them in one column repeatedly, they place the two rings in the column follow the sequence of numbers in the Fig. 10. The surgical task is performed by three doctors and three testers. The experiment participants had experience operating the surgical robot system. Before the experiment, each participant is given 20 minutes of training to familiarize himself with the robotic operation and the surgical task scene. We repeat the 50 trials for the task with the proposed hand-eye coordination algorithm and the traditional master-slave control method, record the completed time for each trail. The experiment results are shown in Fig. 11. With the hand-eye coordination algorithm, the surgical task could be completed with the surgical robot system. Compared two recorded times, the proposed hand-eye coordination algorithm could improve the efficiency, and more in line with surgeon's operating habits.

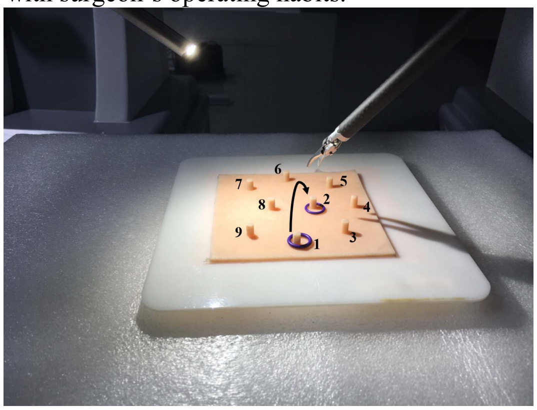

Fig. 10 Scenario of the surgical task

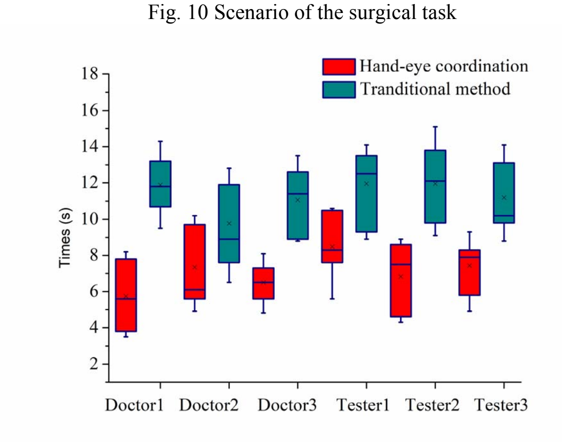

Fig. 11 Task performance results

IV. CONCLUSIONS

In this paper, we present a novel hand-eye coordination algorithm for the robot-assisted minimally invasive surgery (RMIS). We also demonstrate a CC algorithm structure to determine the pose relationship between the RIA coordinate system and the RLA coordinate system. The method does not require external sensors and purely takes advantage of the laparoscope information. The work, represents a novel attempt to perform hand-eye coordination for minimally invasive surgical robot systems that the base coordinate system of RIA is separate from RLA coordinate systems. Finally, the proposed method has been validated by the surgical robot system with two experiments. The experiment results show that the proposed methods could calibration the coordinate system relationship of robot system, and improve the surgical efficiency and the ergonomics.

Future work will look mainly at further improving hand-eye coordination in ex-vivo experiments. It will be attractive to explore visual technology applied to hand-eye coordination.

ACKNOWLEDGMENT

This work is supported by National Science Foundation of China (Grant No.61803341), and Heilongjiang Postdoctoral Scientific Research Foundation (LBH-Q17070, LBH-Q17068), State Key Laboratory of Robotics and Systems (Grant/Award Number: SKLRS201601C).

REFERENCES

[1] Butner S E, Ghodoussi M, "Transforming a surgical robot for human telesurgery," *IEEE Transactions on Robotics and Automation*, vol. 19, no. 5, pp. 818-824, 2003.

[2] Valero R, Ko Y H, Chauhan S, et al, "Robotic surgery: History and teaching impact," *Actas Urologicas Españolas*, vol. 35, no. 9, pp. 540-545, 2011.

[3] Sackier J M, Wang Y L, "Robotically assisted laparoscopic surgery. From concept to development," *Surgical Endoscopy*, vol. 8, no. 1, pp. 63-66, 1994.

[4] Hockstein N G, Nolan J P, O'Malley B W, et al, "Robotic Microlaryngeal Surgery: A Technical Feasibility Study Using the daVinci Surgical Robot and an Airway Mannequin," *Laryngoscope*, vol. 115, no. 5, pp. 780-785, 2010.

[5] Freschi C, Ferrari V, Melfi F, et al, "Technical review of the da Vinci surgical telemanipulator," *International Journal of Medical Robotics & Computer Assisted Surgery*, vol. 9, no. 4, pp. 396-406, 2013.

[6] Hagn U, Nickl M, Jörg S, et al, "The DLR MIRO: a versatile lightweight robot for surgical applications," *Industrial Robot: An International Journal*, vol. 35, no. 4, pp. 324-336, 2008.

[7] Hagn U, Konietschke R, Tobergte A, et al, "DLR MiroSurge: a versatile system for research in endoscopic telesurgery," *International Journal of Computer Assisted Radiology & Surgery*, vol. 5, no. 2, pp. 183-193, 2010.

[8] Spinelli A, David G, Gidaro S, et al, "First experience in colorectal surgery with a new robotic platform with haptic feedback," *Colorectal Disease*, vol. 20, no. 3, pp. 228-235, 2018.

[9] Chou J C K, Kamel M, "Finding the position and orientation of a sensor on a robot manipulator using quaternions," *The international journal of robotics research*, vol. 10, no. 3, pp. 240-254, 1991.

[10] Park, Edward J, Xu, et al, "Calibration-based absolute localization of parts for multi-robot assembly," *Robotica*, vol. 20, no. 4, pp. 359-366, 2002.

[11] Anb A F, Deep K, Yao W, "A multi-modality tracking, navigation and calibration for a flexible robotic drill system for total hip arthroplasty," *The International Journal of Medical Robotics and Computer Assisted Surgery*, 2018, vol. 14, no. 1, pp. e1878, 2017.

[12] Det M J V, Meijerink W J H J, Hoff C, et al, "Optimal ergonomics for laparoscopic surgery in minimally invasive surgery suites: a review and guidelines," *Surgical Endoscopy*, vol. 23, no. 6, pp. 1279-1285, 2009.

[13] Gao Y, Wang S, Li J, et al, "Modeling and evaluation of hand-eye coordination of surgical robotic system on task performance," *The International Journal of Medical Robotics and Computer Assisted Surgery*, vol. 13, no. 4, pp. e1829, 2017.

[14] Bai W, Cao Q, Leng C, et al, "A novel optimal coordinated control strategy for the updated robot system for single port surgery," *The International Journal of Medical Robotics and Computer Assisted Surgery*, vol. 13, no.3, pp. e1844, 2017.

[15] Shiu Y C, Ahmad S. Calibration of wrist-mounted robotic sensors by solving homogeneous transform equations of the form AX=XB," *IEEE Transactions on Robotics and Automation*, vol. 5, no. 1, pp. 16-29, 1989.

[16] Tsai R Y, Lenz R K, "A new technique for fully autonomous and efficient 3D robotics hand/eye calibration," *IEEE Transactions on Robotics and Automation*, vol. 5, no. 3, pp. 345-358, 2002.

[17] Lenz R K, Tsai R Y, "Calibrating a Cartesian robot with eye-on-hand configuration independent of eye-to-hand relationship," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 11, no. 9, pp. 916-928, 1989.