Proceedings of the 2012 IEEE
International Conference on Robotics and Biomimetics
December 11-14, 2012, Guangzhou, China

Euclidean Distance and Workspace Region Based Control Algorithm for Collision Avoidance in a Laparoscopic Surgical Robot: MU-LapaRobot

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***Abstract*—This paper presents an algorithm for controlling the collision avoidance for surgical tools attended to our Minimally Invasive Surgical Robotic system. In our previous work, we have designed and developed Minimally Invasive Surgical Robotics System, MU-LapaRobot for the laparoscopic surgical application. The MU-LapaRobot is designed with mechanically constraint its motion through a small incision point, called remote-center of motion (RCM). The MU-LapaRobot is an active surgical tool holder aimed to use with standard surgical tools based on the collaborative robotic concept.**

This study is focusing on speed control of the robot initiate once the attached surgical tools are inserted into patient's body. The motions are controlled based on the operating regions according to the Euclidean distances and overlap workspace between tools and environment. The control is off once the attached surgical tools are retracted out of the patient's body. The algorithm is relied on the different regions around the operating regions. The motions (translation and rotation) of MU-LapaRobot are improved in its performance, especially, on its higher accuracy and stability without tremor in the operating area after employing our speed control algorithm.

I. INTRODUCTION

Minimally Invasive Surgery (MIS) is a surgical process/ technique where tiny incisions are done on the skin- sometimes it may be just a few millimeters. In this process, a long, thin tube is made to pass through one of the incisions that consist of a miniature camera attached at the end. The surgeon can view the internal abdomen through a monitor which displays real-time images from CCD camera system, attached at the tip of laparoscope. As the incisions are small, patients get the advantage of less blood loss, less pain and low risk of infection, which benefits to the patient as short recovery time. There are usually two to three tools and a laparoscope involved and they are passed through the other incisions made.

This work is supported by the National Research University Grant, Mahidol University, Thailand. The authors would like to thank Prof. Chumpon Wilasrusmee, M.D., Dept. of Surgery, Faculty of Medicine, Ramathibodi Hospital, Mahidol University and Mr. Chawaphol Direkwatana, BART LAB for his contribution on MU-LapaRobot.

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One drawback during operation is that the surgeon needs specific assistances. These types of work require high skill as there are considerable movement limitations and the surgeon needs to improve his hand-eye coordination. Due to fatigue and stress, assistant can cause some mistake during the operation. Replacing the human assistant by robot is the main work of this research during the laparoscopic surgery.

In the past decade, the developments of laparoscopic robots can be separated into two areas: (1) to assist the surgeons during operation, (2) to tele-operate the laparoscopic surgery. Russell H. Taylor and his colleagues developed a complete system that holds laparoscopic camera and other instruments. This robot has 7 degrees of freedom, and is divided into three translations, two distal components. Many researches have been going on since past few decades related to the laparoscopic robotic surgery [1, 2, 3 and 4]. Although these systems perform very well, they are costly and required large space in the operating room. In the commercially available robotic holder, there are chances for collisions to occur between the two tools. In our process, we deal with collision avoidance by controlling the surgical tool holding robot detecting the Euclidian distance by controlling the speed of tool. The speed is varied by the position, orientation and the region of the tool tips relative to each other and internal organs in patient's abdomen based on the robot workspace.

Many people think that da Vinci System is the best for surgical system. It is widely used in USA and Europe. This system is expensive in terms of the causes of usage. Also, the surgeons have to go for hard training to use it, which makes it unsuitable for most of surgeons when any new changes are made in the system. Due to high price and complex in nature to use, this system is not available in poor countries. Our MU-LapaRobot is made very simple and can be cheaper than other commercial surgical robots. This robot is simple in design and can be used easily by any surgeons with spending less time on training [5, 6, and 7]. MU-LapaRobot will need less area and can save lots of space in the operating room. This robot uses parallelogram mechanism. It takes little volume and light weight due to its design. MU-LapaRobot will be helpful in terms of an assistant during operation.

II. MU-LAPAROBOT

MU-LapaRobot is designed and developed based on workspace analysis [7]. MU-LapaRobot has been divided

978-1-4673-2126-6/12/$31.00

into three main parts, robot-end effector, passive arm and driving system. The end-effector has four degree of freedom.

