2014 5th IEEE RAS & EMBS International Conference on
Biomedical Robotics and Biomechatronics (BioRob)
August 12-15, 2014. São Paulo, Brazil

# Surgeon's Third Hand: An Assistive Robot Endoscopic System with Intuitive Maneuverability for Laparoscopic Surgery

Ren C. Luo, Jui Wang, Chih Kang Chang, Yi Wen Perng

***Abstract*— Laparoscopic surgery has to be operated with an assistant during surgery, which requires training and high cooperation work between the surgeon and assistants. The objective of this study is to develop a laparoscopic system providing intuitive maneuverability. We develop a Robotic Flexible Laparoscope System (RFLS) with compliance effect including adaptive impedance and velocity control to assist in laparoscopic surgery. The system is controlled by the surgeon's head movements, so that the surgeon can use his/her hands to manipulate the laparoscopic instruments while maneuvering the laparoscope intuitively, and thus replace the assistant and enhance the efficiency of the surgery. The laparoscope movements are controlled by adaptive impedance control approach, the compliance effect, the impedance with the integral and derivative control design, and the reaction torque observer. We also add zero-point-correcting algorithm and singular situation elimination algorithm. Furthermore, scalable ratio adjustment of head movement with respect to laparoscope movement is also included in our system. This system makes surgeon-in-charge maneuver the laparoscope intuitively without communication and coordination with assistant needed in conventional way. As a result, it is expected to reduce manpower and time during surgery. Experimental results demonstrate that the articulated laparoscope can always follow user's head motion in all necessary orientations.**

## I. INTRODUCTION

Laparoscopy procedure or minimally invasive surgery (MIS) is a specialized technique for performing surgery. Over the last 10 years the use of this technique has expanded into intestinal surgery. In a laparoscopic surgery, several 0.5-1 cm incisions are created and serve as entry points into the abdomen. At each incision a tubular instrument known as a trochar is inserted. A laparoscope, a kind of specialized camera, is then passed through the trochar during the procedure. The laparoscope transmits images from the abdominal cavity to high-resolution video monitors in the operation room. This system largely reduces the size of incisions without losing operation effectiveness. The laparoscope provides surgeons with instant view while the instrument extends the reach of hands.

Advanced flexible endoscopes and instruments [1] are being developed, which enables the surgeon to perform interventions that are not possible using conventional endoscopes. However, a number of assistants are required to control the device because of high Degrees of Freedom (DoFs) and only a small working area is provided. This leads to an unnatural cramped position for both the surgeon and the assistant, which can result in fatigue and stress [2]. Furthermore, as discussed in [3], it is unlikely that the assistant moves the camera in exactly the way the surgeon would like.

An articulating laparoscope , the most popular device at the moment, is manipulated with two handles that bend the device horizontally and vertically respectively. However, due to the lack of intuitive manipulation, assistants need a lot practice before mastering the device. Therefore, we want to make it convenient and practical by enabling the surgeon to turn the front-end of a flexible laparoscope using head movements.

In our previous work[4], the laparoscope based on the adaptive impedance control can actuate the laparoscope to quickly move toward the target but promptly slow down the speed before approaching the target position. The control algorithm also provides a compliance effect. Besides, the laparoscope can track the angle of surgeon's head by Motion Node to take images at current position.

In this study, we implement a Robotic Flexible Laparoscope System (RFLS) based on the previous work, which allows the surgeon to perform the same operations as traditional surgery, but with more convenience and efficiency. We make use of a gyroscope to detect surgeon's head movements, making the laparoscope turn to the corresponding direction. It is our contribution that makes the operation more intuitive. By reducing the training time of surgeons and cutting down the assistants who may have misunderstanding over surgeon's instruction during surgery operation, RFLS gives the surgeons a smoother user experience and enhance the efficiency of surgery.

This paper is organized as follows. To begin with, Section II illustrates the concept of Robotic Flexible Laparoscope System. Then the control algorithms are briefly described in Section III. Section IV presents the implementation of RFLS. In Section V, experimental results with articulating laparoscope and zero-point-correcting algorithm are presented. Finally, the paper concludes by a discussion on the current capabilities of the system.

## II. ROBOTIC FLEXIBLE LAPAROSCOPE SYSTEM

In this section, we elaborate the idea of overall system structure, and information flow between each system block, respectively. The algorithms of articulating laparoscope control are elucidated in next section.

