Title

Master Controller for a Continuum Robot

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INTRODUCTION

Robot teleoperation is an operation of the robot in the distant environments. Teleoperation robot is used in many applications such as high-radiation handling system, underwater exploration, space technology, biomolecular docking, surgery, etc. It is manipulated remotely using master controller by the operator. Many reasons in using teleoperated robot are the safety, remotely control, and scaling the environment. A teleoperation system is separated into two sites, local-site and remote-site. An input device is used to receive operator commands relayed to the remote-site. A human operator interacts to the input device with variety of commands such as body motion, hand movement and speech. A controlling device could be joystick, keyboard, motion sensor, microphone, or even master controller robot. The remote site consists of slave robot, sensing unit, and physical environment to be inspected or manipulated. While the operator is using the master controller to transmit command, manipulated robot in remote site is sensing the physical value of environment and then transmitted back to the operator in the local site. The communication system is medium to relay information in both direction between remote site and local site.

User interface is the device to make interaction between user and device. An operator makes the motion to command the slave robot through the user interface. In local site, it is basically called a master device, whereas the robot in the remote site is called a slave robot. Both worked simultaneously and called as master-slave system. Multi-switch is the user interface in the earlier that use to command the robot. A joystick is one kind of the user interface. Although, the joystick can make a position command, but it still has a motion limitation due to its planar motion, for instance up, down, left, and right. Some controller is used as a 3D mouse that can navigate into 3D space. However, many of slave robots have different kinematics due to their applications from master device, so joystick kinematic are not cover human motion and less intuitive due to dissimilar kinematic. A robot controller has been developed since 1940s.

Most the human operators observe and manipulate the remote environment in teleoperation through vision. Object manipulation tasks require high skills from the operator especially in medical surgery robot, because the operator control a slave robot using only vision clue. That is the reason why sense of touch is normally used as one of the human perception for object manipulation.

A haptic is a sense of touch in Greek language. A haptic technology uses to provide both kinaesthetic and tactile feedback to the operator. A haptic feedback consists of vibrations, pressure, thermal, and surface texture. The operator can sense the force feedback from the slave robot in remote environment. This technology aims to provide “transparency” which means the operator can likely senses the touch and investigate the environments directly. A sensor from slave robot in the remote site senses a reaction force with the robot end effector. This information will have transmitted back to the master controller and then convert into mechanical force back to the hand of the user.

Manipulability of the robot which used to measure arbitrarily changing in position and orientation of the end-effector is a quantitative measure of manipulating ability. Robot have specific manipulability in particular configuration. This measurement can measure in two aspects, velocity ellipsoid and force ellipsoid manipulability. The velocity ellipsoid use to analysis the velocity in the particular axis, whereas the force ellipsoid presents the changing force in particular direction. Both human arm and master device has different manipulability which some specific configuration could be limited by each one of them. To provide high manipulability for the teleoperation, both should be measure the manipulability in the same position and measure the similarity between both kinematic. The joint manipulability could be measured by the matrix similarity method.

Recently, natural orifice transluminal endoscopy surgery or “NOTES” is the new technique which uses a natural orifice of the body as an instrument entry point. It provides less trauma injury than conventional technique like an open surgery. Due to the complexity of a lumen in a body, a surgeon cannot use a long rigid instrument to operate inside human lumen. A flexible shape instrument has more intuitive for this technique. A continuum robot is a robot which have many degrees of freedom and can be used as a flexible instrument. Redundant degrees of freedom can form the robot shape to complex configuration. With this advantage, it can traverse across a confined space such as colon or respiratory pathway to target area. This robot is using wire-driven mechanism to rotate each joint of the robot.

Although, the use of robot assisted surgery arise continuously, the major challenge of the use the robot is the control between operator and robot. The complexity of the continuum robot kinematic and large number of degree of freedom are difficult to manage for a simpler user interface. An available commercial product like Omega, Phantom Omni, and etc, which has different number of degree of freedom from the continuum robot cannot control all the joints in the continuum robot, because they are used to control only end-effector position of the continuum robot, thus intermediate joints of the robot might collide surround environment.

Almost of continuum robot for NOTES are driven by the tendon which difficult to sense the force from the environment.

Most of the master device has a 3 DOF wrist designed as the gimbal lock. This mechanism could also lead to the singularity. The nonholonomic system has a state which depend on the path not from the variable configuration. For the spherical joint, it could be change the orientation by path function. A friction-driven mechanism might be used to drive the spherical wrist in order to avoid the singularities. In addition, the nonholonomic system can be used to control the spherical joint in an infinite motion which mean the user can rotate the orientation more than one-fold.

Although, the replica kinematic of this master device to slave robot can control the whole continuum robot, but it is not possible for the human operator to adjust the master controller pose with one hand. This is less intuitive for a bimanual continuum robot. A scaling motion of the master controller and slave robot is another issue. Both force and position are being scaled due to their applications. Hence, the haptic sense of the human is affected by motion scaling like in a microsurgery application. An incorrect force feedback might lead to damaging of the environment without notice to the operator.

To evaluate the quality of the master-slave system, both performance of the master-slave system and task objective is can be used to evaluate the manipulation capability in each application. telemanipulation tasks is used to evaluate the performance of the master-slave performance, while the validation of the master-slave performance measures the realistic interaction between master and slave device for example stability, passivity, position error, force errors, etc. There is a several numbers of researches about the performance of master controller and continuum robot. There are some reasons which should be considered for master controller and continuum manipulation for instance force ellipsoid, shape-based energy conformation, intermediate avoidances, etc. These above reasons could be used to improve in a development of master controller for a continuum robot.

Hamlyn centre developed single-port robotic system by (1) for transanal endoscopic microsurgery as shown in figure 1a . Dual articulated instruments are inserted via the surgical port and perform the submucosal or dissection. This master-slave system is controlled as a teleoperation. The slave robot is mounted on the passive support arm and controlled by a pair of haptic device, Omega 7 as shown in figure1b. The operator manipulated robotic instrument via the 3D display. The slave robot is designed as a highly articulated robot. The articulated instrument has a 7 DOFs. It includes 2-DOF wrist, 2-DOF elbow, shaft linear translation, shaft rotation and grasper. The articulated join is driven by the antagonist pair of tendon. The maximum force at the tip is 3.5 N. The haptic interface is controlled to interface the workspace, scale the human-machine motion, clutching the robot reference, and haptic feedback. Slave motion is scaled only the position.

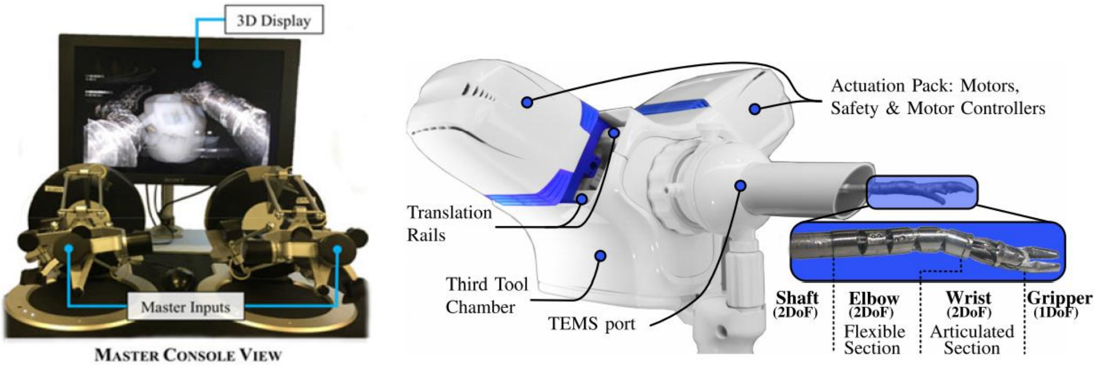

Figure 1: Master manipulator for a highly articulated instrument for transanal endoscopic microsurgery surgery (2), a) Master controller, Omega7, b) Highly articulated instrument

Although a pair of haptic device able to control articulated instrument, it presented few problems. First problem is a clutching. The operator has to clutch the workspace due to the mismatch in the workspace which cause unsmooth control. The operator not known the joint limit of the slave robot, the slave robot is not able to follow the position command due to it joint limitation. The master manipulator proposed by (3) as shown in figure 2 is designed based on the joint-space decouple from the slave robot. This designed proved that the master manipulator is no need clutch to register the workspace. The joint-space mapping also resolved the inverse kinematic computation delay. Even the manipulator uses a mechanical constrain as a joint limit for a slave robot, the user also not realize the joint limitation due to hand-eye coordination problem.

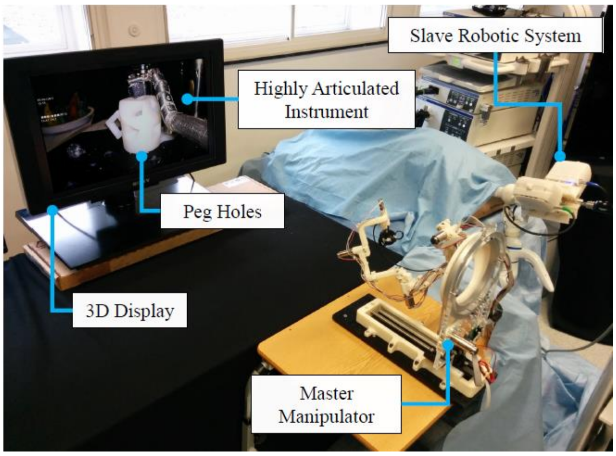

Figure 2: Master manipulator developed in Hamlyn Centre

This master manipulator must have a force/torque sensor to relay the force from the operator to enforce the translation to specific joint. Although the bandwidth is not being test, high inertia and high friction from transmission system lower the bandwidth.