This robot is developed in following stages: Stage 1: development of a surgical tool's passive holder with mechanical constraints based on workspace analysis; Stage 2: development of an active wire-driven robot based on the mechanical design from previous work or Stage 1; Stage 3: development of the robot control based on force and image-guided surgery for collaborative or tele-operative purposes.

Stage 1: The passive instrument tool holder is installed at the side of surgical table, and the robot clamp is attached to the rail of surgical table as shown in Fig. 1. There are two main control switches that are used to control the brake systems of the robot. The first switch controls the planar robot arm to find the incision point, and the second switch controls the robot end-effector to lock and unlock the movement of the surgical instrument. The mechanism at robot end-effector provides constraint movement of instrument manipulation that generates cone-shape working space by the incision point. There are two types of brake system; manual and electrical are used in the robot arm. The manual brakes uses the friction method to hold the position of joint, and the electrical brake use an electromagnetic to release movement of joint. The overall weight of this prototype is quite heavy about 8 kilograms. This paper focuses on the control of Stage 2 robot.

Fig. 1: Passive MU-LapaRobot (Passive Surgical Tool Holder).

Stage 2: This stage is to continue the design and development of the first stage. The newly developed design supports cooperative purpose for laparoscopic surgery. The robot can be fixed beside surgical table by the use of passive arm. This system has end-effector which has lighter weight of about 1.5 kilograms.

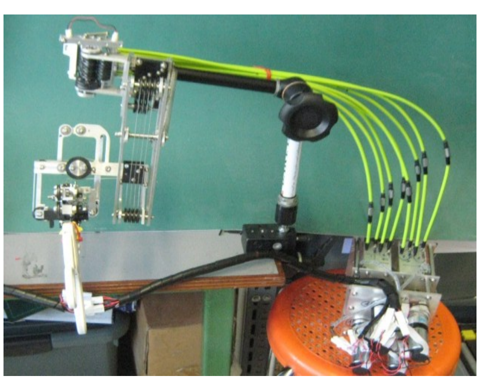

Fig. 2: MU-LapaRobot

The advantage of wire driven transmission is the solution over the back lash problem. The cable does not have backlash, and hence slow and smooth motions can be performed with this robot. The free hand mode can be used when there is no command signals supplied to the robot. The surgical tool holder mode can be used when all clutches turned on. The MU-LapaRobot is shown in Fig. 2. As per the design, the range of MU-LapaRobot is shown in Table I and Fig. 3.

Table I: Range according to different DOF

Degree of Freedom	Range (angle/ displacement, mm.)
# 1 DOF	90 degree
# 2 DOD	75 degree
# 3 DOF	75 degree
# 4 DOF	160 mm.

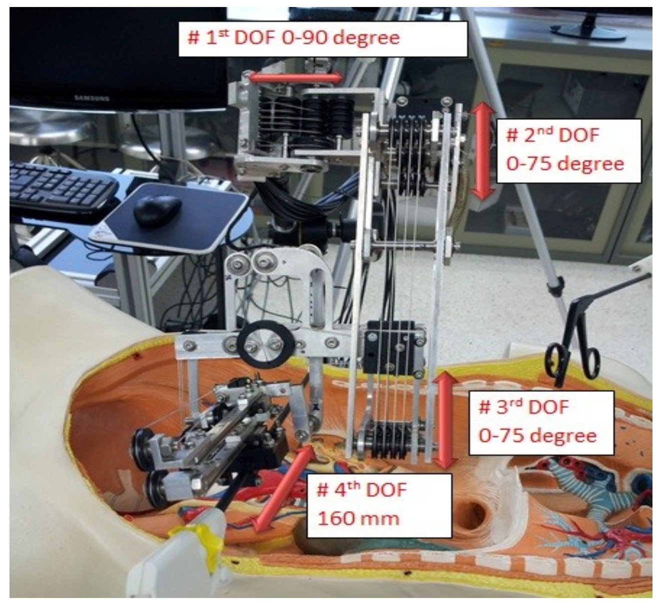

Fig. 3: MU-LapaRobot showing kinematics.

This robot uses parallelogram mechanism. The advantage of this system is that it occupies little space and is designed to be lightweight. Due to its light weight, it can be easily moved according to the required position during laparoscopic surgery.

