Proceedings of the 2011 IEEE
International Conference on Robotics and Biomimetics
December 7-11, 2011, Phuket, Thailand

Development of Wire-Driven Laparoscopic Surgical Robotic System, "MU-LapaRobot"

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***Abstract*— This paper describes the design and development of a new wire-driven laparoscopic surgical robotic system. The aim of our design is to develop a surgical robotic system to work with traditional surgical tools to reduce the surgeon's learning curve in using our robotic system. The overall design is strictly based on surgical requirements which our specific workspace analysis also plays an important role. The motion of laparoscopic tool creates a unique constraint which is a remote-fulcrum point away from the robot at the small incision on abdominal wall. Our robot consists of 3 sections; 1) 2-link passive planar manipulator with level adjuster for locating the fulcrum point in 3D-space, 2) 2-DOF distant-parallel mechanical linkage for generating a cone-shape workspace, and 3) tool's quick release for switching tool during the surgery. Our current study and mechanical design is based on our first design of "A Passive Laparoscopic Tool Holder with Electromagnetic Brake System" in full motion constraint. The new design is a wire-driven and motorized system. The design, implementation, experiment and results are discussed here. The ultimate goal of this project is to develop an interchangeable surgical robots which capable of human-robot collaboration and tele-operation.**

Keywords—Surgical Robots, Laparoscopic Surgical Robot, Workspace, Robot-Assisted Surgery, Robot Design

I. Introduction

Minimally Invasive Surgery (MIS) is a surgical technique which surgeon performs an internal operation through small incisions. MIS requires small trauma, less blood loss, less pain and lower risk of infections, which benefits a very much shorter recovery time. MIS covers many types of surgical procedures, such as, thoracic surgery, stereotactic surgery and laparoscopic surgery. 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 long instrument is used instead of surgeon's hands and standard surgical tools. The surgeon can view the internal abdomen through a monitor which displays real-time images from a CCD camera system attaches at the tip of laparoscope. Most of the cases in laparoscopic surgery are Cholecystectomy surgery. However, the special instrument for laparoscopic surgery requires a certain internal and external workspace in order to perform its tasks.

A. Background and Motivation

During the laparoscopic surgical procedures, the patient's abdomen is filled with the non-flammable gas, CO_2, to create a larger workspace at the internal surgical site. Therefore, each small incision at the abdominal wall, called "port," is used as the fulcrum point for a surgical tool. There are usually two to three tools and a laparoscope involve with the surgical protocol.

In operating room, there are a number of surgeons and assistants to involve with the surgery based on cases. In general, primary surgeon stands beside camera operator and opposite a first assistant which supports the primary surgeon in the operation. The camera operator must provide the right field of views based on the command from primary surgeon.

Although MIS has several advantages for patients, the limitations for surgeons have occurred, such as, lack of direct palpation, loss of direct visibility on organs, motion constraints through small incision, hand-eye coordination without sensation, depth information, and force feedback from the organs. Consequently, surgeons need trainings and practices to approve their skill before attending a real operation. In several cases of laparoscopic surgery take a long period (two or even more hours) that causes fatigue to the surgeon.

This study focuses on designing a laparoscopic surgical robot based on the workspace analysis. The newly designed laparoscopic surgical robot, called "MU-LapaRobot," is planned to develop in stages, and is aimed to use in collaboration or tele-operation by surgeon for existing surgical tools and procedures. The development stages include: Stage 1: development of a surgical tool's passive holder with mechanical constrains base on workspace analysis; Stage 2: development of an active wire-driving robot based on the design from Stage 1; Stage 3: development of the robot control based on force and image-guided surgery for collaborative or tele-operative purposes.

B. Related Works and Their Analyses

Many of the robotics system have been developed during the last decade. The Robot-Assisted Surgery (RAS) is the development of an accuracy model on the patient. The applied robotics system provides advantages such as high accuracy, stability without tremor, working without tired, unaffected by radiation and remote control. Even many advantages of robotics system compared with human surgery which best hand eye-coordination, good judgment but on the other hand is lower geometry, more fatigue and limited dexterity but there are limitation such as problem of reliability, expensive, size, experimental trials and maintenance [1, 2]. An enhanced of surgical dexterity may lead better patient outcomes.