As shown in Fig. 1, the surgeon wears a gyroscope(Gyro for short) that measures his/her head movements. The mea-

*Ren C. Luo is with the Center for Intelligent Robotics and Automation Research, National Taiwan University, No. 1, Sec. 4, Roosevelt Road, Taipei, Taiwan 106 (corresponding author to provide phone: +886-2-3366-9822; e-mail: renluo@ntu.edu.tw).
Jui Wang(e-mail: juiwang@ira.ee.ntu.edu.tw)
Chih Kang Chang(e-mail: b99901128@ntu.edu.tw)
Yi Wen Perng (e-mail: d97921001@ntu.edu.tw)

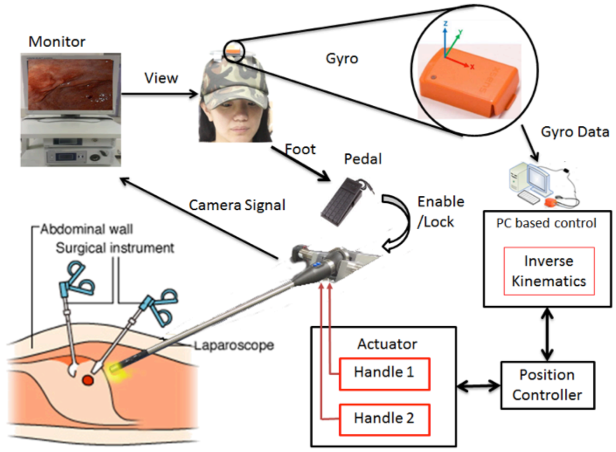


Fig. 1. **Overall system of Robotic Flexible Laparoscope System with user:** The user can see the image displayed on the monitor. When he/she turns his/her head, the Gyro mounted on his/her head will read the direction. The data is then read by the PC. Through the controller, the PC will output the result of how much the motors should move. If the pedal is stepped, motors will move and the articulating laparoscope turns respectively. The camera on the front-end of the laparoscope takes the image and sends it to the monitor.

sured data is processed by the control algorithm and used to actuate the laparoscope tip if the pedal is pressed. The surgeon sees the laparoscopic image on a monitor or on a head-mounted display (HMD).

The robotic system is based on [4]. This system, aimed for minimally invasive surgery, is composed of a 10mm articulating laparoscope and one wireless gyroscope (Xsens, Netherlands) and two motors. The main laparoscope has two deflection DoFs; it can turn to all field of human vision view.

We developed a location-based algorithm to convert the data from gyroscope into positions of laparoscope handles through inverse kinematics. With servo motors installed on laparoscope handles, the laparoscope is controlled through the wireless gyroscope.

RFLS combines the advantages of the Traditional Laparoscopic Surgery (TLS) and Minimally Invasive Robotic Surgery (MIRS) [5]. To begin with, the system is manipulated by an intuitive method and further training of users is not needed. Moreover, because the system substitutes for laparoscopic assistant, it can reduce manpower and improve surgical efficiency and efficacy. Finally, RFLS is more affordable than MIRS. Table.1 shows the Advantages and Disadvantages of TLS, MIRS, and Robotic Flexible Laparoscope System. Some inevitable drawbacks are inherited from traditional operations and those are not in the scope of our discussion in this research.

### A. Articulating Laparoscope

Like conventional laparoscopes, the main part of this system is composed of a 10mm articulating laparoscope (Fig. 2) equipped with an laparoscopic camera, a fixed shaft (about 40.6cm long) and two handles on the proximal side to control bending.

A laparoscope is regarded as a kind of mechanical arm,

TABLE I
ADVANTAGES AND DISADVANTAGES OF TLS, MIRS AND RFES

| Process | Advantages | Disadvantages |
|---|---|---|
| **TLS** | -Well-developed technology<br>-Affordable and ubiquitous<br>-Proven efficacy | -Loss of touch sensation<br>-Limited degrees of motion<br>-The fulcrum effect<br>-Amplification of physiologic tremors<br>-Required experienced endoscopic assistant |
| **MIRS** | -3D visualization<br>-Multi degrees of freedom<br>-Elimination of fulcrum effect and physiologic tremors | -Absence of touch sensation<br>-Very expensive and heavy<br>-May require extra staffs to operate<br>-Increasing the patient's stress |
| **RFLS** | -3D visualization<br>-Tactile sensor feedback<br>-Simple and light devices<br>-Affordable and ubiquitous<br>-Proven efficacy<br>-Reduced manpower<br>-Decreasing the surgery time | -Loss of touch sensation<br>-Amplification of physiologic tremors<br>-The fulcrum effect |