III. KINEMATICS AND WORKSPACE ALGORITHM OF MU-LAPAROBOT

As per Kumar and Waldron [8], the manipulator workspace is defined as the region of reachable points by a reference point H on the extremity of a manipulator chain. As per Gupta and Roth [8], the workspace W (H) of a point H of the end-effector of a manipulator is the set of all points which H occupies as the joint variables are varied through their entire ranges. And the point H is usually chosen as the center of the end-effector, or the tip of a finger, or even the end of the manipulator itself.

The workspace requirement is important point for the placement of port so that it is properly placed angle to each other. This kind of surgery uses several types of instruments such as laparoscope, grasper, dissector, scissors, forceps etc. For surgical manipulation, we have four degree of freedom for the movements, which are shown in Fig. 4.

- The 1st DOF is the rotation of instrument
- The 2nd DOF is the translation of instrument
- The 3rd DOF and the 4th DOF are both combined for the two axes to generate the cone-shape working space, as shown in Fig. 4.

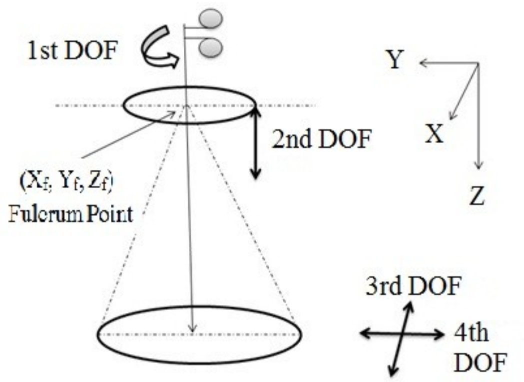

Fig. 4: DOF of the surgical instrument.

During the surgery, the tip of the instruments should be able to reach the working area (which may be around 15 cm or half of the length of instrument), sleeve of trocar within abdominal cavity of about 10 cm within abdominal cavity. Fig. 4 shows DOF of the surgical instrument. From study, it is recommended that the conical range of motion is 60^0 angle in stools operation called dexterous workspace (DWS), and full range of tool motion called extended dexterous workspace (EDWS) needed to move 90^0 in left to right direction and 60^0 in foot to head direction. The workspace of the mechanism can be calculated by the mathematic equation as follow:

$$ {}^{A}_{B}R = [\ {}^{A}\hat{X}_{B} \quad {}^{A}\hat{Y}_{B} \quad {}^{A}\hat{Z}_{B}\ ] = \begin{bmatrix} r11 & r12 & r13 \\ r21 & r22 & r23 \\ r31 & r32 & r33 \end{bmatrix} \quad (1) $$

$$ {}^{A}_{B}R = [\ {}^{A}\hat{X}_{B} \quad {}^{A}\hat{Y}_{B} \quad {}^{A}\hat{Z}_{B}\ ] = \begin{bmatrix} \hat{X}_B . \hat{X}_A & \hat{Y}_B . \hat{X}_A & \hat{Z}_B . \hat{X}_A \\ \hat{X}_B . \hat{Y}_A & \hat{Y}_B . \hat{Y}_A & \hat{Z}_B . \hat{Y}_A \\ \hat{X}_B . \hat{Z}_A & \hat{Y}_B . \hat{Z}_A & \hat{Z}_B . \hat{Z}_A \end{bmatrix} \quad (2) $$

The above equation is modified from the right $R_x(\Upsilon)$, then $R_y(\beta)$, and then $R_z(\alpha)$.

$$ {}^{A}_{B}R_{XYZ}(\Upsilon, \beta, \alpha) = \begin{bmatrix} r11 & r12 & r13 \\ r21 & r22 & r23 \\ r31 & r32 & r33 \end{bmatrix} \quad (3) $$

$$ R_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\Upsilon & -sin\Upsilon \\ 0 & sin\Upsilon & cos\Upsilon \end{bmatrix} \quad (4) $$

$$ R_y = \begin{bmatrix} cos\beta & 0 & sin\beta \\ 0 & 1 & 0 \\ -sin\beta & 0 & cos\beta \end{bmatrix} \quad (5) $$

$$ R_z = \begin{bmatrix} cos\alpha & -sin\alpha & 0 \\ sin\alpha & cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (6) $$

