Layered Workspace Based Control Algorithm for Collision Avoidance in a Laparoscopic Surgical Robot: µ-LapaRobot

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Abstract

In our previous work, surgical robot known as µ-LapaRobot have been successfully designed and developed [2, 3], for the laparoscopic surgical application. The µ-LapaRobot is designed for the ease of surgeon in the minimally invasive surgery which is performed at a constraint movement through small incision point. The main goal of this robot is to perform as a surgical instrument holder for any position of constraint movement.

This research work focuses on the control of speed beginning from the inserting the operating tools inside the body, and the movement of tools around the operating region according to the distance of the two tools. This method also takes into account of different regions around the operating regions. The µ-LapaRobot is able to move or rotate during the laparoscopic surgery, providing high accuracy, stability without tremor in the operating area with the controlled speed.

Keywords: laparoscopic surgery/ robot assisted surgery/ computer integrated surgery/ robot motion control/ speed control surgical robot

1. Introduction

Minimally Invasive Surgery (MIS) is a surgical technique that is performed by surgeon on internal operation through small incision. MIS requires small trauma, less blood loss, less pain and low risk of infection, which benefits to human being as short recovery time. Laparoscopic surgery utilizes a set of small and long instruments and a laparoscope to insert through small incisions on the patient's abdominal wall. The surgeon can view the internal abdomen through a monitor which displays real-time images from CCD camera system that is attached at the tip of laparoscope. During the laparoscopic surgical procedures, the patient's abdominal is filled with the non-flammable gas, CO_2, to create a larger workspace at the internal surgical site. There are usually two to three tools and a laparoscope involved with the laparoscopic surgery.

During the last few years, laparoscopic robots have been developed in two areas: for assisting surgeons during operation and for teleoperation laparoscopic surgery. As per Yun-Ju Lee, Jonathan Kim and Seong-Young Ko [1], in 1995 Russell H. Taylor and his colleague developed a complete system that holds laparoscopic camera and other instruments. This robot has 7 degree of freedom and is divided into three translations, two distal components. In the same year [1], the HISAR system that is of 7 degree of freedom ceiling-mounted surgical robot was developed by IBM Research and Johns Hopkins Medical Centre for camera navigation. Commercial surgical assistant robots such as the AESOP® and EndoAssist have been developed and are used in real surgery for laparoscopic camera control [1]. Although these systems are good to use, they are too costly and takes large spaces in the operating room.

In the commercially available robotics holder, there are chances for collisions to occur between the two tools and no control of the speed when operating tools are inserted into the body. Our research process, deals with collision avoidance by controlling the surgical tool holding robot detecting the speed of tools movement. The speed is varied by the position and orientation of the tool tips relative to each other and internal organs in patient's abdomen based on the robot workspace. This research will produce low cost laparo surgical tools holding robot with precision control utilizing both force and position control.

2. µ-LapaRobot

In order to overcome the disadvantages of available surgical robots and to enhance the performance of surgery, µ-LapaRobot has been successfully designed and developed as shown in fig 1. The main purpose of developing this robot is to perform as a surgical instrument holder and assist surgeon during laparoscopic surgery.

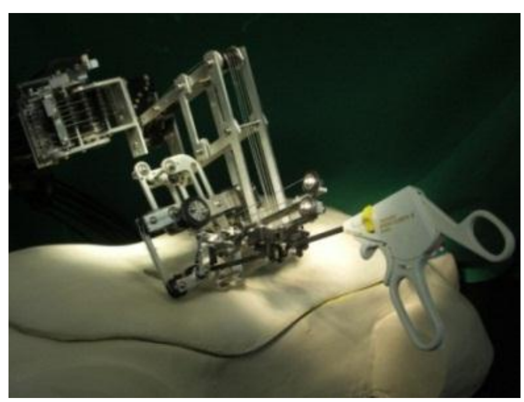

Fig 1: µ-LapaRobot

This robot uses parallelogram mechanism. Advantage of this system is that it takes little volume and is designed to its light weight, it to be lightweight. Due to its light weight, it can be easily moved according to the necessity during laparoscopic surgery. The µ-LapaRobot should be used to assist surgical systems for laparoscopic surgery in terms of the tools movement. There must not be any cross-over between the tools and no any tremor be felt to the patient that may happen to the surgeon knowingly or unknowingly.