978-1-4577-2137-3/11/$26.00 © 2011 IEEE

Since the early 1990s, the commercial robot surgery was available in market especially two systems: The Zeus system (computer Motion inc.) and the da Vinci system (Intuitive Surgical Inc.)

The Zeus uses a serial chain in a SCARA-like configuration, planar movement and consists of three robotic arms: two arms to hold surgical instrument and the laparoscope that is attached on the third arm which is AESOP™ voice-controlled endoscopic camera. Arms are six joints but only four joints can be actuated at the console. The others two are passive joints. Surgeon console has a video system to show 3D images by endoscope camera. At present, the ZEUS system was taken over by Intuitive Surgical and not commercially available [3].

The next generation is da Vinci Surgical System which is a robotic surgical system made by Intuitive Surgical. It performs in complex surgery using in a minimally invasive approach and uses a remote center parallel mechanism to constraint instrument movement. This system is a remote operation by a surgeon from a console [4]. It provides surgeons with 3D visualization, enhanced dexterity by EndoWrist Instrument, high precision and comfortable pose. The da Vinci Surgical System compost of three components: a surgeon's console, a patient-side robotic cart with 4 arms, and a high-definition 3D vision system.

Although these systems are high performance but the drawbacks are cumbersome, large mass, large volumes around the operating table and above the patient. These systems cannot feedback force interaction. The commercial robotics surgical system is not wildly use because limitation by their size, complexity, time-consuming setup, maintenance, and sterilization procedures, and cost. At the same time, many researchers try to develop robot surgery which improves the drawbacks of currently systems. For example, the lightweight and compact robot surgery such as LER robot, MC^2E Robot and CURES robot, are a target for robot surgery but should perform in equivalent functions.

LER Robot is a compact endoscope manipulator which is developed for holding endoscope as human assistant in minimally invasive surgery [5, 6]. It has a full motion range of rotation with actuators. Therefore, an endoscope passes through an incision point in any movement. The design based on the LER uses actuators to control the rotation and translation of instrument. The robot uses standard surgical instrument in this prototype. A rack-and-pinion mechanism is used to control the insertion of instrument with two vertical rods because of force requirement. It may be held in place on the abdomen by adhesive strips or sutures, or attached to the sides of the table with clamps.

The MC^2E robot is also a compact manipulator for endoscopic surgery [7]. The design is small, light weight and force measurement that provides the sense of touch. The operation is from remote or tele-operation. The structure use spherical mechanism with actuated by motors. The motors are mounted at the joints which the axis of each joint is intersection. There are six degrees of freedom (DOFs) force/torque reflection at the master console and only four degrees of freedom (DOFs) remains inside patient by standard instrument. The co-manipulation is presented in this work by surgeon uses surgical instrument as normal surgery but mechanical constraint and also controls instrument by tele-operation. The robot is placed on the abdomen and mounted by stripes. Many cables and stripes may obstruct in procedures.

The CURES is a surgical robot developed by BioRobotics Laboratory at the University of Washington [8]. The commercial surgical robots are very expensive and huge system. They propose compact and cost-effective of surgical robot which has five degrees of freedom, 2 DOFs is passes through incision point, insertion, rotation and grasp. The structure uses spherical mechanism by using wire-drive method and direct-drive with actuators. Consequently, the structure of robot can be made lighter in wire-drive transmission with actuators compare to the straightforward direct-drive with actuators because it needs less pay load for movement.

In full system consists of instrument and camera robot but this paper we focus on the instrument robot that applies the robotics system for assisting in laparoscopic surgery. Even surgical robotics technology has advantages but there are not widely uses in hospitals because limitation of their considerable size, complexity, and cost, and their time-consuming setup, maintenance, and sterilization procedures.

In this project, we propose a robot assisted surgery which aids surgeon as an assistant for human-robot coorperation as a holder and tele-operation system. The development of surgical robot with equivalent performance and potential and compact, lightweight, ease of use, more versatility, would be needed as robotic assistance without deviation from conventional laparoscopy.