Even the highly articulated instrument is proved that can be operated in transanal microsurgery, an I^2Snake robot (4) is a continuum robot which designed to has a main continuum robot to traverse into confined space and transfer the dual highly articulated instrument to the tip of main body. This robot has been developed for the transoral surgery. The main body has numerous number degrees of freedom with specific arrangement. The dual articulated instrument depicts the human arm kinematic and uses as the micromanipulator. The I^2Snake is mounted on the light-weighted industrial robot to translation the base of the main body and to adjust the workspace of the slave robot. This robot is required a special master device to manipulate its kinematic intuitively. The first version of the robot controller is the use of electromagnetic tracking to track the operator hand. The position and orientation information of the controller was tracked by the trakSTAR, electromagnetic and relayed the pose information to the slave robot. However, this controller worked as a passive controller which cannot provide force feedback to the operator, so the operator could manipulate the slave robot to hit no intention region without notice. Even the operator can control the main body of slave robot freely in the 3D space, the position of the robot is relatively changed followed the controller. Recently, The I^2Snake is controlled with the Oculus Rift developed by Pierre and Andreas, Hamlyn Center, the virtual reality game controller. Oculus rift controller is tracked the controller pose by the IMU sensor and registered frame with IR optical tracking sensor to solve a shifting problem in IMU sensor. It controlled both main body and instrument of the slave robot. The user has to select mode to switch the control mode of the robot between the articulated instrument and main body. This lead to unsmooth movement. The controller used the same method to manipulate robot which cannot solved the problem of the relative movement.

The master controller for the continuum robot are still in the developing phase. It has a many intuitive challenges that can be separated into two main gaps, haptic feedback control, whole kinematic. The research in the development will be fulfil these research gaps for a benefit for the operator in the teleoperation to fulfil realistic manipulation. for the surgical application, the seamless designed of the master controller assist the operator to reduce their fatigue, restore the realistic sensation, and intuitive.

Objectives

The objective is mainly focus on the development of a haptic controller for a continuum robot.

- To develop the master controller for a continuum surgical robot more intuitive
- To develop master controller as a haptic device with transparency properties.
- To control the slave robot with smooth movement and provide maximum exert force in particular direction using the auxiliary algorithm
- To develop a master controller with shared control architecture

Expected Results

The master controller for a continuum in this development expected to be an intuitive device that used to control a continuum robot with the advantage from the design and assist algorithm. This master device aims to be achieve the realistic sensation and intuitive control which can be used with continuum robot in different kinematics.

LITERATURE REVIEWS

Content in this section is literatures review relevant to master controller for a continuum robot. These include the haptic, teleoperation, and continuum robot reviews.

2.1 Haptic

A Greek word which called 'Haptios' has a meaning of sense of touch. Human uses a sense of touch to inspect objects mechanical discrimination by many different functions. The perception of sense of touch is used to discriminate surface properties to examine the object roughness and force reaction. The haptic can be separated into 2 types, kinaesthetic and tactile. Kinaesthetic is a sense of force simulated by the movement of the organs like muscle, tendons, and joints, whereas tactile is a sense of touch related to skin. The haptic is used in many applications for examples, braille's language, object recognition, localization, and virtual/ augmented reality.

A haptic feedback is used to improve operator manipulating skill for teleoperation robot manipulation using sensation feedback and other human sense. A haptic Interface consists of three mains components. A haptic device is a controller which has ability to sense and actuate force perception to the operator. The input of the operator such as command position, velocity, force, human motion, etc. is sensed by the haptic device. The input command is relayed the information to the virtual environment. The haptic rendering is virtual environment algorithm to display a haptic feedback using virtual physical model or real environment.

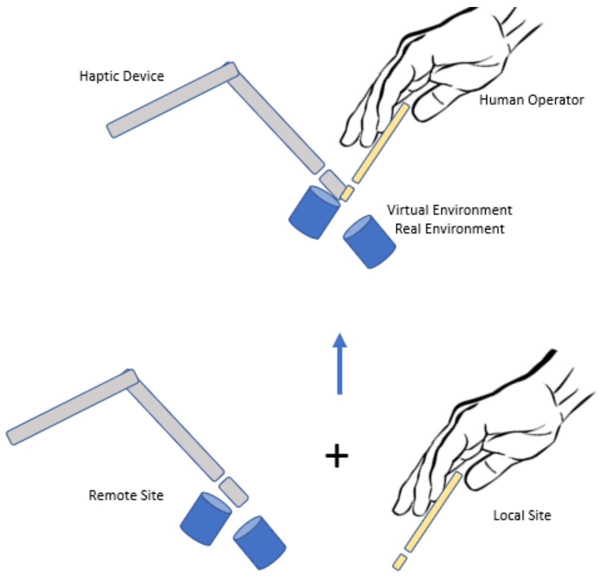

Figure 3: Haptic System

The robot or mechanism at the real environment or the model in virtual environment render the haptic feedback and send back to the haptic device. The actuator at the haptic is used to convey the physical force feedback to the human operator. The force that applied to the human operator and the position of the device is updated in the haptic rendering to modified in the haptic device display corresponding to the touch information. Figure 3 shown the haptic system.

2.1.1 Human perception

(5) reported human procedures to explore object. There are main 6 procedures to explore the object which includes, lateral motion, pressure, enclosure, static contact, unsupported holding, and contour following shown in figure 4.

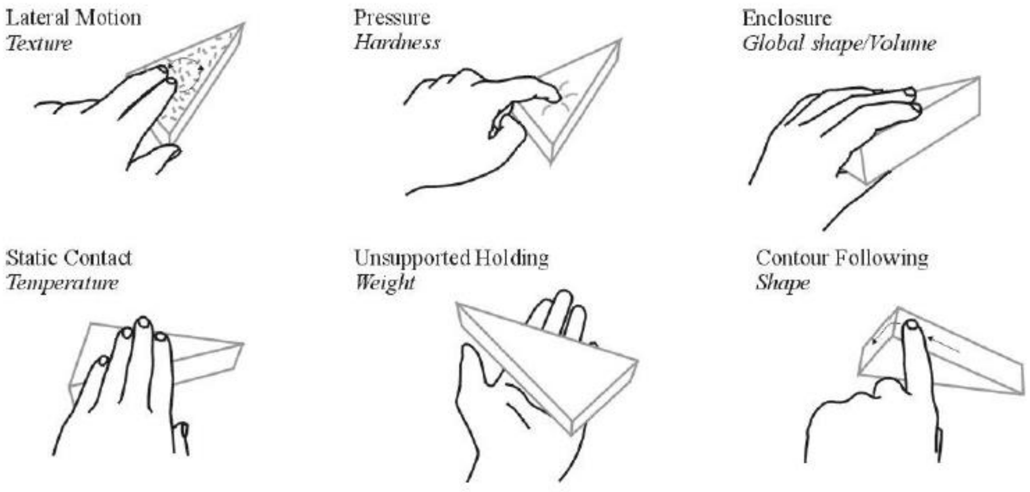

Figure 4: Human hand motion for environment exploration

Lateral motion is the procedure to explore object texture by using finger swipe tangent to surface with low force. This reveals the examiner about the texture how the surface smooth or roughness. Pressure procedure is used to examine object hardness object by pressing the finger or palm directly to object. The global shape or the volume of the object can be approximate by enclosure procedures. The examiner uses both hand to measure a volume relatively to his own hand position. Exact shape of the object can be inspected by swipe the finger following the object contour. Object weight can be approximated by holding the object without support. Another exploration procedure is static contact procedure which is used to feel the object thermal. All of the exploratory procedure is relatively measurement, not quantitative measurement.

Our body has a different sensitivity across the body surface (6) shown in Figure 5. There are three types of touch sensing in our body, thermal receptor, mechanical receptor, and pain receptor. Our skin rich with the numerous somatosensorial cell as a touch sensor. The pathway of sense of touch starts from somatosensorial cell generates nerve impulse to central nervous system.

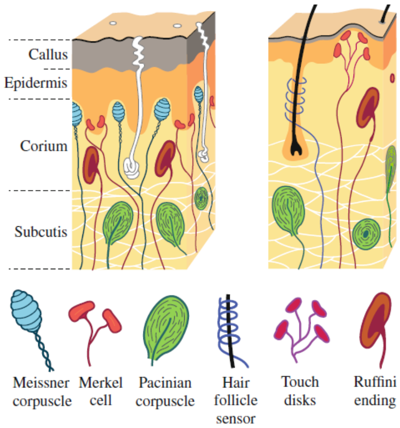

Figure 5: Discrimination cell across body

The characteristic of different somatosensory has a different function to perceive a sense of touch which included cell location, adapting, responding frequency, and respond stimuli. Common receptor for tactile consisted of Meissner corpuscle, Merkel receptor, Ruffini Cylinder, and Pacinian Corpuscle. Meissner corpuscle is a dominant receptor, 40%, of hand receptor. It is rapidly adapting localized below epidermis which can be stimulated by tapping, swipe across skin with 3-40 Hz response. It is best for dynamics response such as vibration and swipe velocity. Merkel Receptor is a sensory cell which has disk shape. This receptor located between epidermis and dermis perceived a pressure stimulus with slow adapting on 0.3-3 Hz response frequencies. Ruffini Cylinder is another slow adapting receptor which is stimulated by stretching of skin, shear, thermal change, and joint movement. It responses with the frequency 15-400 Hz. Pacinian Corpuscle located in deep skin can sense rapid vibration or acceleration. This receptor has a fastest response with the frequencies 10 to above 500 Hz. The combination of sensing signal is used in exploratory procedures to from the haptic sensation. For the manipulation scheme, a passive touch focuses on experienced sensation, whereas the active touch focus on manipulation which is good for the virtual reality. Kinaesthesia & proprioception is the sense of touch termed in force perceive, static position, limb movement, and relative positioning to the environments. our body uses muscles receptor joint receptor, muscle receptor, even skin receptor to sense kinaesthetic.