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, there are four degree of freedom for the movements, which are as follows as shown in Fig 2.
- 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 cone shape working space.

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 2 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.

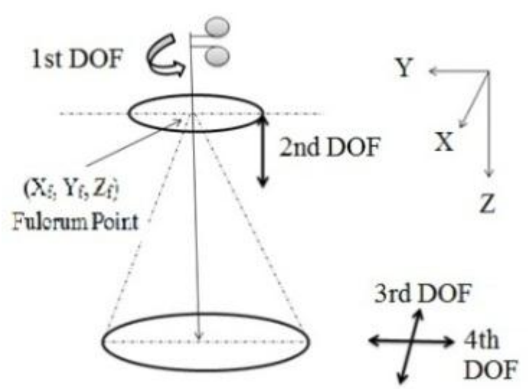

Fig 2: Degrees of freedom of the surgical instrument

As per the designed [2, 3, 4], the end-effector of µ-LapaRobot is used to calculate mechanisms that provide the constraint movements. The axis of movement is passed through the fulcrum point. The robot is designed to stay above the abdomen with a small distance away from the incision point.

3. Kinematic Analysis: Robot End- Effector

Fig 3 illustrates the kinematic model of the robot end effector with parallel mechanism.

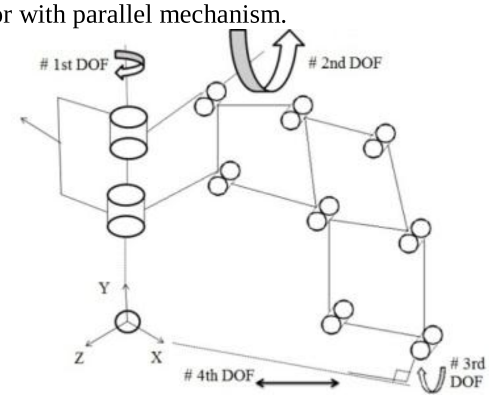

Fig 3: Kinematics of Robot End Effector

As per the design, the range of µ-LapaRobot is shown in Table I.

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.

4. Workspace

As per Kumar and Waldron [6], 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 [6], 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. As per Craig, J. J. [5], the result of rotations can be described as the rotation matrix, ${}^{A}_{B}R_{XYZ}$ (ϒ, β, α), as in equation (1):

$${}^{A}_{B}R_{XYZ}(\Upsilon,\beta,\alpha) = \begin{bmatrix} c\alpha\, c\beta & c\alpha s\beta s\Upsilon - s\alpha c\Upsilon & c\alpha s\beta c\Upsilon - s\alpha s\Upsilon \\ s\alpha c\beta & s\alpha s\beta s\Upsilon + c\alpha c\Upsilon & s\alpha s\beta c\Upsilon - c\alpha s\Upsilon \\ -s\beta & c\beta s\Upsilon & c\beta c\Upsilon \end{bmatrix} \quad (1)$$

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 $R_Z(\alpha)$.

5. µ-LapaRobot Control Algorithm

For the tool movement in the surgery area, the tools entering the body organ and moving downward, and the tool's speed decrease as it passes through the different regions and be too slow near the operating area. The speed of the tools should vary as per the distance between the two tools. It is assumed that the two tools are covered by two imaginary layers from the center of tools as shown in the fig 4.