According to Craig, J. J. [9], the result of rotations can be described as the rotation matrix, ${}^{A}_{B}R_{XYZ}(\Upsilon, \beta, \alpha)$ as defined in equation (1):

$$ {}^{A}_{B}R_{XYZ}(\Upsilon, \beta, \alpha) = $$

$$ \begin{bmatrix} c\alpha\, c\beta & c\alpha s\beta s\Upsilon - s\alpha c\Upsilon & c\alpha s\beta c\Upsilon - s\alpha s\Upsilon \\ s\alpha c\beta & s\alpha s\beta s\Upsilon + c\alpha c\Upsilon & s\alpha s\beta c\Upsilon - c\alpha s\Upsilon \\ -s\beta & c\beta s\Upsilon & c\beta c\Upsilon \end{bmatrix} \quad (7) $$

Here, cα is the shorthand for cosα, sα for sinα and so on and ϒ, β, α are the angle of rotation of $R_X(\Upsilon)$, then $R_Y(\beta)$ and then $R_Z(\alpha)$.

IV. MU-LAPAROBOT CONTROL ALGORITHM

For the tool movement in the area, the tools entering the body organ and moving downward, the tool's speed decrease as it passes down through the different regions and be too slow near the operating area. The speed of the tools should vary as per the euclidean distance between the two tools. In this algorithm it is assumed that the two tools are surrounded by two imaginary layers from the center of tools as shown in the Fig. 5.

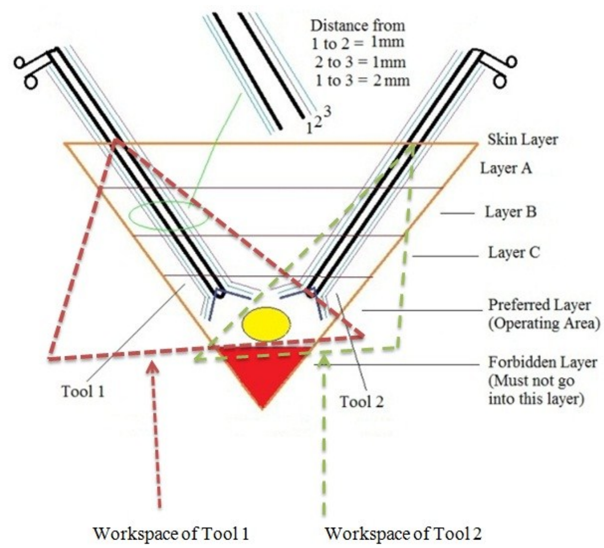

Fig. 5: The tools' inserting in different layers with its workspace.

Surgical tasks have certain degree of uncertainty that arises from factors such as registration errors, variations in anatomy and changes during procedures. Surgeons would like to have some preferred motion. The speed of the tools change as per the distance between them. Tool(s) is/are surrounded by two imaginary lines with 1 mm distance from the tool to 1st surrounded and 2 mm to the 2nd surrounded line (Fig. 5). The original surface of the tool is marked as point 1. It is surrounded by two imaginary protecting layers by 1mm. The inner point is marked as 2 and outer point is marked as 3. If the tools point is 1-3, it means the original surface of one tool and outer protecting layer of second tool. Similarly, 3-3 means, the outer layers of both the tools. In this case, we summarize the speed as per the distance as in Table II.

Table II: Speed according to the distance of the tools

Tools Point	Distance Considered	Speed
3-3	Far	Normal
2-2, 2-3, 3-2	Near	Slow
1-2, 2-1, 1-3, 3-1	Nearer	Slower
1-1	Nearest	Stop

We have defined 3 different regions of operating area. They are defined as follow and shown in Fig. 6.
1. Preferred region: this region defines the operating area.
2. Safety region: the tool could temporarily be in this region for fulfilling some expected task during the operation.
3. Forbidden region: The tool should never be in this area safety purposes. This is shown in Fig. 6.

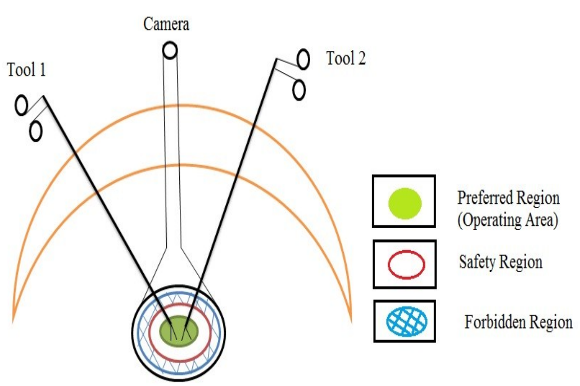

Fig. 6: Tools in 3D view.

