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Workspace Analysis for A New Design Laparoscopic Robotic Manipulator, "MU-LapaRobot1"

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Abstract

This paper describes workspace analysis used for designing a compact robot for laparoscopic surgery, called "MU-LapaRobot." 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 to develop the first stage of "Passive Laparoscopic Tool Holder" with full motion constraint. The second stage is to improve and integrate wire-driving and motorizing systems on the MU-LapaRobot. The third (final) stage is focusing on robot controls, force feedback and human-machine interface. 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

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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 attached at the tip of laparoscope. Most of the cases in laparoscopic surgery is Cholecystectomy surgery. However, the special instrument for laparoscopic surgery requires a certain internal and external workspace in order to perform its tasks.

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 trainnings 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.

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. 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 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 comanipulation 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 cooperation 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.

Objective/Research Question

Although there are advantages on patients, MIS has drawback for surgeons as direct palpation and visible organs. Surgeons must be trained and practiced by using surgical instruments before the real operation. MIS has also disadvantages compare with open surgery such as limited motion of surgeon, hand-eye coordination without sensation, depth information, and force feedback of the organs.

This surgery uses special instruments such as laparoscope which is CCD camera system and small long stem instruments which motions are constrained. The surgeon can manipulate instruments constrained by the fulcrum point and see the surgical area on the monitor by a laparoscope. The fatigue from operation time can be tried to surgeon. The requirements of surgeon are to overcome the problems in surgery. The problems are a motivation to research group for engineering field. Engineers can develop of the new technologies and devices to overcome these problems.

Many of the robotics system have been developed during the last decade. The Computer Assisted System (CAS) is the development of an accurate model of the patient. The applied robotics system can give advantages such as high accuracy, stability without tremor, not be tried, unaffected by radiation and remote control. Even many advantages compared with human surgery which good hand eye-coordination, good judgment but on the other hand is lower geometry, more fatigue and limited dexterity but it has limitation such as problem of reliability, expensive, size, experimental trials and maintenance

Although many of advantages of surgical robotics system but most of people have not got chance to use it because high cost treatment and only a few big hospital can be able to afford it. There are few hospitals that have surgical robotic system in Thailand. The current commercial robotic surgical system is used in limitation because of their considerable size, complexity, and cost, and their time-consuming setup, maintenance, and sterilization procedures. Only big hospital can effort this system. Therefore most of people have not chance by using surgical robot. The development of surgical robot with equivalent performance and potential and compact, lightweight, ease of use, not expensive, more versatility, would be needed as robotic assistance in standard surgical procedure.

Research Methods

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.

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.

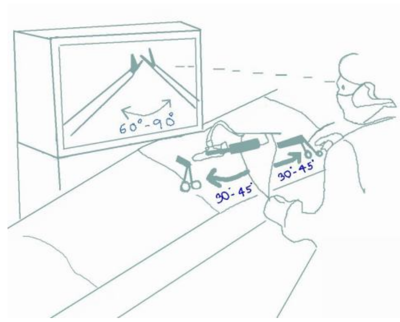

Figure 1. The range of instrument manipulation

In operation, the constraint of the incision limits motion of manipulation because there are only three rotations and one translation in laparoscopic surgery (Figure 1.). 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).

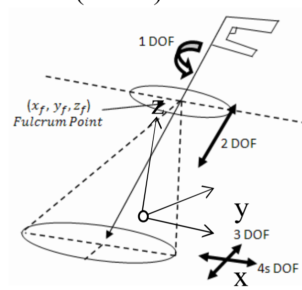

Figure 2. The degree of freedom of the surgical instrument manipulation

A. 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.

1) Passive Robot

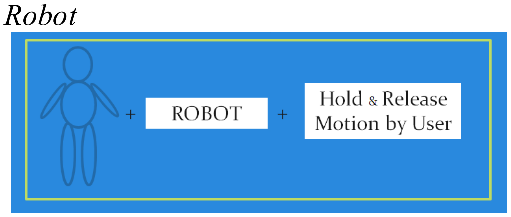

Figure 3. The diagram of passive robot.

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. The robot controller is from remote that user need robot training.

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.

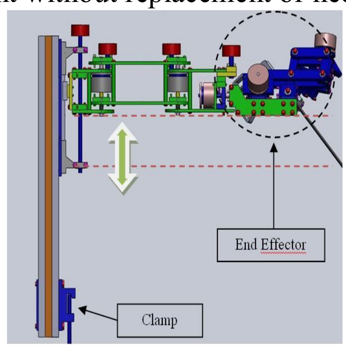

Figure 4. The robot CAD

In Figure 4. 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.

After design and assemble parts for a prototype of robot. The robot arm mounts beside the surgical table. The surgical instrument is used with a prototype and manipulated through a small incision. We put knobs for manual lock and electromagnetic brakes at joints. The procedure takes short time for set-up step. Currently, end-effector can perform in two degree of freedom in cone shape.