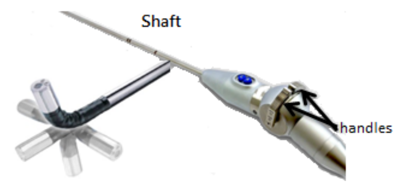


Fig. 2. **Articulating laparoscope:** On the left is the end effector of our Robotic Flexible Laparoscope System. The front-end can move in 2 DoFs, which is controlled by the handles.

with a camera at the front-end. Through controlling two handles, users can adjust the direction of the front-end to a target direction. These two handles control up and down, left and right, respectively. During operation, an assistant helps surgeon operate the laparoscope.

### B. Wireless Gyroscope

A gyroscope is a device for measuring angular information or orientation, based on the principles of angular momentum. We could measure the amount of rotation, angular velocity, and angular acceleration in three dimensions (Fig. 3). Moreover, the wireless gyroscope fixed on the body impedes none of user movement, unlike a wired one.

Effective wireless transmit distance (20 m) is long enough for a general surgery. Typically, the distance is less than 2m from surgeon's head to the target.

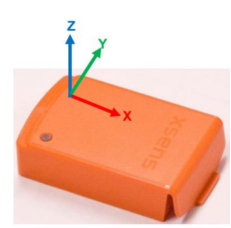


Fig. 3. **Gyroscope:** Axes x, y, z show raw, pitch, yaw direction of the gyroscope respectively. The data is sent to PC by Bluetooth.

### C. Servo Motor and EPOS 24/1 Controller

To achieve a more precise controllability, we use a relatively large gear ratio, which is 103:1. Since the operation speed range of motor is relatively low in our implementation, we can use a controller of smaller output current (1A only) than a suggested controller. The small package size and cost-effective design makes EPOS 24/1 an ideal choice for controlling small motors. Due to its high efficiency and small size, EPOS 24/1 is especially suitable for hand-held devices.

## III. CONTROL ALGORITHM FOR 2-DOF LAPAROSCOPE

### A. Structure of Control System

This research uses the PC based programmable multi-axis controller (PMAC) motion control to implement the impedance with velocity control algorithm. The PMAC provides 1ms servo interrupt time for the routine of the control, and sends out the control command to the servo driver through the D/A converter. The servo driver is configured to the mode which receives the torque command and takes the responsibility of the current control loop. The laparoscope is actuated by servo motor with harmonic drive which bridges the laparoscope and servo motor. The structure of the control system is shown as Fig. 4.

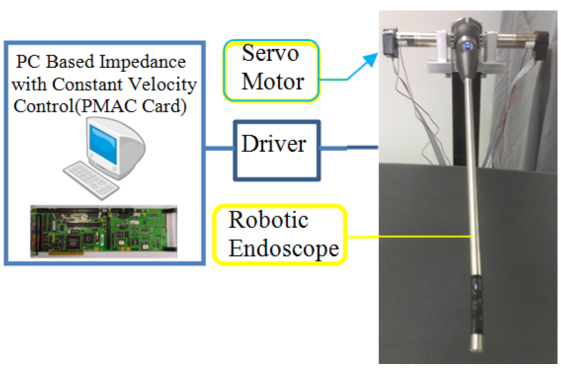


Fig. 4. **Structure of the control system:** The servo motors are attached to the Robotic Laparoscope. And they are driven by PC Based Impedance with Constant Velocity Control (PMAC Card).

### B. Control Algorithm

We design a controller incorporated with impedance control, integral and derivative control. According to our previous research, the impedance gain can be described as (1).

$$Impedance_{gain}(s) = \frac{Q_u \Theta_{com}(s)}{following\_error_A(s)} \cdot \frac{1}{A_{tor\_vel}} \quad (1)$$

The adaptive $Impedance_{gain}(s)$ is used to compensate the velocity dropping due to the constant impedance gain design. The adaptive $Impedance_{gain}(s)$ will depend the changing of $following\_error_A(s)$ and will be calculated a suitable value to achieve the constant speed moving plan. Experimental results show that steady state errors and overshoots are eliminated (see section V). This design fulfils the need for safety and precise control.