I. Conceptual Design and System Overview

A. Overview

The procedure starts from positioning patient and port placement. After that, surgeon makes wound for inserting trocar and fulfill CO_2 to create workspace in abdomen. The working area depends on port placement because two surgical instrument tips have to reach target organ together. Ideally, the tip of the instrument should easily to reach the working area, (approximately 15 cm or a half of instrument length) sleeve of trocar within abdominal cavity about 10 cm within abdominal cavity. The trocar will not obstruct the field of view. The inter-trocar should not too close together that obscure visualization or called "sword fighting" [9].In Figure 1.show two instruments should form a 60˚ to 90˚ angle from the tips of instruments for ergonomic approach.

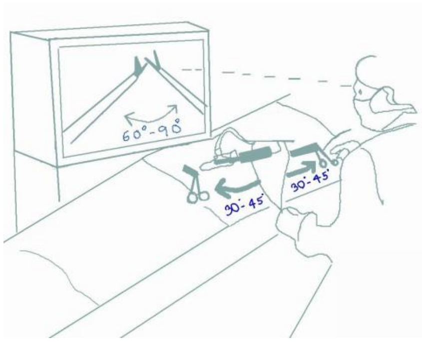


Figure 1. The range of instrument manipulation

The instrument tips should be at a working distance of 80 mm to cover working area. From study [10,11], they recommend the conical range of motion is 60˚ angle in stools operation called dexterous workspace, DWS and full range of tool motion called the extended dexterous workspace (EDWS) needed to move 90˚ in left to right direction and 60˚ in foot to head direction (See Figure 1).

In operation, the constraint of the incision limits motion of manipulation because there are only three rotations and one translation in laparoscopic surgery (Figure 2.). Two of these rotations at fulcrum point around the small wound. The combination of two perpendicular axes (x, y axis), the third is rotation, and insertion displacement along longitudinal axis (z axis).

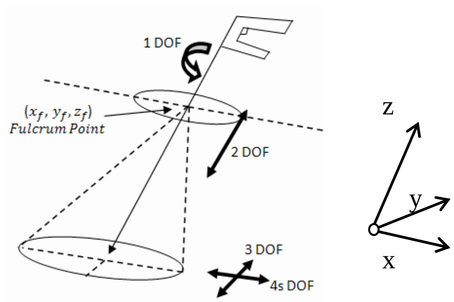


Figure 2. The degree of freedom of the surgical instrument manipulation

B. Robot Functions

In previous study, the requirements in laparoscopic surgery have constraint movement and limit degree of freedom. In conceptual design, the mechanism has three rotational and one linear DOF which pass through incision point. The size of robot should compact and lightweight. The robot collision can occur when two or more robots are working in procedure. In this current study, we propose the development of passive tool holder, called passive robot and in future function, called active robot. We would the active-passive robot for laparoscopic surgery.

i. Previous Stage: Passive Robot

First, design and development of prototype is instrument holder which is surgeon can interact with the device. Normally robot has a high torque actuator at each joint. So users cannot rotate a robot linkage by themselves

Our project also makes a robot that works as instrument holder. The robot can hold and release the movement of instrument that depends on surgeon control. After surgeon adjusts robot arm for port placement by laser guidance, the end-effector is fixed a position of incision point on patient's abdomen. The brake system use electromagnetic brake in the joint movement in robot arm and end-effector. When the electromagnetic brake gets electricity, the brake is on to allow movement otherwise it stops movement. Surgeon can use surgical instrument with passive robot as an assistant. It is easy to use passive holder when surgeon use instrument because robot can hold position of instrument without replacement or needed assistant.