2) Active Robot

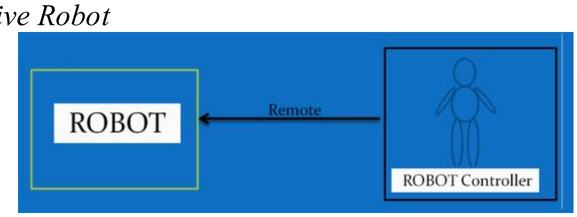

Figure 5. The diagram of active robot

Second, we try to apply the actuator system to the passive robot to active robot in tele-operation. The wire driven method is used for force transmission which make the robot arm lighter than a straightforward actuator method. The actuators place on other position of robot to reduce weight on 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. 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.

B. Robot Kinematics

We use parallel mechanism to constraint movement. The combination of axis which pass through incision point and parallel joint axis generate working area as cone shape. In each point represents a coordinate frame.

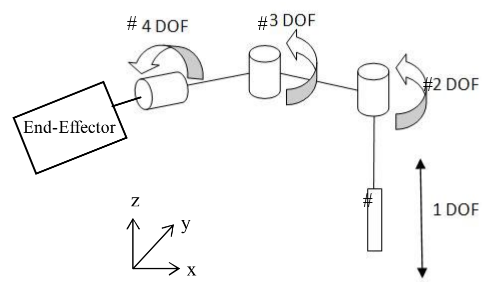

Figure 7. The kinematics of planar robot arm

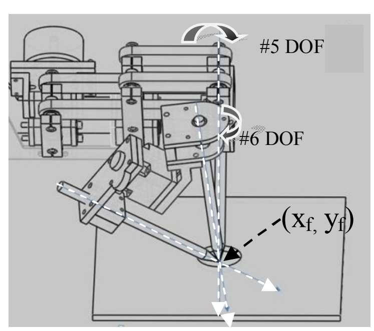

Figure 6. The kinematics of end-effectors

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

DOF	Motion
1	120 mm.

2	$\pm$76
3	$\pm$74
4	$\pm$10

Table 1. The range of the robot arm for passive

DOF	Motion(degree)
5	$\pm$70
6	$\pm$80

Table 2. The range of the end effector

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. In general, kinematic analysis can be divided into direct (forward) kinematic and inverse kinematics. In order to find rotation and position in each point, the coordinates of the robot can be got by homogeneous transform matrix (*T*) [12]

$${}^{0}_{1}T = {}^{0}_{1}T\,{}^{1}_{2}T \ldots\ldots {}^{j-1}_{j}T\,{}^{j}_{t}T$$

Where are of incision coordinate frame and instrument tip coordinate frame respectively. The workspace depends on pathway of instrument which passes through incision point. The optimize workspace cannot be fixed because the volume in the abdomen.

Each port projects to the middle between two ports which are intersection of each working area of manipulation. Circles are conic sections attained when a right circular cone is intersected with a plane perpendicular to the axis of the cone. In an x-y coordinate system, the circle with center (h, k) and radius r is the set of all points (x, y) such that.

$$\frac{(x-h)}{a^2} + \frac{(y-k)}{b^2} = 1$$

Where, a is major radius and b is minor radius.

Results

In our robot, it consists of end-effector and robot arm. The end-effector has a mechanical constraint that provides a trajectory pass through a fulcrum point. The parallelogram mechanism is selected for rotation joint movement. The axes intersection provides the same fulcrum point. The robot does not put on abdomen but is over abdomen in small distance. Electromagnetic brakes are placed at joints. In Figure 8. show the mechanism and the fulcrum point that is incision point.

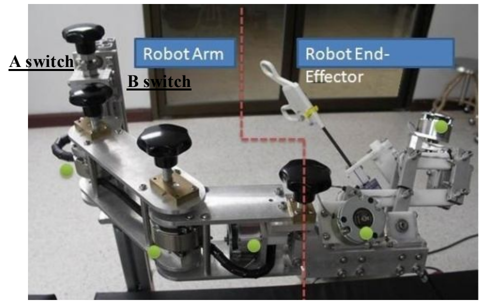

Figure 8. The prototype of passive robot

In this prototype, we assemble parts in passive robot which consist of robot arm and end-effector. In Figure 8., the circle dot represents the electromagnetic brake in each joint. First, after attachment robot beside of surgical table, the robot arm is adjusted position by switch on electromagnetic brakes on robot arm to find the position of incision point. The electromagnetic brake release movement when get an electricity otherwise it is off. In prototype we use knob in each joint with electromagnetic brake for double lock. Second, the position of port is selected in first step. The instrument passes through incision port in any movement by mechanical constraint. The end-effector is switch on not only surgical instrument can be moved same like normal procedure but also be as holder. In this prototype at end-effector, there are two DOF which create movement in cone shape functions at end-effector but the other two DOF are improving for rotation and translation. The instrument change with easy design can work well by two finger control. In this part, the components that installed in instrument can be sterilized at all. We simulate the workspace of passive holder kinematics in end-effector which generates cone-shape.