The relation between stimulus and human sensation is a term of psychophysics. This used to explain behaviour of a haptic devices and virtual environments. An evaluation of the haptic device is separated into two principles, descriptive and analytical. A first principle evaluates the specification of sensory capacities whereas analytical principle tests a hypothesis underlying biological to determine human sensory capacity. Wundt used a measure threshold to notice a sensation. An absolute threshold measures the smallest energy to stimulate the sensation, sensitivity. Difference threshold measure amount of change of stimuli required to produce just noticeable difference (JND). The dimensions of stimuli is grouped as intensity, quality, extension, and duration. One of the performance evaluation is a Fitts' Law which explains the difficulty in user interface. A psychophysical methods is used to determine the sensory threshold.

Not only the psychopysical methods is used to study relation between stimulus and sensation, human subject experiments are also used to study psychophysics based on subjective experiments. The subject experiments are categorized into three class, system performance, psychophysics, and ergonomics. System performance evaluate human machine interaction performance by task-oriented experiment. It determines the performance metrics and implement in experiment condition. Ergonomics measures effect of the system on human well-being.

2.1.3 Haptic Design

The haptic design is categorized into two main types, admittance and impedance apply. Impedance haptic device is a device that being command by the position of the operator, then applies the force feedback to the operator based on the haptic rendering. Another type of the haptic device is an admittance haptic device. This type required to have Backdrivability, low friction, low inertia, and high bandwidth. a well-known product of impedance haptic device is the PHANToM Omni form Sensable. The admittance haptic device used the force command from the operator to explore the remote environment and limit the position of the operator correlate to the object position. While impedance haptic device requires Backdrivability, the admittance haptic device requires non-backdrivability for the force control. Two choices of haptic device type depended on the slave robot and application.

A teleoperation robot has two types of control respect to information direction. One direction control is called unilateral control. The master controller is used only to send the position/force command to the slave robot without the feedback of information from the slave robot in the unilateral control. In contrast, bilateral control sends commands and receives feedback between both master controller and slave robot. Force and displacement feedback is reflected to the end effector of the master controller. This bilateral direction control exchanges the state between two sites. The control loop of the control operation can be defined as an electrical diagram. (7)] models the input, output and the system in the teleoperation system as an electrical diagram. A control law used to determine input by the master and slave actuators.

Control laws for the teleoperators has four types include Position Forward (PF), Position Exchange (PE), Position Forward/Force Feedback (PFFF), and Position Exchange/ Force Feedback (PEFF). Position forward has position or velocity command that sends to the slave robot which has a position control. The operator senses the interaction force only from the robot's impedance. Position exchange controls the slave robot position by the command position and the slave position. The operator sense the force feedback which determine by the difference of the master-controller and slave-robot position. Position forward/ force feedback control the slave robot position by dynamic model. The force feedback which applied back to the operator consists of the robot impedance and sensed force from the environment or model. Position exchange/force feedback is the controller law that control the slave robot position and force feedback that model by the interaction force, robot impedance, and dynamic feedback.

2.1.3.1 Backdrivability

An ideal haptic device is an interface between user interact with the remote environment directly like using bare hand. This idea terms as a 'transparency'. Backdrivability is an issue to determine how operator manipulate device while the motor power is off. one of the factor to increase backdrivability is to lower the gear ratio or decrease motor impedance by lower inertia and coulomb friction to be able to drive back the motor. To transfer input force to output force, master device should provide same amount of force between input end and out put end. The operator manipulates the input device effortless meaning not have to apply large force to move the output end. The input end and output end can be controlled the output force using force-torque sensor.

In mechanical design, there are 3 main factors that affect backdrivability. Transmission ratio is the value that can be used to show the relation between input and output torque. For example, input driver and output effector which has a transmission ratio 100:1 must drive the input turn 100 times to turn one output turn. Torque output is multiplied to be 100x times of the input drive torque while its speed is reduced by 100x times. From this example, the operator must apply force at the output with multiplied friction force by 100 times. Motor friction multiplied with transmission ratio is the amount of torque that can perceive while back driving.

Not only the gear ratio that affect backdriavability, transmission efficiently in the gear mechanism is multiplied and reduced the input torque.

2.1.3.2 Bandwidth

Bandwidth is used to consider the responsiveness of a mechanism. A master controller with high bandwidth can change both force and velocity rapidly in order to response the motion command of the operator. Both impedance and admittance system required high bandwidth and stable of mechanism for accuracy response. A motion scaling between master device and slave robot needs to scale force and range of motion of the user. This must be considered carefully the inertia, stiffness, and dimension in designing to not reduce bandwidth. The haptic system which can modelled as linear mechanical system, the bandwidth equals to square root of stiffness over inertia. An ideal haptic system require to maximize the bandwidth as much as possible. The direct method to maximize bandwidth is to design mechanical system to be high stiffness and low inertia as possible.

2.1.3.3 Manipulability

One of mechanism performance is to determine manipulating ability of the robot in both position and orientation at the robot end effector point (8). The manipulability of robotic mechanism can be measured as the quantitative measures. This information is used to consider the support for robot decision process. High manipulability shows that the robot has ability to adapt the pose of end-effector, whereas the lower manipulability means there are constrain for the motion adaptation. (9) reported that both manipulability ellipsoid is an important factor for master controller design. The dynamic manipulability was used to determine manipulability in two situation, the operator manipulate the master controller and the operator has no payload. the ellipsoid manipulability describes the manipulability in the directional property which can used to determine which direction should be manipulate by the operator. (10) used the idea of manipulability to navigate the snake-like robot in minimally invasive preoperative planning.

2.1.3.4 Sensing

Haptic device must have a sensing element to measure device status. following the haptic control law, sensors require to measure both position and force. These sensors are used in both haptic device and slave robot for a control computation. An ideal sensor should not interfere in the control loop. The position sensor which has coulomb friction in the sensor element increase impedance in the haptic device. High accuracy and resolution is required for the sensing data to reduce error. The sensors mentioned above is the sensor for the haptic device for the haptic control. However, there are other controller that used to control the slave robot in the remote area. (11) used head tracking to control the camera for the laparoscope. An inertia measurement unit(IMU) tracked the operator head to measure the orientation. The operator controls the passive manipulator and tracks both position and orientation to control. The hand gesture also used to control the slave robot. This sensor application is a non-contact motion tracking which used in the surgery. Body motion tracking was used to. The slave robot which manipulated by two hands controller are not able to control the camera, the visual is used to assist the operator to change the camera pose.

Non-contact sensor like optical encoder and magnetic encoder is typically used as position sensor. most of the actuator are rotary motor is tracked by the encoder from the rotary shaft, while the linear actuator also can be tracked by the hall-effect encoder. These position sensors also were used to measure the velocity by differentiating the position with time variable. For the velocity control, these sensors play a major role in the control loop.

Force sensors like load cell or strain gauge are used for force control loop. Sensor provide the force or torque value by the micro displacement in the sensor and measure the voltage. Admittance haptic device used a force sensor to perceive force command from the operator. Force sensor also used to explore the reaction force between slave robot and environment for impedance haptic device.

2.1.3.4 Available Commercially Haptic

Phantom Sensable

The first commercially available product of haptic system is PHANToM haptic interface from MIT Artificial Intelligence Laboratory. This product is a haptic device in a desktop version which used to interface between user and virtual environment. This version of the PHANToM manipulates by using index finger thimble or stylus connected to user. This system tracks user motion as the input command and apply force back to user hand to sense the interaction with virtual object in the computer graphic. To provides realistic experiences, PHANToM haptic as shown in fig. 6a is designed to has low backlash, high stiffness, good Backdrivability, and low inertia. There haptic rendering generates the constrain motion, contact force, surface texture, and various characteristic of simulated object.

There are main three features which are principle of design for this haptic device. The virtual object is explored and is cognitive by the force feedback to the user, Kinaesthetic. The design as index finger thimble and stylus used to avoid the torque at the haptic interaction point which must provides the actuator at the tip. The last feature to consider is the workspace sufficient that allow user to move freely without workspace constrain. To achieve the realistic force feedback, PHANToM haptic provides minimum force at 0.1 N for backdrive friction in statics and maximum exert force back to the user 35 N/cm at servo rate. Geomagic Touch company of PHANToM haptic has various version haptic device depended on the range of motion and amount of force feedback.