With the concept of motion control, we use gyroscope to obtain signals from head rotary motion. With the programming algorithm we developed, the position of the motors to move the handles will be determined. After initialization and all the setups, the output signal will be sent from the controller.

As for the control structure, an adaptive impedance controller with acceleration feed forward and gravity compensation are applied. Some researchers had provided control structure based on robot safety with velocity loop control, such as Wyeth [6]-[8]. A straightforward feature of the impedance controller is that the control system approaches target position well and has a low-stiffness response.

For the initialization, we set the starting direction of gyroscope as the origin, which is the reference point for the operation. To avoid noise, we average 100 gyroscope readings when setting the origin. Averaged roll/pitch/yaw angle is the new reference point.

With gyroscope default setting, roll/pitch/yaw returns angle value in the interval (-180, 180). If the initial measurements are about 180(-180) degrees, it would swing between positive and negative. This causes a problem with the programming algorithm. We call it singular situation. Therefore, if the angle value is in the interval (-180, -90) or (90, 180) (i.e. the angle lies direct westward in x-axis), it turns out to be a singular situation. In the case of singular situation, the axis should reverse from left to right. (i.e. (-180, -90), (90, 180) change to (-90, 0), (0, 90)) In doing so, we avoid the mentioned singular situation error.

Moreover, we add a zero-point-correcting algorithm into our design. In general, surgeons want to make the laparoscope return to the original zero point before each operation. However, prior movements can cause a deviation due to backlash problems from the origin point. We need to add a mechanism that allows the front-end to accurately return to the origin point. Therefore, we designed a mechanism called zero-point-correcting algorithm. Experimental results show that after adding compensation, the laparoscope well returns to the zero point.

Besides, executing the full-range rotations in required orientation, it is also important to maintain the position in the proposed configuration with a high stiffness and rigidity.

When the external force disturbs the laparoscope, the output torque increases to resist the force. Then, the laparoscope returns to equilibrium point with output torque approaching to zero simultaneously. Therefore, the control strategy not only provides safety and compliance but also maintains position precision.

$$\begin{aligned} &[\Theta_{com}(s) - \Theta_{feedback}(s)]\, K_{Impedance} \\ &- \left\{ \omega_{feedback}(s) \left[ J_s + (C + \frac{K_t K_b}{R}) \right] + \tau_d \right\} = Torque_{com} \end{aligned} \quad (2)$$

Equation (2) is a relationship between the load torque and the command torque; it computes how much torques has to be generated for the system load.

The equation (2) tells us how much torque you have to impose on the system.

$\Theta_{com}(s)$ : Command position
$\Theta_{feedback}(s)$ : Actual feedback position
$K_{impedance}$ : Impedance gain
$J$: Inertial of the system load
$C$ : Viscosity coefficient of the system load
$K_t$ : Torque constant
$K_b$ : Back EMF coefficient
$R$ : Resistance of the servo motor driver
$\tau_d$ : Disturbance torque

In out experiment, the system is assumed to have no gravitational torque because the end effector is relatively light.

## IV. IMPLEMENTATION

We have implemented the Robotic Flexible Laparoscope System that is a realization of our architecture. In order to implement the system, all of the control algorithms mentioned above are developed.

### A. Hardware

An articulated laparoscope was used as the basis for the control system to implement the algorithms described in the previous sections. Fig. 5 shows the structure. The system is composed of three parts: flexible laparoscope, control platform, and supporting holder. On the front-end, a camera, which is certified for surgery, and a light source are attached. The control platform contains the control handles actuated by motors, and buttons for controlling airflow and for taking a snapshot of the current camera view.

All of the parameters of the experimental system are shown in the Table II.

The third part is the supporting holder. The height of operating table usually ranges about 1 meter. In order to fit these criteria, we design a two DoFs adjustable supporting holder, which can be adjusted from 1.23 to 1.63 meter. Also, the upper holder can bent from 0 to 90, which helps surgeons do the operation conveniently. As a result, it extends our system into 4 DoFs.

The articulating laparoscope has been motorized, while the supporting holder remains manual because it is usually only used during the initial stage.


Fig. 5. **Solidworks drawing of the total mechanical design:** supporting holder of RFLS can be adjusted in height and direction.