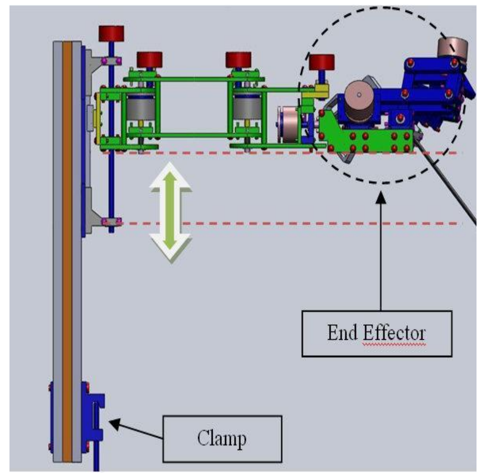


Figure 3. The robot CAD

In Figure 3 show the planar robot arm that is designed to attach with surgical table. The parallelogram mechanism and spherical mechanism are selected in the structure to move axis of rotation which does not obstruct area over incision point. The robot arm can be adjusted in vertical direction and horizontal plane. The configuration of robot arm are adjusted for port placement and fixed position for mechanism which constrain pathway of surgical instrument at end-effector.

In operation, surgeon often changes instruments to cut, grasp and clamp. The idea is not only surgeon use surgical instrument in normal procedure with robot but also can change surgical instrument which attach with robot. In robot surgery, the sterilization problem is important for instrument which touch organ inside or outside body because it take time to change or cannot change by structure. The design is easy to release surgical instrument from robot by holding socket and press button to release surgical instrument.

ii. Current Stage: Active Robot

Second, we try to apply the actuator system to the passive robot to active robot with cooperative purpose. The wire driven method is used for force transmission which make the robot lighter than a straightforward actuator method. The actuators place another position of robot to reduce weighton root in linkage. The heavy weight of robot arm needs strong structure. The high torque actuators are expensive. The lighter robot arm needs lower capacity of actuator for movement. The fast and smooth movement can present in light robot arm. The criteria are such as size, load, weight, strength, safety, fabrication and cost. The materials should not be toxic for short terms.

II. ROBOT KINEMATICS

We use parallelogram mechanism to constraint movement. The combination of axis which passes through incision point and parallel joint axis generate working area as cone shape. In each point represents a coordinate frame. Figure 2 and 3 show kinematics models of the robot.

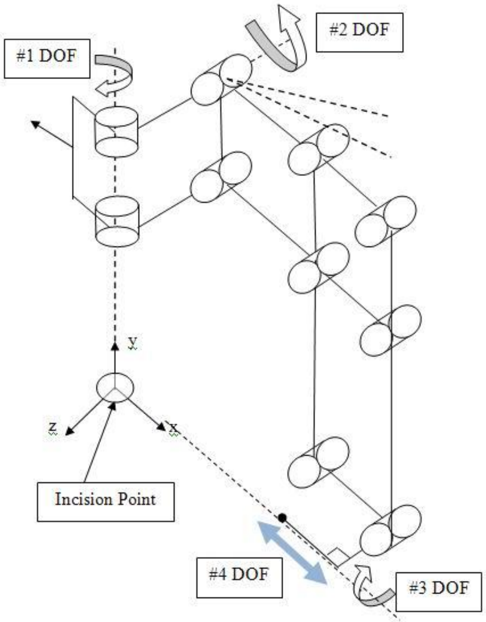


Figure 4. The kinematics of robot end-effector

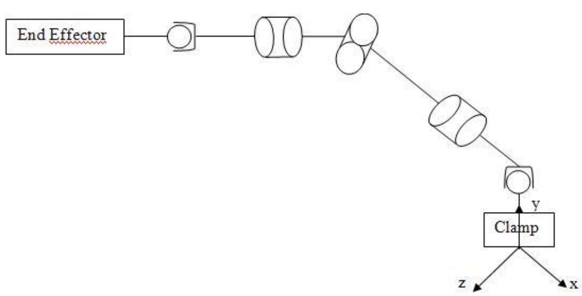


Figure 5. The kinematics of passive arm

On the design, the range of the robot arm including rotation and translation show in Table 1 and Table 2.