Novint Falcon

Due to the expensive cost of the PHANToM haptic, Novint Technologies developed and sell the Novint Falcon as shown in fig. 6b. This haptic device has been designed as a parallel delta robot which has 3 degrees of freedom. This product is less expensive than the Phantom Omni. Falcon has three parallel linkage that connected together to control only the position. The user manipulates the device by grasp the gripper at the end-effector of the Falcon to control the HIP. Three capstan mechanism driven by servo motors provides force feedback to the user. The delta mechanism which was used in the Falcon haptic device has many benefits such as high force to weight ratio, high payload, and low inertia, but a disadvantage for this mechanism is workspace limitation which lead to the clutching the workspace. The Falcon haptic device is famous in gaming and medical simulator.

Quanser

Quanser haptic device which known as Quanser HD2 is an in-parallel manipulator by using a decoupling of two pantograph mechanism. This decoupling mechanism use universal and revolute joint to connect each pantograph mechanism. 5 DOFs of force feedback is provided by these coupling mechanism as shown in fig. 6c. Two additional controllable DOF is not the direction along the axial axis of the coupling link. The haptic device meet the requirement of low inertia, large orientation motion, high force, high bandwidth, and compact design. To fulfil 6 DOFs of force feedback motion. master controller designed add another DOF by rotating the handle in the axial direction. The 7th DOF of modified 6 DOFs two pantograph is an actuated gripper. This 7 DOFs teleoperated haptic system was used to perform minimally invasive surgery with cable driven instrument and used to provide kinaesthetic feedback to the surgeon. Various configuration of Quanser haptic were used in many application.

Omega, Sigma (Force Dimension)

Series of the haptic product from Force Dimension company are the desktop haptic interface with high contact force, high precision and good gravity compensation. The recent haptic device from Force Dimension is called Sigma7 as shown fig 6d. This device has a unique parallel mechanism which controlled at the 8 KHz rate. Not only the high stiffness that has benefit from the delta parallel structure, but also profile low minimum force in statics mode due to the combination of motor and passive coupling for gravity compensation.

Due to it high accuracy in control both kinematic and dynamic, the haptic devices from the Force Dimension were used in many application

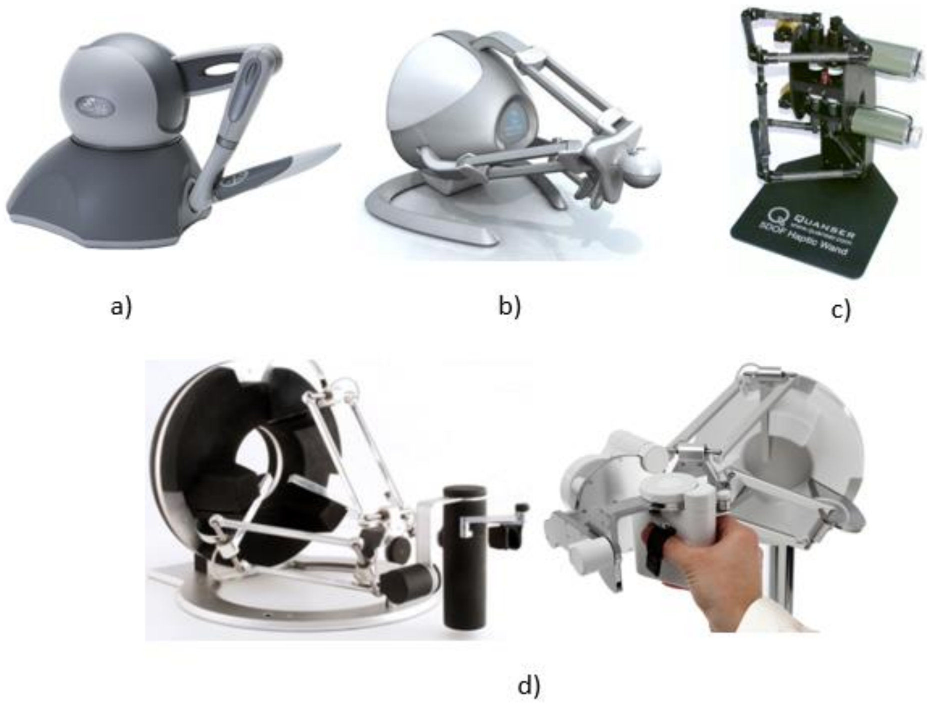

Figure 6: Examples of commercial available haptic device, a) Phantom Sensable b)Novant Falcon c) Quanser magic wand d) Omega and Sigma, Force Dimension

2.2 Teleoperation

Teleoperation has the meaning operation at the distant. An aspect of using robot at the distant is one of the function that user need from the robot. Distant between the operator and the environment insists the direct exploratory. A teleoperation robot is used to breakthrough this barrier as the remote controller. Once teleoperation robot is used, the teleoperation in hazardous environment, remote environment, and scaling environment. The telerobotics has three main types in the control architecture. Direct control is the control without the assistance of the robot autonomy. Supervisory control is the control with the providing information feedback from the robot at high level interface. The autonomy at the remote site assist the user in a shared control architecture.

The teleoperation is separated into two sites as shown in figure 7, local-site and remote-site. The operator manipulates a user interface to control the remote robot by the operator motion. The robot at the local site is called the master robot, whereas the robot in the remote site is called the slave robot. both robot might have the same kinematics. The less of this section cover the history, applications, control architecture, master controller design, and operation performance.

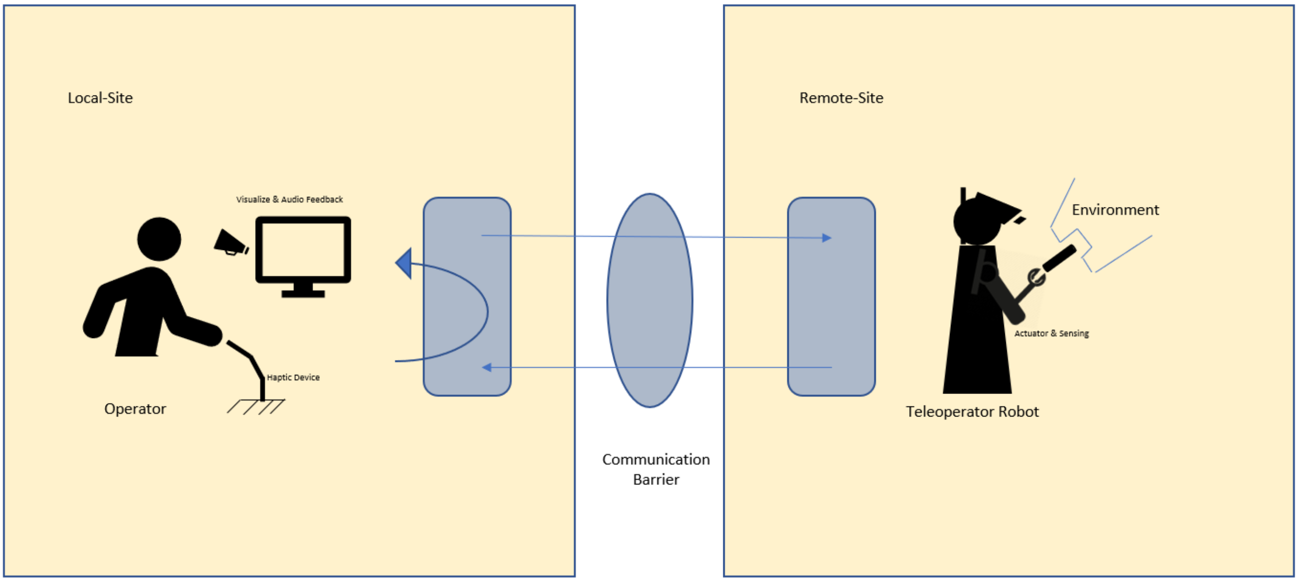

Figure 7: Teleoperation Scheme, Operator at local site and teleoperator robot at remote site

2.2.1 History

In 1940s, the remoted controller was firstly used in the nuclear application to handle the radioactive material behind the shield wall. Raymond Goertz is a pioneer in the robotic field especially in the remote-control robot. He invented the first master-slave system for handling robot (12). He also developed the electrical master-slave systems in the 1950s using the switch in console. The slave robot is driven by the electromechanical actuator. However, the slave robot has a difficult to control, he developed mechanical linkages as a direct control. This mechanical linkage has a handle to manipulate the distal grasper. This mechanism connected the environment and the operator using gear train, linkages, and transmission cables. This approach allowed the operator to use the hand motion to manipulate the grasper and transmitted back and force for more intuitive. The figures 8 shown the mechanical master-slave systems created by R. Goertz.

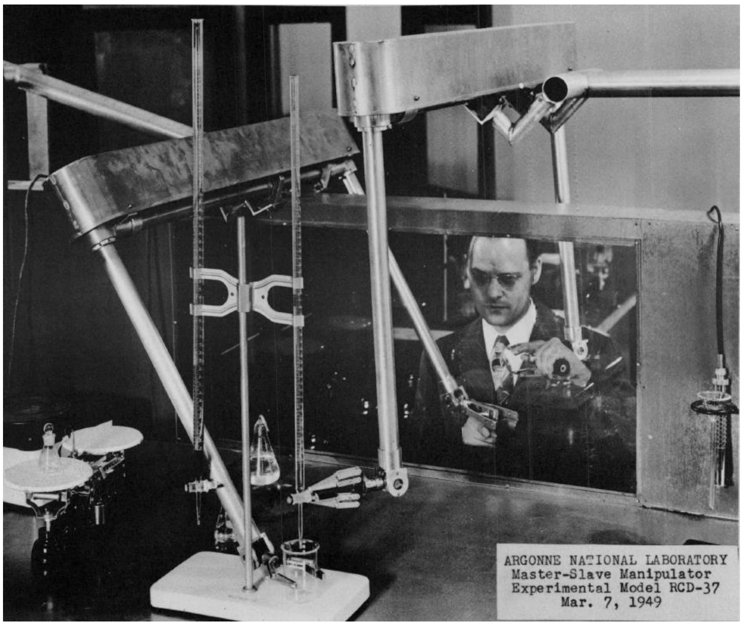

Figure 8: Mechanical master-slave system by Raymond Goertz

The concept of remoted control is widespread, (13) Oak ridge national laboratory was constructed the high radiation-level analytical facilities with the master-slave system designed by Argonne national laboratory for transporting samples, disposing waste, and continuous monitoring. The mobile master-slave systems by the Fermilab, US, requires the visualisation to control the slave robot. (14)A TV camera mounted in pan and tilt system to monitor the slave robot during the teleoperation. The added pan-tilt stage was controlled by the second operator which can lead to non-synchronous manipulation.