TABLE II
SPECIFICATION OF OUR ROBOTIC FLEXIBLE LAPAROSCOPE SYSTEM

| Parameter | Value |
|---|---|
| **Articulating Laparoscope** | |
| Working length | 330mm |
| Tip diameter | 10.0 +0.0/ -0.5mm |
| Field of view | 80 deg |
| Depth of field | 20mm-150mm |
| Articulation angle | Maximum 100 deg |
| **Gyroscope** | |
| Continuous operating time | 4 hours |
| Transmission range | Up to 20 m in an office space |
| Angular resolution | 0.05 deg |
| Static accuracy | 1 deg |
| Dynamic accuracy | 2 deg RMS |
| **Motor** | |
| Weight | 165g |
| Gearhead reduction | 103:1 |
| Max. continuous torque | 1.2 Nm |
| Recommended speed | 12000 rpm |
| **Position Controller** | |
| Weight | 45g |
| Dimensions | 55 X 40 X 25 mm |
| Requiring supply voltage | 9-24 V DC |
| Max. continuous current | 1 A |
| Efficiency | 85% |
| Max. input frequency | 1 MHz |

### B. Software

The software is written in C++. The program is implemented with Simulink and C interfaces. Simulink is used to implement the robotic control system. The foot pedal is a switch for position data transferring to motor. A flowchart of the main program can be seen in Fig. 6 Most of the software setup has already been successfully implemented in the previous research [8], except for zero-point-correcting algorithm, singular situation elimination, and adjustable head movement to laparoscope movement ratio.

## V. EXPERIMENTAL RESULTS

We develop the entire system with all mentioned software and hardware, and made a prototype. In this section, we evaluate the accuracy of motor, articulating laparoscope control and zero-point-correcting algorithm to test feasibility of the system. Through experiment and evaluation, the prototype works with all the performance which meets the design requirements. The set-up time of the system is approximately 2 minutes, mainly due to the synchronism of gyroscope and wireless dongle.

### A. Motor Control by Gyroscope

Given the joint positions measured at the motors level and gear reduction ratios, one can easily obtain the handles positions. The experimental results show the position response as we expected. The motor trajectory is achieved and shown in Fig. 7.

### B. Laparoscope Control by Gyroscope

We let the ratio of head rotation angles and laparoscope rotation angles be freely adjusted. Surgeons could adjust this parameter to fit every situation in need. Fig. 8 and 9 represent the position response. In Fig. 8, We set the

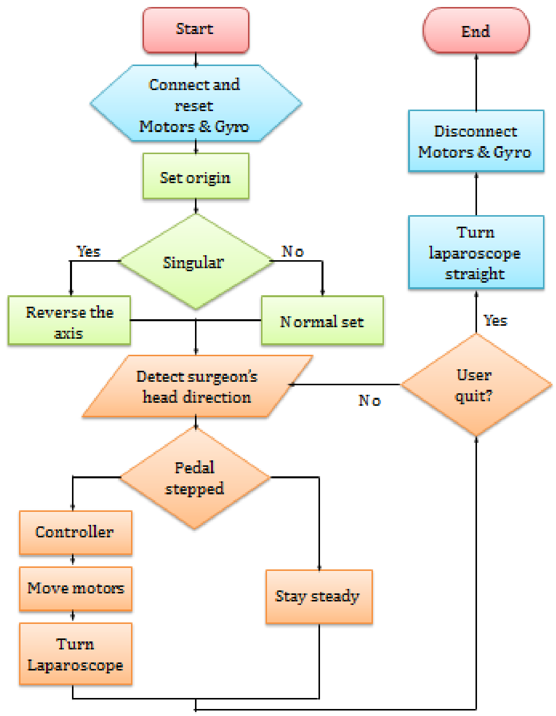


Fig. 6. **Flowchart of the main program:** The red parts are the start and the end. The blue parts are procedures to turn on and turn off the system. The green parts are settings before we start using the system. And the orange parts are repeating steps when we are operating.