TABLE I
RANGE OF THE END EFFECTOR

DOF	Range (angle/ displacement, mm.)
1	180°
2	75°
3	$\pm 75°$
4	150 $mm.$

By the mechanical constraint, the end-effector is fixed on the distance between abdomen to robot and incision point. To enhance the set up procedure, an additional laser beam source can provide the guidance to an incision area. By trigonometric calculation, the incision point can be show while the robot is moved to exact incision point.

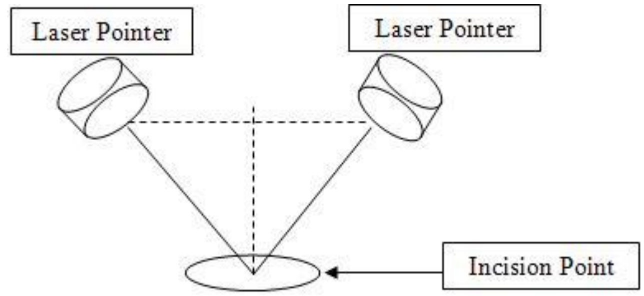


Figure 6. The kinematics of passive arm

Laser pointers are selected to robot end-effector project for visual alignment on surgical port. When the two dots projected on the skin of the patient converge become to one dot, it is a position of the center of rotation of the surgical manipulator aligned with the pivot point on the abdominal wall. We use a passive arm for holding the mechanism of robot. For future stage, we will group all function to be active-passive robot which can change their function for laparoscopic surgery.

(a) (b) (c)

Figure 7. The incision point's alignment system. (a) the system shows the surface is too closed to robot, (b) the system shows a single laser point at exact fulcrum point, (c) the system shows the surface is too far to robot.

When the two dots projected on the skin of the patient converge become to one dot, it is a position of the center of rotation of the surgical manipulator aligned with the pivot point on the abdominal wall (see Figure 6 and 7). The multi-degree of freedom of passive arm is used in robot arm which is able to attach at the rail of surgical table.

In each joint, the wire-driven is used for force transmission. It has a pattern for wiring cable. There are two cable lines in each joint. When the joint is turned, the distance of rotation will be the same in cw and ccw in angle of rotation movement at each joint. The robot has 4 dof which motorize by 4 actuators and 4 brake systems. The electromagnetic micro clutch fit for our robot feature. There are 3 features which are freehand, surgical tool holder and cooperative or teleoperative purposes. The pulley has small groove is connected to the one side of clutch which attach to the other side when clutch get electricity and other side is connect to the actuator. The two end of cable install at the pulley by rolling cable in the groove. The cable has to roll in the pulley groove with a number of turn depending on the rotation angle in each joint and distance of translation joint of instrument insertion.

There are three features of this robot compose of freehand, passive holder and tele-operation. In this prototype has a driving system which can switch functions in this system. The freehand mode allows surgeon use standard surgical instrument same like conventional procedure but the passive holder mode use for holding surgical instrument as an assistant. Finally, tele-operation is the future development with complex control which will perform in cooperative purpose on this robot. Figure 8 shows the robot features.

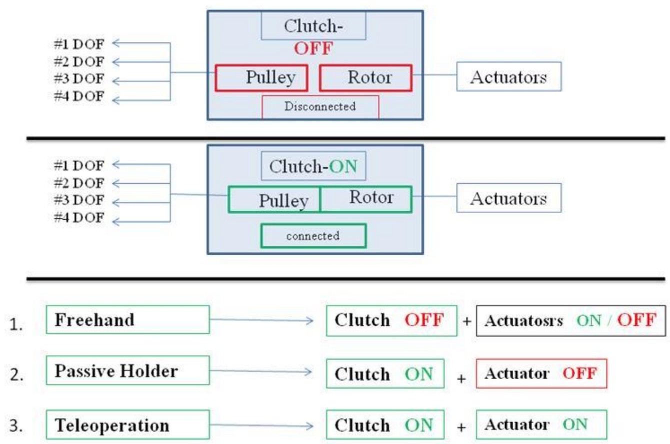


Figure 8. the robot features

III. ROBOT DESIGN

The conceptual design of developed passive robot to active robot has three main parts. Robot end-effector, passive arm and driving system are the component of cooperative robot assisted surgery. There are four degrees of freedom at robot end-effector using with standard surgical instrument in laparoscopic surgery.