The further distance increase by the applications such as the mobile robot, underwater robot, space robot, etc. Time delay affected the operator in manipulation. (15)The operator cannot see the results in actual time. During the transmission delay, the operator might over manipulate the robot and the environment may changed over the time. This delay time can cause physical fatigue and frustration. M2 master-slave system(16) is the first system providing force feedback with separated hardware from remote and local site. A servomanipulator, MA23, was developed for nuclear application with computer assisted function, virtual stiffness wall (17).

Not only the handling system, the teleoperation robot has been introduced in space exploratory application. JPL(18) developed the force reflecting teleoperation system. This system was a non-replica kinematic between the master and slave robot. The master controller has the backdrivable mechanism. After the first industry arm was created, the Rancho Arm is the robotic manipulator designed as a human arm with six joints. This robot manipulator aimed to assist the handicap patients for daily activities. This manipulator is manipulated by the exoskeletal goniometer. (15)This exoskeletal-like master controller was also used as motion recorder to measure task performance in the time-delay condition. The different kinematic increase delay time by the kinematic calculation, (19) proposed replica master to reduce motion rate control and mental fatigue.

The industrial manipulator was used in the handling object. It used as a power-assisted, Kraft telerobotics invented the master-slave manipulator with the force feedback for transferring cargo. After the development in the nuclear application from the 1940s to 1990s, the teleoperation robot shifts the research direction to another applications including space exploration, deep mining, underwater exploration, micro docking, defence and security, and medical applications. PHANToM haptic system is the commercial available product for the master-slave system which mention earlier. This product is the platform for research in many fields.

Earlier of 1990s, (20)the manipulation on the mobile robot for the high radiation investigation is manipulated by the MA 23 master which is a 6 DOF force reflecting master arm. (21)used the master controller with the force reflection for the mobile robot in surveillance and security application. The manipulator of the mobile robot attached a force-torque sensor to relay force/torque feedback to use during open a door.

Figure 9: Master console and da Vinci surgical system

The surgery procedure trended to become minimally invasive surgery. This procedure helps the patients to faster recovery, reduce the inflammation, and less scar. However, the operation though the small is a major constrain to reach the target. The robot manipulation is used to operate the surgery inside a patients’ body. In 1994, (22)Robot Assisted MicroSurgery is a microsurgery teleoperation robot system that scale the motion of the operator into the small robot size. This approach minimizes the involuntary tremor and jerk from the surgeon hand. The operator and slave robot also shared the information in the teleoperation. The laparoscopy surgical robot is controlled by the cartesian robot(23) with the wrist joint.One of the success surgical teleoperation robot is the Da Vinci Robot system as shown in fig. 9. This tele-surgical system is the commercial product which is widely used (24). The well-known operation for the telesurgery across the continental is the operation Linberg. The Zeus system is operated at the France where the operator manipulated the remote robot at US.

2.2.2 Applications

High Radiation

The industries of high radiation need the device that can manipulate form the distant. R Goertz is a pioneer of the master-slave robot system. The radiation material is manipulated, investigated, and dismantled by using the telemanipulation arm. The electrical and mechanical master-slave system was introduced in 1940s. in the earlier period, the operator observed and manipulated the object through the shield window, then the TV camera is used to monitored inside the reactor room. Due to the increases of the teleoperated distance, the delay in the communication cause ever effect in telemanipulation. The spearhead in development of the master manipulator was an Argone National Laboratory, Oak ridge National Laboratory, and Fermilab. In the 1980s, the unmanned mobile robot was used to operate inside the nuclear reactor. (25)JARM-10 is light-duty telerobotic manipulator from the Japan Atomic Energy Reseach Institute. (26)Stewart Platform of 6 Axis which has a dissimilar kinematic was used to manipulated the mobile robot system KAEWROT,Korea, to overcome the high inertia form similar master robot. MA 23 remote handling system was frequently used in the nuclear application(27). The list of the master manipulator can be investigated in (28).

Industrial

Most of Excavation and construction used hydraulic actuators. (29)The master controller with the force reflection for the hydraulic is used in construction for the sensitive objects. (30)The master-slave system for construction robot as shown in fig. 10 integrated with virtual reality that overlay on the video image to guide the construction. controlled the excavator by using the arm motion tracked by IMU(31).The live-line maintenance works need the safety and comfort for the worker. (32) A pair of master-slave teleoperated manipulator developed with 3D vision is used to operate this application. a remote manipulator is used in forestry operation to reduce the risk from hazardous tree trimming and cut the power line(33).

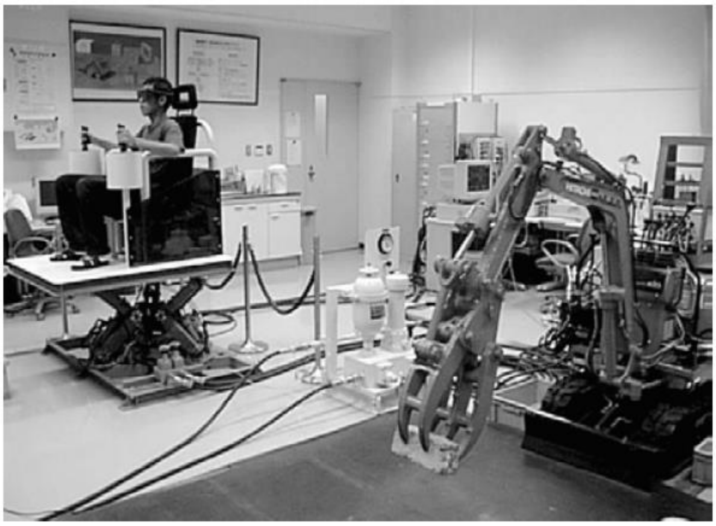

Figure 10: Master controller for the construction robot

(34)The teleoperated controller used to control the pneumatic robot in rescue operation in the disaster. (35)Stewart platform with the handle was used to fit a glass window. (36) Grips system form Kraft Telerobotics is a master-slave system used for transferring the cargo from the ship and other mobile robot. Welding process has been widely used for welding the pipeline includes space, underwater, and nuclear maintenance application. (37)The teleoperated master-slave integrated with the automatic weld speed control increase tracking accuracy.

Defense security

The security and guard service need the robot to detect unusual situation such as intruder, alarm, fire, and etc. The robot is used to inspect the interest area and manipulate the object with the camera and manipulation. the master controller with force reflection from the mobile robot is able to help the operator to open a door(21). Disarm the mine is one of dangerous task for the human. Telerob explosive ordnance disposal and observation robot(tEODor)(38) are use by the responder to disarm the bomb. Packbot by iRobot was used in the US military in the Iraq war. Clement sent the robot to cooling the reactor core(20). Not only the mobile robot is operated at a distance. (39)Aerial Unmanned Vehicle (AUV) manipulated by the haptic feedback for environment inspection and surveillance tasks. (40)The attractive force field applied to haptic controller was used in an aircraft manipulation to follow the desired path.

Cell and Atomic docking

The biology technologies experiment operates in the micro scale. Scienctist have to confront the movement problem that cause by the hand vibration and speed control. The micromanipulator is a tool aimed to helps in position the probe in microscale. (41) purposed the passive hydraulic micromanipulator to scale the motion with the continuous motion and modified the trust motion. (42) developed the dexterous micromanipulation system as shown in fig.11 for the micro assembling. (43)Chaillet developed 2 DOFs parallel mechanism as a two fingered hand mechanism design to grasp the micro object. The object is a glass ball with size 2 micrometers. (44)used the teleoperation to scale the probe motion for Nano scale interaction. 6 DOFs parallel link manipulator for the micromanipulation is manipulated by the 6 DOF haptic interface(45). For microassembly, the process needs multi manipulator to manipulated objects then assembled together. The concept of the cooperation robot includes single master single slave robot (SMSS), single master multi slave (SMMS), multi master multi slave (MMMS), and multi master single slave (MMSS). In 2008, (46)the nanomanipulator which is driven by the optical combined with video analysis were used to measure reaction force in real time.