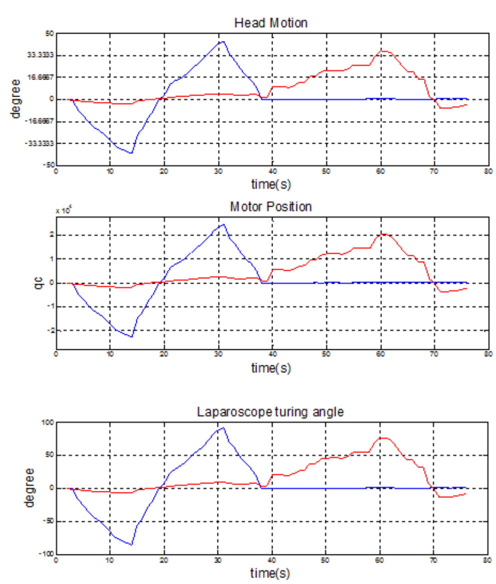


Fig. 7. Head motions control the handles of the laparoscope. The laparoscope tracks well with the rotational angle of the surgeon's head. Blue lines mean "gyroscope Pitch" and "laparoscope up & down"; Red lines mean "gyroscope Yaw" and "laparoscope left & right".

head movement to laparoscope movement ratio = 1:2 and let the front-end of the laparoscope follow the Pitch/Yaw angle of the gyroscope. While in Fig. 9, the head movement to laparoscope movement ratio is 1:1, as if the articulating laparoscope camera is an extension of surgeons eyes.

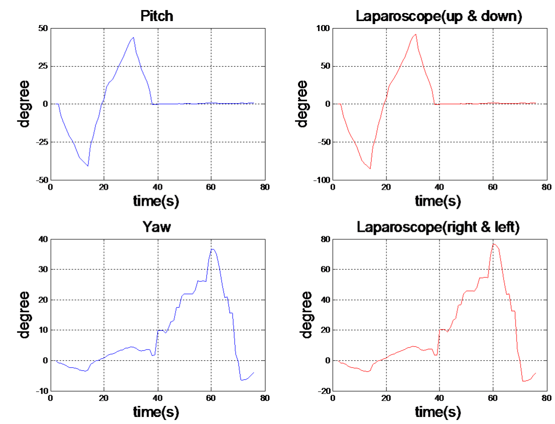


Fig. 8. The gyroscope controls the flexible articulating laparoscope. (the ratio of head rotation angle and laparoscope rotation angle = 0.5)

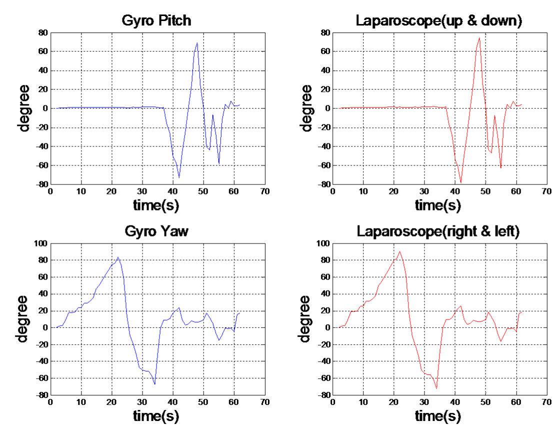


Fig. 9. The gyroscope controls the flexible articulating laparoscope. (the ratio of head rotation angle and laparoscope rotation angle = 1)

### *C. Zero Point Correcting Algorithm*

Before a section of movement begins, we should make the end effector return to zero point. But we find that, during earlier experiments, it appeared that the laparoscope can not go back to the initial position after operation - if we make the articulating laparoscope left turn 90 degrees, it turns out 5 degrees deviation from the origin point when zeroing (Fig. 10(a)). After position compensation, Fig. 10(b) shows that the laparoscope goes back to the initial position after operation.

## VI. DEMONSTRATION

To evaluate the quality of the system, an operation was performed by a user, as shown in Fig. 11. In this head

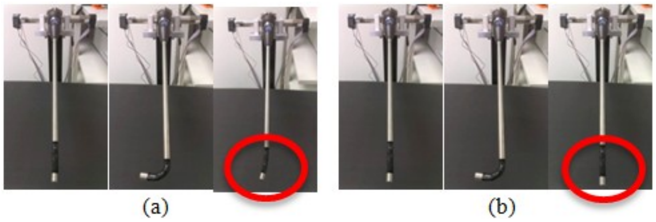


Fig. 10. **Snapshots of the compensation experiment:** (a) without compensation, (b) with compensation

movement & laparoscope movement demonstration, we use all of the technologies described in this paper, such as zero-point-correcting algorithm, singular situation elimination, adjustable head movement to laparoscope movement ratio, etc. After "Initial Position Setting Mode" is completed, we change the articulating laparoscope control mode to "Head Motion Mode", and we can see the articulating laparoscope follow the trajectory of human head motion as shown in Fig. 11.