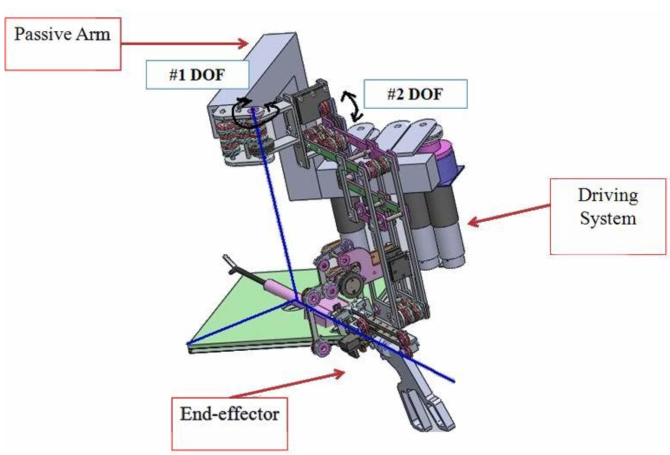


Figure 9. the robot CAD design

The rotation and insertion of surgical instrument use a small mechanism which allows movement same like conventional movement. The small part has light weight assembled to the structure has the overall light weight.

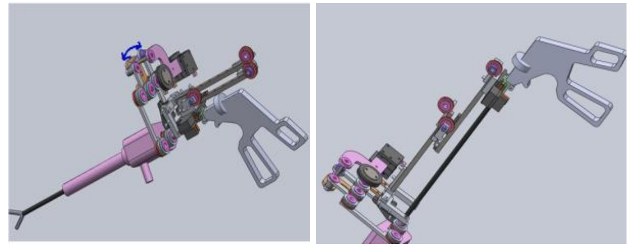


Figure 10. Rotation and translation of surgical instrument

The end-effector has a system which allows surgeons change surgical instrument by themselves. The small structure made from polymer or plastic which has a socket for locking by compression force. The insert parts attached with surgical instrument should be able to sterilize without deformation. Figure 9-11 illustrate the robot design.

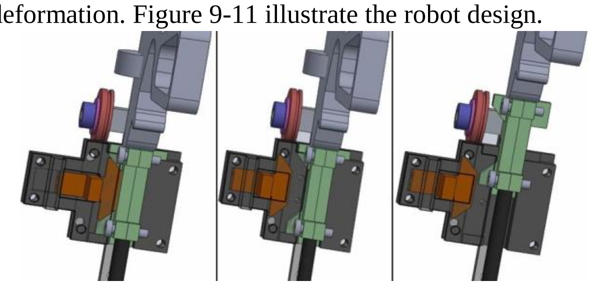


Figure 11. The structure of tool interchangeable system

IV. PRELIMINARY EXPERIMENT AND RESULTS

The MU-LapaRobot, robot-assisted surgical system has been designed and developed. The robot is tested for its range of motions and its properties. The robot is very light weight with extremely low impedance for every degree of freedom. Figure 12 displays the MU-LapaRobot with its #1 and #2 DOF to generate the cone-shape workspace. Figure 13 displays the image of #3 and #4 DOF. Figure 14 displays the overall final system.