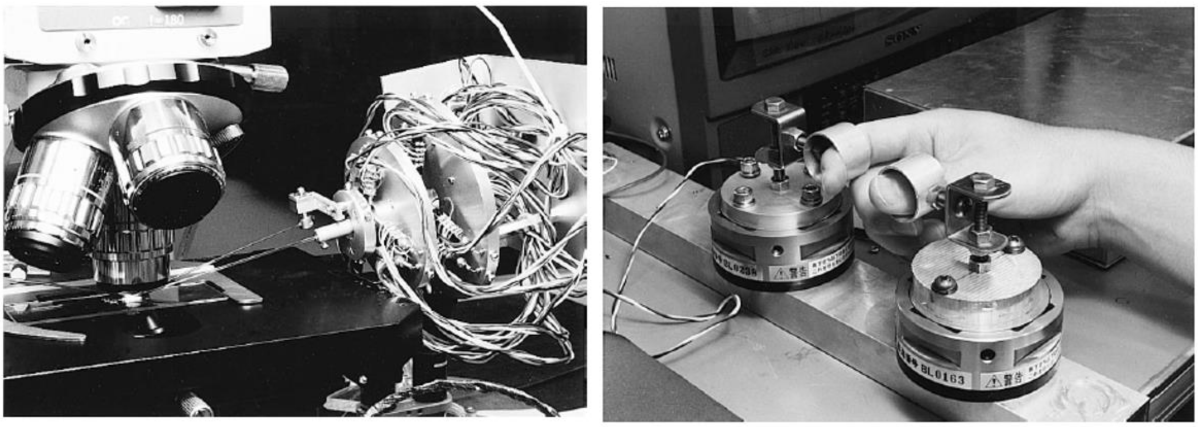

Figure 11: Micro manipulation for a micro assembly system

Medical

The microsurgery is a surgical manipulation in micro scale. it requires the scaling motion and force feedback in the operation. A motion scaling from macro to micro scale breakthrough the barrier of scale. However, the master controller need to reject the vibration and to feed back a kinaestic feedback to the operator. (47, 48)] purposed the magnetically levitated master which is 6DOF hand controller to control both coarse and fine motion scale.

After the used of robot for the surgery is introduced, an aim of minimally invasive surgery has become a key challenge for a medical robotics. (22)The system called RAMS has a slave surgical robot and master controller robot. dual slave robot has 6 DOF which one holds the surgical instrument and another holds the imaging tools each robot arm has workspace around 20 cubic centimeter. This system used the shared control architecture to shared information between slave robot and master controller. (49)The similar kinematic of RAMs was design to more intuitive. (50)proposed a 3DOF cartesian stage and 3DOF rotation wrist as the master controller to control laparoscopic robot. The virtual realty has been developed for medical training. With the VR, the medical student can simulate the surgical operation, diagnosis, and rehabilitation. The haptic system interfaces the medical student by providing the tool manipulation and force feedback.(51) PHANToM master was used as the surgical training platform. (52-54)6 DOF Stewart platform parallel robot with the instrument handle was used as the master controller to use in surgical application.

The da Vinci system, Intuitive Surgical is a surgical teleoperator system which breakthrough the conventional laparoscopic procedure by extra additional degree of freedom to the instrument. This system consists of 7 DOFs in both master and slave robot(24). Additional 7th joint of the master controller extent the range of motion and intuitive. The da Vinci System was the success medical robotic system with 4 main features, high quality stereo vision, alignment of hand-eye coordination, additional joint for motion compensation, and the motion scaling. These systems were distributed and performed many operations, laparoscopic, cholecystectomy, hernia repair, etc. (55)VerroTouch is a high-frequency Acceleration feedback from University of Pennsylvania was used to recover the touch feedback for da Vinci system.

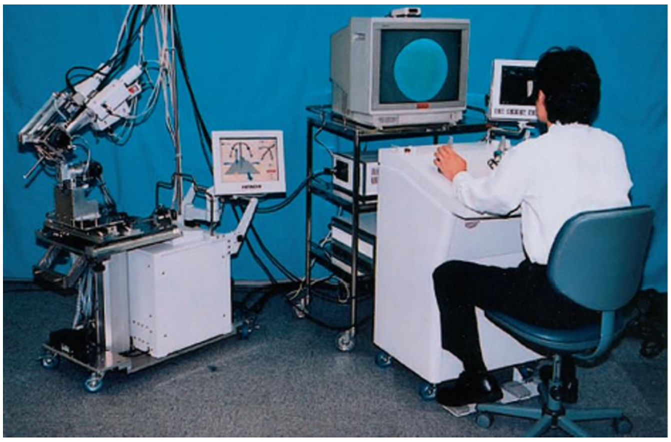

Figure 12 Neurobot teleoperation robot for a micro neurosurgery

An organ movement is one of the surgical problems. A beating motion in cardiac surgery was cancelled by the motion synchronization (56). To achieve robot stabilization, visual/motion synchronization and master control is implemented. (57)NeuRobot, a teleoperation micromanipulator system for minimally invasive microneurosurgery as shown in fig. 12 were performed with cadaveric head. The dual micromanipulator with 4 DOFs is attached at the 6 DOFs as a coarse motion. (58)developed master manipulator which matched motion of surgeon.

Zeus telerobot was used in laparoscopic surgery. Two manipulator of Zeus is controlled by the interface which has 6 DOFs with ball like handle (59). Steady hand from John Hopkins university (60) implement admittance control on an impedance master which resulted in virtual guidance that keep slave robot avoid undesired area. The list of the master-slave robot from 1993-2003 was reviewed in (61). (62, 63)Gastrointestinal Endoscopic is performed by cable driven flexible robotic manipulator which can be inserted along the rigid endoscope. The natural orifice transluminal endoscopic surgery is introduced for the medical approaches. ViaCath Master manipulator was used to control the NOTEs robotic system(64). The master manipulator for notes also included in (65, 66). Master-μslave system was performed in eye surgery(67). Steerable needle and catheter is another applications which need the performance of the master-slave system (68-70). Not only the surgical robot, the rehabilitation robot is designed to be as exoskeleton robot (71, 72).

2.2.3 Architecture

Teleoperation robot has a different control architecture standalone robot. The teleoperation robot has to collaborate work with the user, so it has to follow the command or to provides the information. The control architecture can be categorized into three main categories, direct control, shared control, and supervisory control based on the level of the connection between user command and information feedback. Various control architecture was shown in fig13.

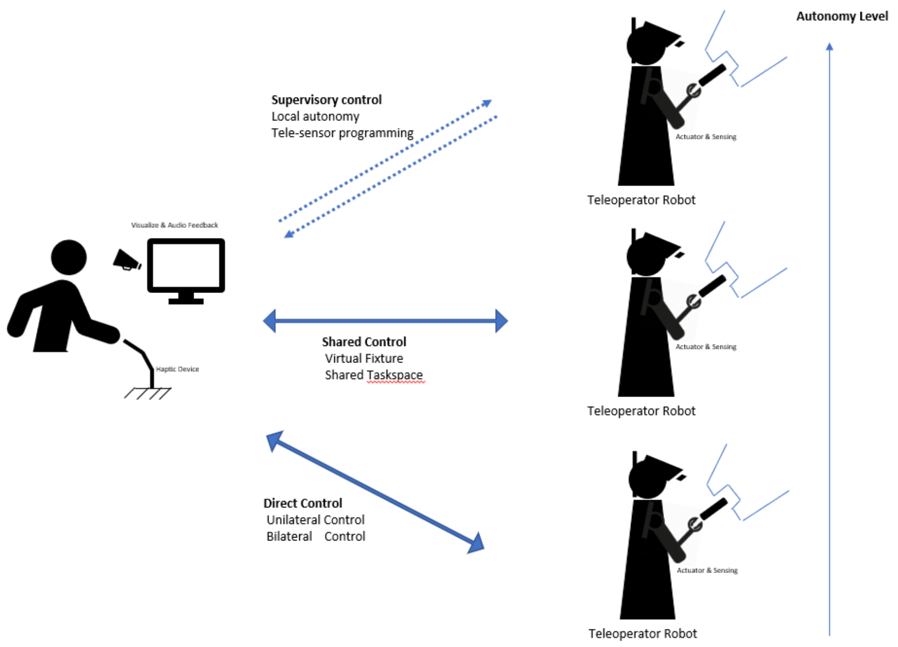

Figure 13: Control architecture of Teleoperation Robotics

2.2.3.1 Direct control

Most teleoperation robots are used the direct control architecture. The slave robot is followed the user command without autonomous. Motions of the user either position, velocity of acceleration are used as the robot commands to specify the slave robot motion. A control direction of the direct control is separated into two types. Unilateral control and Bilateral control. The unilateral control is a one-direction control from user to slave robot. Master controller either joystick or mechanism input device required the user to command position, velocity, and acceleration. The rate control responses to the proportional of the motion. This direct control was frequently used for the slave robot without the workspace boundary. The bilateral control will be discussed in the further section.

- Clutching

A mapping between slave robot and master robot position is considered as a kinematic coupling. However, the different workspace between slave robot and master robot introduced the unsmooth motion, so the operation needs a clutch to offset the robot end effector. In practical, the initial position when it turned on during a set up of both slave robot and master controller are different. There are three options to reference both robot in the same reference frame. Firstly, both robot is initialled in the same position and orientation in the same reference. One of the robot site is adjusted by the user to match same pose. Last option, both robot is linked together with the offset transformation. In practical, some occasion need to disconnect the command and the state of the user and slave robot. This action is called clutching which used to offset the pose of two reference frames. When the master controller workspace is at the boundary, the user cannot to go further. The Clutch is used to shift the workspace in the joint workspace to cover slave robot workspace.