Among different factors, speed control and positioning accuracy are of great interest due to the following reason:
1. Certain constant minimum velocity of the operating tool in terms of translation and rotation must be realized in the operating field. This is important for the motions done by the surgeon performed by the robot system.
2. The positioning of the tool tip must be highly accuracy in the operating area. The tools should not move in unnecessary area. This is highly important when operation is done in the sophisticated area consisting blood vessels. There are many researches going on regarding the collision avoidance on different robotics field [10, 11, 12, 13, 14 and 15].

V. CONTROL ARCHITECTURE

Surgeon operates with its force and speed to surgical tools that is fixed at our MU-LapaRobot. MU-LapaRobot control forces and the speed on the tool, the tool in turn interacts with the environment (operating portion). The MU-LapaRobot simulates forces for the surgeon based on forces imparted by the surgeon. Control architecture of MU-LapaRobot is shown in Fig. 7.

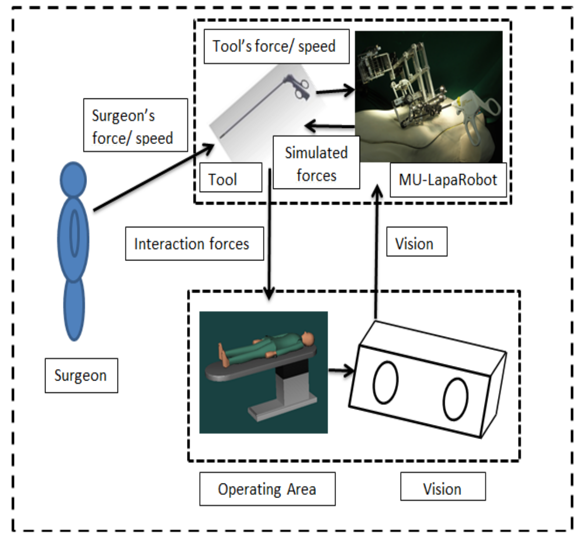

Fig. 7: Control Block Diagram

VI. SIMULATION AND RESULT

I. Tools Entering Different Regions

The tools slows down the speed as it enters inside the body and speed increases slowly when the tools are taken out of the body system. When the tool(s) enter the layer A, speed is decreased by 25%, in the layer B, speed is decreased by 60% and in the layer C, speed is decreased to 80%. The matlab simulation result is shown in Fig. 8.

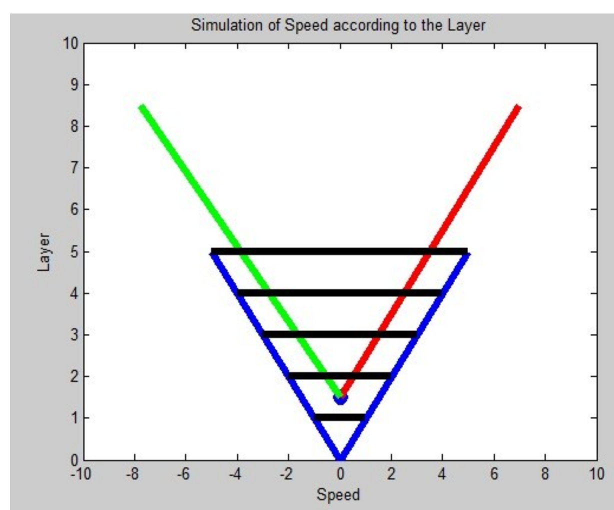

Fig. 8: Simulation result of speed reduction as per changes in different layers.

II. Stopping the Tools When the Distance Approaches Near

The tools are able to move freely without collision in the operating area. When the tools are near to each other and about to cross each-other, then the speed must not stop suddenly. Instead, it should stop slowly, so that no any jerk be felt by the surgeon. For example, we have defined if the distance between two tools are 6cm, its speed is 5cm/s and if the distance is less than 0.2cm, speed be 0cm/s. The matlab simulation result is shown in Fig. 9.