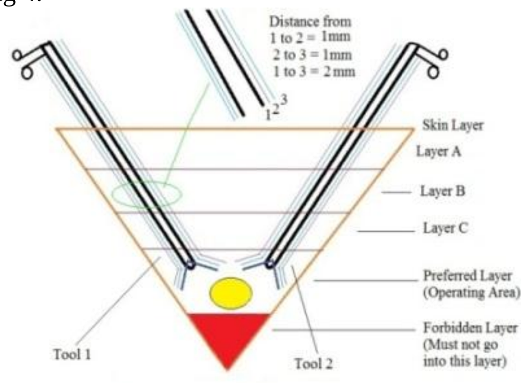

Fig 4: Simulation result of the tools inserting in different layers

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 and it can be defined as follow and shown in Fig 5.

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.

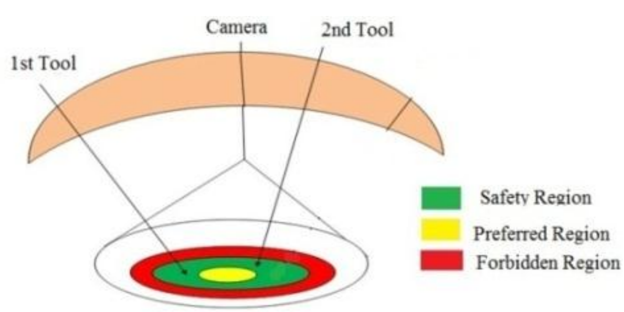

Fig 5: Surgical tools in different regions

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.

6. Simulation Result for Tools Entering Different Regions

As this work is related to laparoscopic surgery, the speed of the tools must be slowed while entering into the body and can increase while coming out of body for the safety purpose. In this simulation, our body parts are divided into five different layers and in each layer, speed is decreased. The tools slows down the speed as it enters inside the body and speed increases slowly when the tools are coming 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 6.

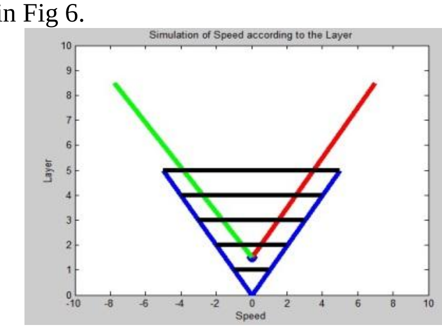

Fig 6: Simulation result of speed

The speed of the tools changes as per the distance between the tools. Tool(s) is/are surrounded by two imaginary lines with 1 mm distance from the tool to 1^{st} surrounded and 2 mm to the 2^{nd} surrounded line (Fig 4). The original surface if 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. For this case, the speed and distance are summarized 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

7. Simulation Result for Stopping the Tools when the Distance Approaches Near

The tools are able to move freely without collision in the operating area but never able to move freely outside 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 should be felt by the surgeons. For example, it has been defined that if the distances 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 is shown in Fig 7.

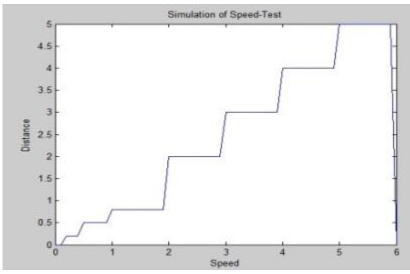

Fig 7: MATLAB simulation for stopping tools in decreasing speed

8. Conclusion

Our research are interested in controlling of force and speed during laparoscopic surgery using µ-LapaRobot by which the surgeon manipulate tools in contact with operating environment. The µ-LapaRobot can scale down the surgeon's force and it should be at precisely low-speed and low-acceleration motion. Also, the µ-LapaRobot can control any type of tremor that may occur due to the mistake of surgeon. Our goal is to develop a system that can control the speed of operating tools precisely and sensitively, utilizing both force and position control. The µ-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. From the simulation work, it has been proved that the four algorithm selected to control the speed of movement during laparoscopic surgery can be successfully done on our MU-LapaRobot that is having 7 degrees of freedom.

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