The mechanism of the slave robot and master controller may be having the similar kinematic or dissimilar kinematic. the system which has the similar kinematic can be called replica kinematic system. The replica master and slave mechanism can be mapped in the joint coordinate level. Although, the similar kinematic similar seem like to be more intuitive, most of teleoperation robot has the different kinematic between master and slave robot. for example, number of DOF the hyper redundant robot like snake robot which has the different from the PHANToM omni which has only 6 DOFs. The alternative method to control dissimilar kinematic robots is the mapping of the tip pose on both master and slave robot. Both master and slave robot can be tracked the position and orientation by tracking system such as optical tracking, electromagnetic tracking, and camera tracking system.

- Scaling and workspace mapping

Not only the kinematic of both robot to be considered, the both master and slave robot are usually has different scale of motion. The workspace of both robots is in different scale. In order to map in one workspace, the motion is needed to be scaled. The orientation is normally not scaled. Not only position and orientation are being scaled, force is also being scaled. Even the linear scaling is frequently used, but the non-linear scaling mapping can also be being scaled to fit in some situation. For the redundancies robot, the robot should be controlled under some criterion as an auxiliary modifier.

2.2.3.2 Supervisory control

A supervisory control architecture is a control that the slave robot fed the information back to user and autonomously move under the programming model. In this scheme, the operator supervises and decide the telerobotic system to act in different situation. The slave robot control autonomously itself to follow the supervised command. The aim of the supervisory is to solve the problem in severe time-delay like space application. The operator have two approaches to do telesensor programming, task-oriented and sensor-based. Under supervisory control, the sub control is separated into two sites which working parallel, model simulation and real system. The model simulation is a predictive model of the real system.

another control loop is the local autonomy. The optimal model is adapted by the feedback from the real system. In practical situation, the severe time delay is just a few second and can make stress to the operator.

2.2.3.3 Shared control+

This control architecture is a combination of the direct control and virtual physics to guide the operator for safety in autonomous control. The compensation of motion due to the object movement shared back to the user, the master controller is used the feedback information to override on the human command. The example is breathing compensation of the lung or cardiac movement which these two can be model as a periodically movement. (60, 73, 74) Virtual fixtures is a method that applied to master controller to limiting moment in the unintentional regions. The attractive force field is also applied to the retract the control point into attractive center (75).

2.2.4 Master controller design

Master controller has been developed since 1940s for many applications. Various design of master controllers can be separated into serial manipulator, parallel manipulator, and hybrid manipulator. Serial manipulator is the manipulator which form by the links and connected by the actuated joint. The series of links is extended from a manipulator base to an end-effector. In contrast, the parallel manipulator is the manipulator which has a close chain of serial link to support a platform. A hybrid manipulator is a combination of parallel robot and the serial manipulator. Most hybrid manipulator used the parallel robot as a manipulator base and a top-up with the serial manipulator.

The first master controller was designed as the serial manipulator. R. Goertz developed the mechanical serial manipulator which connected to the slave robot. This manipulator had 6 DOFs (3 for translation and 3 orientation). (19) the replica master was proposed to resolve the motion rate. (76)the master controller is design as coordinated control. all the control axes are in the spherical shape. (77) LARTs is a master controller that command the slave robot with both motion and human language. The language command was used as an auxiliary command to state the process. (23)Inoue developed cartesian master manipulator with gimbal wrist. (78)the operator wear a 3D screen in the Tele-existence.(79, 80)spherical wrist was to have a compact designed and driven by the magnetically levitated. A multi DOF of master slave system for a spherical wrist driven by the ultrasonic motor(81)and electrorheological fluid(82).

(83-89)a pantograph master controller was developed to control the redundant arm. (88). Auto-regulation counterweight (ARC) (90)was applied to pantograph mechanism with 3 DOF wrist for a gravity compensation. (11) the operator head connected with the head-stick system was also used as the master controller. (49) The RAMs master robot with stylus handle has the same kinematic to the RAMs slave robot. (91-93)master controller that replicate the same kinematic with the 4 DOF of flexible laparoscopic instrument. in 1994, PHANToM omni(94)from sensable is the widely used as haptic device for the research. Later, PHANToM haptic premium was also used in research(95). A various serial manipulator based on pantograph as shown in fig. 14.

Figure 14: Example of pantograph based a serial master manipulator

[(96)A multi fingered master introduced the concept of inverse haptic interface. [(97) A mobile haptic interface was developed for a mobile robot with a manipulator. The wheel can be controlled teleoperated via a wheel master controller(98). (99)An underwater vehicle-manipulator system has a master controller that have 3 DOF for control R-P-Y direction and altitude and the handle for manipulator. (100) developed the master controller for an underwater with dual manipulator. the figure 15 shown the master controller for mobile application.

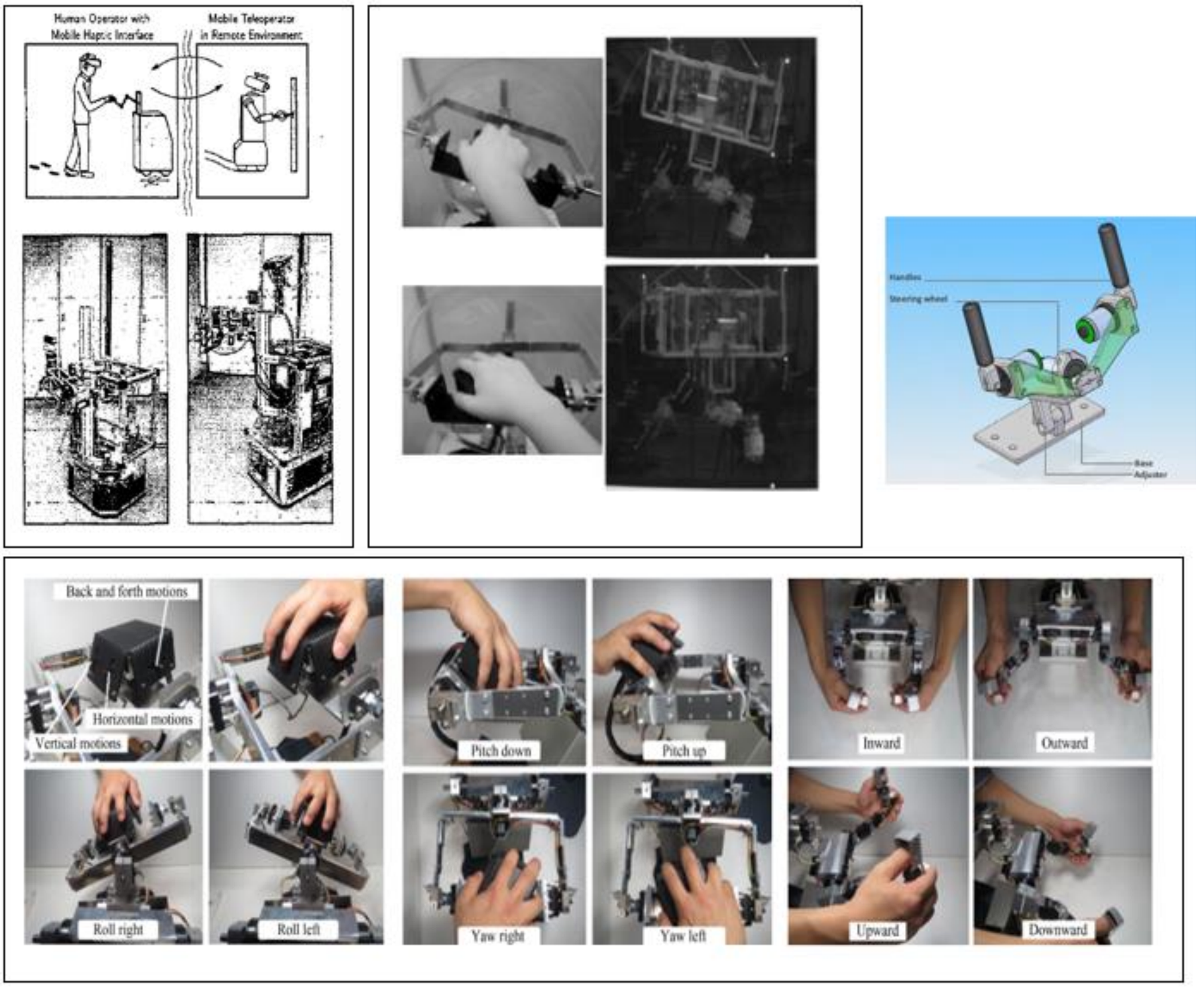

Figure 15: Examples of master controller for mobile applications

(101-107) are one of the master controller that used in surgery. The da Vinci System proposed 7 DOF of master console to enhance the movement of hand motion and to avoid the singularities of the gimbal mechanism lock. Due to the lack of force feedback to the user, the VerroTouch is attached to the da Vinci console to create high frequency acceleration feedback to the user. MASTER(62) is the master controller of the flexible instrument for GI surgery. (58) developed the micro manipulation for neuro surgery. The similar kinematic master control (108) is developed for Natural Orifice Transluminal Endoscopic Surgery. The figure 16 shown variation of master controller with serial manipulator in surgery.

Figure 16: Examples of articulated master controller in academy level for surgery

Some master slave system has the specific approach due to its application especially for the medical robot. (109) is the master device that used to control the insertion of the colonoscope by twisted motion.(110) a 6 DOF mouth motion master was developed to control the slave robot in mouth opening slave robot. (111-114) master slave system was used to replicate the laparoscopic instrument motion. JHU developed steady hand which is master controller in impedance mechanism type for eye surgery also in (67, 115). (116) a haptic master-slave system which controlled in admittance control was used for the upper-limp rehabilitation. (117) demonstrated the teleoperation of steerable needle with 6 DOF force feedback. The electromyography, EMG, was used as the command to control slave robot as an artificial arm(118). A 3 DOF planar master(119) was developed for hand drawing teleoperator. Figure 17 shown other medical application using master controller.