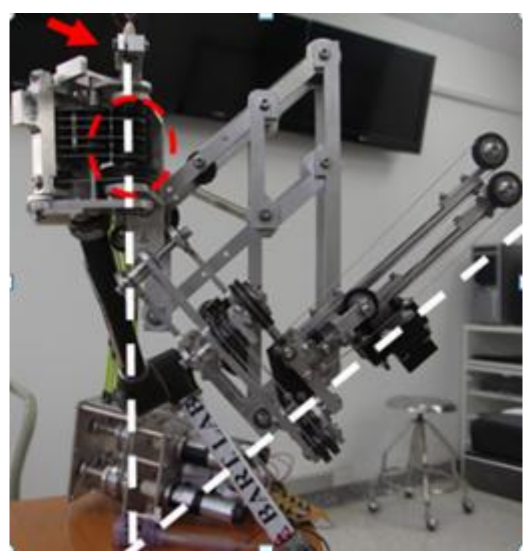
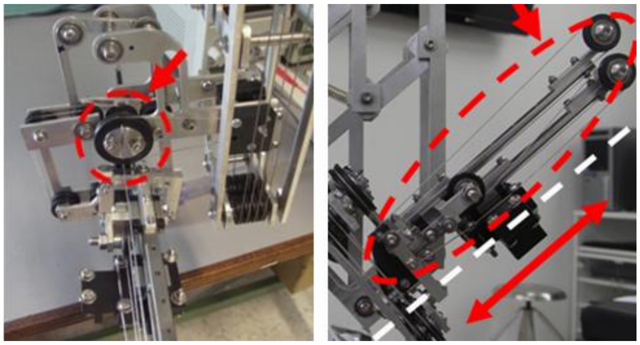


Figure 12. Image displays the MU-LapaRobot system with #1/#2 DOF for generating the cone-shape motion both internal and external motions.



(a) (b)

Figure 13. Images display #3/#4 DOF for Axis's Rotation and Translation Motion

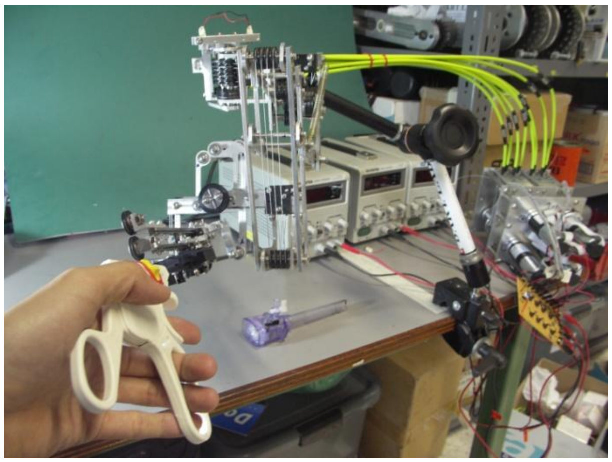


Figure 14. The Final System

V. CONCLUSION

This paper presents the design and construct of a new wire-driven robot-assisted surgical system which can be bothered cooperative and tele-operative. This design uses parallelogram mechanism which has virtual pivot constraint. There are 4 DOF while the robot provides required motions in laparoscopic surgical manipulation. The system is designed to use with traditional laparoscopic tools. The slow and smooth movement is controlled by this transmission. The clutch help to change function of robot as an assistant.

The design and development of cooperative robot assisted surgery is presented in this thesis. This thesis describes about surgical instrument robot which is a part for minimally invasive surgery. Another part is the camera robot system which is not presented in this thesis. The newly designed laparoscopic surgical robot, called "MU-LapaRobot," is planned to develop in stages, and is aimed to use in collaboration or tele-operation by surgeon for existing surgical tools and procedures. The development stages include: Stage 1: development of a surgical tool's passive holder with mechanical and Stage 2: development of an active wire-driving robot based on the design from Stage 1; The goal of project is that robot will be applied in the procedure with less interference in operation.

Normally, surgeon need with surgical manipulation. This system should perform same like conventional way so that surgeon does not need more training with robot. This work was developed step by step. The design and development of surgical instrument holder, called passive robot, is the first stage of this project. The passive robot is able to be installed beside surgical table. The setup procedure takes a few minutes. The brake system helps to hold the position of robot arm and robot end-effector. The important part is the constraint mechanism which allows surgical movement through the incision point only. The brake system is controlled separately in robot arm and robot end-effector. After the incision point is found in robot setup, only end-effector works along operation. Surgeon can control the movement of surgical instrument by themselves to hold or release surgical movement of instrument. In first prototype, we are more understanding about the design and conventional procedure of laparoscopic surgery which guides to improvement for the second stage.

ACKNOWLEDGMENT

This project is supported by the National Research University Grant through Mahidol University. We would like to thank other BART LAB members for their helps.

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