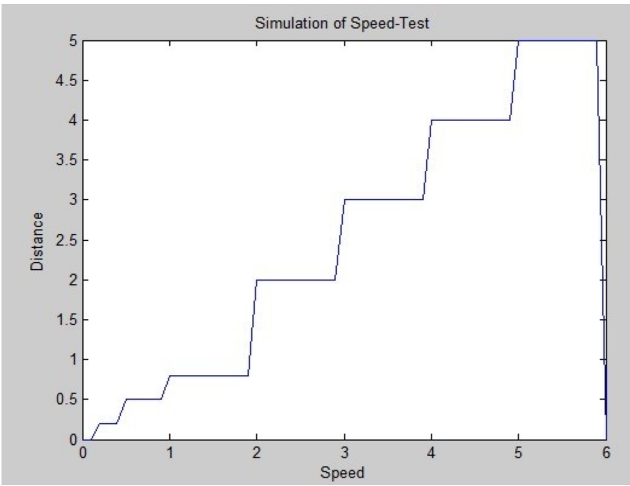

Fig. 9: Matlab simulation for stopping tools in decreasing speed.

VII. PRELIMINARY EXPERIMENT

In the preliminary experiments, a motor was fixed on a stand and it could hold the surgical operating tool. This experiment is of one degree freedom. The tool was moved in the same condition with the same workspace as it would be inside the operating environment. For this one degree of freedom, workspace was divided into four regions in two equal parts (clockwise and anti-clockwise direction). The regions were divided according to the angles from center with some speed as in Table III.

Table III: Movement of tool as per the workspace

Angle (degree)	Speed	Remarks
0-20	Normal	Can easily rotate/ move the tool
20-35	Speed controlled (slower than normal)	Can rotate/ move the tool but not as easy as normal speed
35-45	Speed highly controlled with difficult in movement	Can rotate/ move with controlled speed
45 and above	No movement above this angle	Can't move below this angle

For this experiment, angle was set and the operating tool was tried to move in left-right direction. The movement being normal in the center from 0-20 degree. Crossing this region more than 20 and less than or equal to 35 degree, the speed was reduced and also the movement was not as free as it was in the first case. When the tool was tried to move beyond 35 and below 45 degree, the speed was too slow and also it was difficult for the movement. Beyond 45 degree, the tool was not allowed and was stopped at this point. Same was the case for the movement of tool in anti-clockwise direction. Fig. 10 will make the picture clear about the movement in both the direction.

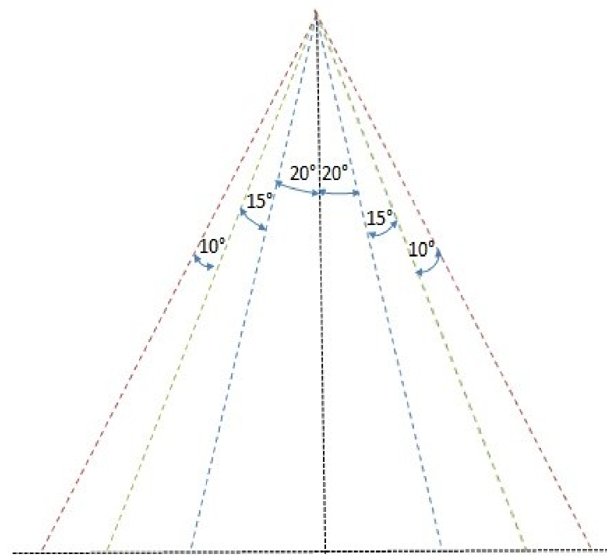

Fig. 10: Controlling surgical tool as per the workspace.

VIII. RESULT

From the preliminary experiment of one degree of freedom, we can control the surgical tool movement according to the workspace. So, it's possible to control the tool with 7 DOF at MU-LapaRobot.

Also, the tools speed can be decreased while entering the tool inside the body organ and increased while taking out of the body.

IX. CONCLUSION

This paper presents control algorithm of the MU-LapaRobot. We are interested in controlling of force and speed during laparoscopic surgery using MU-LapaRobot for the use of surgeon. The MU-LapaRobot can scale down the surgeon's force and it should be at precisely low-speed and low-acceleration motion. Also, the MU-LapaRobot can control any type of tremor that may occur due to the mistake of surgeon. Our purpose is to develop a system that can control the speed of operating tools precisely and sensitively, utilizing both force and position control in the operating workspace. We have got positive result with the experiment of one degree of freedom. So, we are positive that we can success for the MU-LapaRobot that is of seven degree of freedom. The MU-LapaRobot consists of four DC motor with low speed with low backlash that is better for driving system for accuracy movement. Each joint is individually controlled by different DC motors and joint velocities are limited for safety considerations.

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