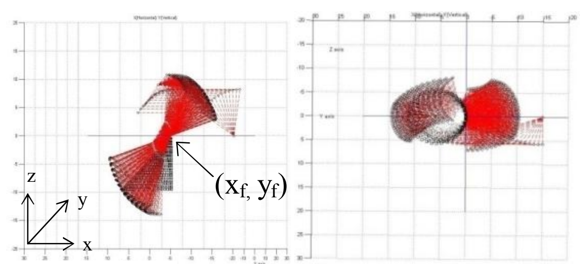

Figure 9. The workspace of robot from simulation

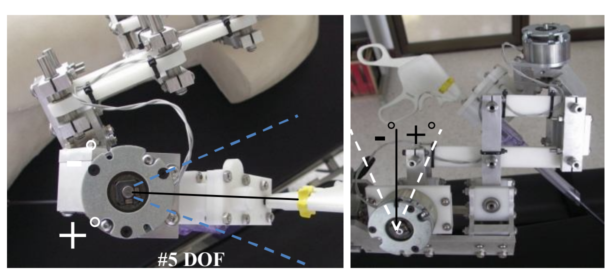

Figure 10. The workspace of robot in bottom view (top)

The set-up procedure time take about five minute to fix the incision position. The main pole attach with the manual adjustment robot arm in vertical direction. The link length of robot arm is enough for the area of abdomen over patient. It takes space over patient because the size of electromagnetic brake attached in each joint. The switch B allow instrument to move for end-effector. It works well in constraint movement but quite heavy structure on mechanism. Another is the weight of electromagnetic brake at the last joint. On the top of trajectory movement, it have problem when the linkage move down in horizontal level angle because of the weight of mass of electromagnetic brake. As a result, the instrument manipulation will get stuck in some degree. So it has to move the weight in linkage to recover the smooth movement. The instrument interchange works well in prototype. One hand release instrument from robot with small bottom and lever adaptor. We conclude the problems of moving structure weight and electromagnetic brake weight make non-smooth movement for manipulating the surgical instrument with passive robot. The robot structure is very strong by using aluminum alloy, POM and stainless steel. The pole which attached with table carry all structure made of aluminum profile. The pole structure is hollow structure effects vibration from weight of robot. The adjustment of vertical direction use lead screw by manual adjustment without electrical brake system. The other three joints in planar robot arm use manual and electrical brake and two electrical brakes in end-effector.

Discussion and Conclusion

In this paper studied many robots such as commercial laparoscopic robot assisted surgery (for examples: Zeus, da Vinci) and non-commercial laparoscopic robot assisted surgery (for example: LER, MC^2E, and CURES). In this paper considered the focus on a new design and function of laparoscopic robot assisted surgery. The robot design combines a holder which can be as assistant using standard instrument and surgical robot together. In operation, Surgeon can interact with robot either passive mode or active mode. In operation where has not enough assistant, robot can help for holding surgical instrument in fatigue or instrument change problems. In active robot applied with computer guidance or virtual environment can enhance the function in surgery [13].

The first prototype is currently passive holder robot which made of metal and plastic pieces. The robot arm can be adjusted a position in movement and mechanical constraint for surgical instrument at end-effector controlled by switch separately. The electromagnetic brake has some drawback in rotor part and stator with small backlash. For testing, instrument passes through incision point by mechanism. In installation procedure, it is easy to install with surgical table and not too much step for installation for robot arm and robot end-effector. Thus, the design and function of our robot can help to hold surgical instrument and enhance performance in the laparoscopic surgery.

Suggestions

Our future work is improving a passive robot to active robot. The wire-drive method is selected for active robot. The 4 DOF which are at end-effector will drive by wire and actuators will place beside of surgical table. By the way, the transmission can place anywhere depends on the way of wire. As a result the robot arm and robot end-effector can be reduced weight compared to this prototype. To switch the passive mode to active mode, this part is developing by mechanical based with electrical components.

The next section, we will use a commercial passive arm which is a fully articulated allows partial loosening by knob for holding and precise positioning of robot. Each actuator is attached with two line cable for joint rotation. The tension adjustment prevents the possibility of cable slack. The actuators box lead cables to the robot to transfer the joint rotation. The tool interchange allows for quick changing of tools in the socket by release a small lever to unlock tool. The movement of small mechanism for rotation and translation allow from tool manipulation. Surgeon is able to use in the same procedure through mechanical movement. In this prototype, the robot can swap from active robot which operated by remote to passive robot by using clutch in each joint. For this part, it will be the active-passive robot applied to standard procedure and operated in passive holder and tele-operation robot.

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