Fig. 11. **Snapshots of the experiment:** The motion sensor that measures the head orientation is worn on top of the head. User rotates his/her head to control the laparoscope. (The laparoscope can be moved with 8 difference orientations.)

## VII. DISCUSSION

In this paper, we have described the advantage of our design of the laparoscopic surgery:

- The surgeon does not need the assistant since he can process the surgery and operate the 2-DoF laparoscope (can see the fields of 8 difference directions) himself at the same time.
- Solving the problems of the manpower deficit and the relative hand in cooperation between the assistant and surgeon. Potentially it can save surgery time, and increase the efficient of the surgery.
- We provide a way to accord the different angle of the Motion Node, which mounts on the head of surgeon with an ENABLE/LOCK function to operate the 2-DoF laparoscope. It makes the surgeon able to process the surgery and operate the laparoscope by himself at the same time.
- Surgeon will not lose the 3D image which comes from the camera during the position adjustment of the camera, because the HMD is mounted on the surgeon's head.
- The compliance effect design will provide the moving resistance of front-end to surgeon when it moves. This design can avoid patient's organ to be hurt by moving laparoscope.

## VIII. CONCLUSIONS & FUTURE WORK

We develop a system that is capable of controlling an articulating laparoscope through Motion Node and force feedback device. Since the system and all of the algorithms are well integrated, the Robotic Flexible Laparoscope System can be controlled by the head motion of a user in real time, intuitively. By adjusting the ratio of head rotation angles and laparoscope rotation angles, we can calculate the desired trajectory references for articulating laparoscope using inverse kinematics. The system is capable of moving the camera according to surgeons head direction, which can increase surgical efficiency and reduce manpower. The great advantage of this research is that the Robotic Flexible Laparoscope System can be controlled intuitively, so it is promising for realtime on-line operation.

More elaborate experiments will be required to get quantitative data on the effectiveness of the system. The vision system needs to improve and there is already a new version of it under development.

## REFERENCES


[1] A. D. Donno, L. Zorn, P. Zanne, F. Nageotte, and M. de Mathelin, Introducing STRAS: a new flexible robotic system for minimally invasive surgery, in IEEE International Conference on Robotics and Automation, Karlsruhe, May 2013

[2] L. Kranenburg and D. Gossot, Ergonomic problems encountered during video-assisted thoracic surgery, Minimally Invasive Therapy and Allied Technologies, vol. 13, pp. 147155, 2004.

[3] G. Buess, A. Arezzo, M. Schurr, F. Ulmer, and C. Nobman, A new remote-controlled endoscope positioning system for endoscopic solo surgery, Surgical Endoscopy, pp. 395 399, 1999.

[4] R.C.Luo, J. W. Chen, and Y. W. Perng, Robotic endoscope system with compliance effect including adaptive impedance and velocity control for assistive laparoscopic surgery, in Proc. IEEE Int. Conf. Biomedical Robotics and Biomechatronics., 2010, pp. 100-105.

[5] A. R. Lanfranco, Robotic surgery: a current perspective , Ann Surg 2004; 239:1421

[6] G. Wyeth, Demonstrating the Safety and Performance of a Velocity Sourced Series Elastic Actuator, 2008 IEEE International Conference on Robotics and Automation, Pasadena, CA, USA, May 19-23, 2008

[7] G. Wyeth and G. Walker, Assessing the Safety of a Velocity Sourced Series Elastic Actuator Using the Head Injury Criterion, Australasian Conference on Robotics and Automation (ACRA 2007), Brisbane, Australia, December 2007

[8] G.Wyeth,Control Issues for Velocity Sourced Series Elastic Actuators, Australasian Conference on Robotics and Automation (ACRA 2006), Auckland, New Zealand, December 2006.

[9] R. Reilink, G. de Bruin, M. Franken, M. Mariani, S. Misra, and S. Stramigioli, Endoscopic camera control by head movements for thoracic surgery, in Biomedical Robotics and Biomechatronics(BioRob), 2010 3rd IEEE RAS and EMBS International Conference on. IEEE, pp. 510515.