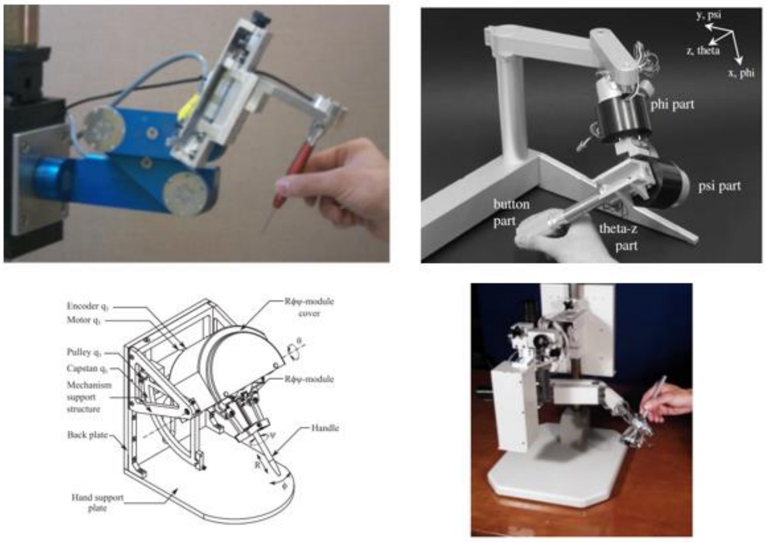

Figure 17: Master controller for eye surgery and

the application is bio technologies need the manipulator which able to tweeze the object in the micro scale. (42, 120-124) developed a finger master controller for a micro manipulation. The frictional force between hand and object is investigated in (125). A 2DOF parallel in planar motion was developed for the micro manipulation(126).

Rancho arm is designed as a exoskeleton arm which replicated the human arm(15, 127-133)in fig. 18. (134) Pneumatic actuator was used to developed light-weight exoskeleton master. the full arm and hand pneumatic master was developed in (135, 136). The muscle actuator was used in exoskeleton master to control humanoid robot(137, 138). 7 DOF upper-limp Exoskeleton was develop for rehabilitation(71).

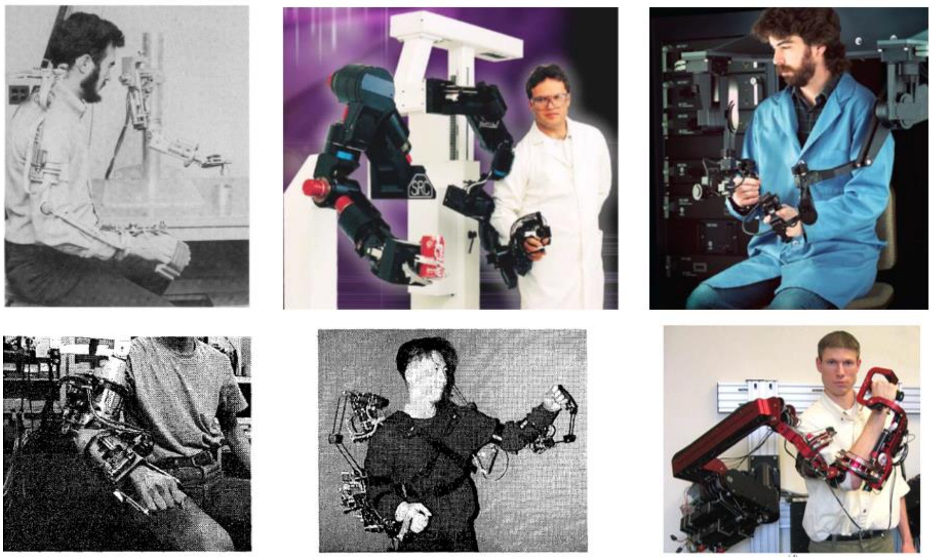

Figure 18: Master controller designed as the exoskeleton robot

A dexterous hand was developed to increase the object manipulation capability (139-144)Rutger Master(145) has been well known in the ungrounded dexterous hand with force feedback for the virtual reality simulation. It has force feedback from inner palm. (146) ORBITEC telerobotic design the master controller to have 6 DOF to cover the end-effector motion and a record glove to track the hand movement. Unlike Orbitec master controller, (147-150) 6 DOFs master with the force reflection hand glove is implemented. A variation of hand master controller is shown in fig. 19.

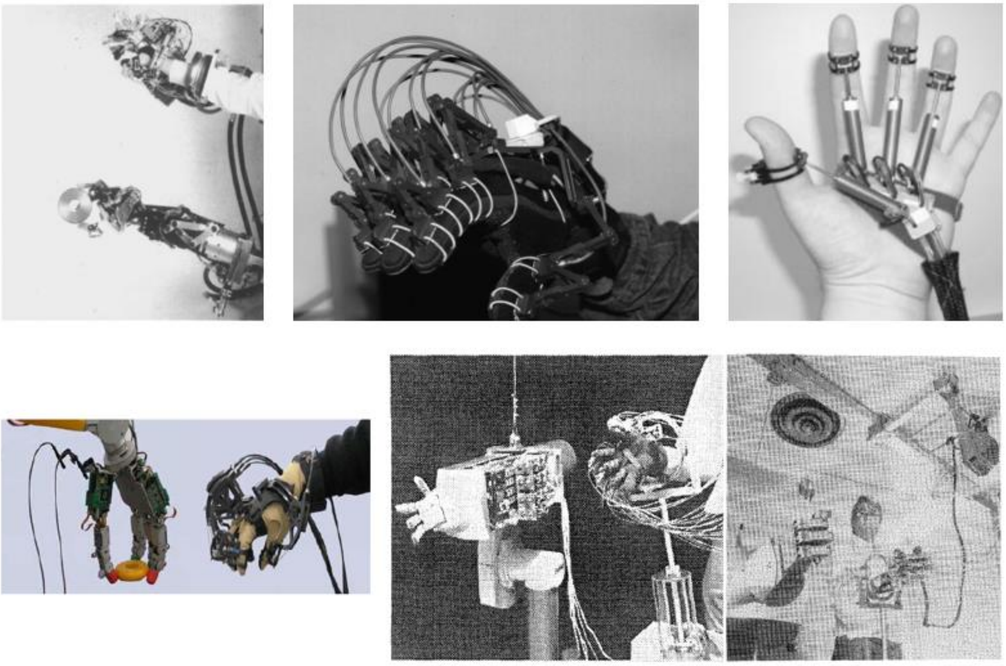

Figure 19: examples of hand master controller

A parallel manipulator was used as master controller. In 1986, Inoue developed master controller as a parallel manipulator design. a Various design of parallel platform for the master controller reported in (35, 151, 152).(153) is a parallel platform for a neurosurgical robotic system. (154) 6 DOF of URS parallel robot used as a master controller. The parallel kinematic master which widely used in the research is the haptic device from the Force Dimension, 2004. (155) are the example of Omega, the haptic device from Force Dimension. (156) A parallel mechanism and an insertion mechanism are developed to be a master controller for 4 DOF steering needle. (157, 158) two pantograph mechanism which consisted of 6 DOFs was connect with the stylus to form a pen-based master controller. A double 3 DOF parallel structure forms 6 DOF haptic interface(159) and additional actuated handle for 7 DOF haptic interface(160). The parallel platform for the master controller shown in fig. 20.

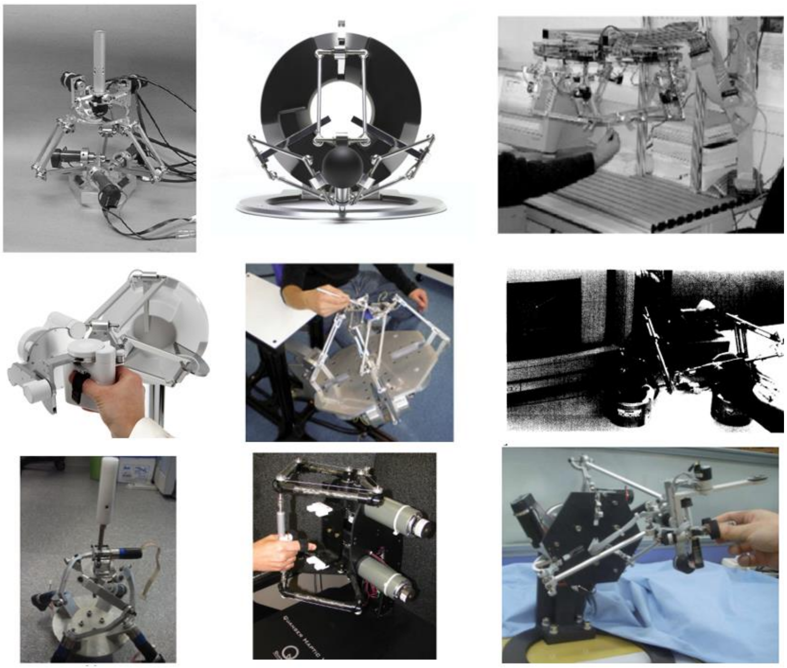

Figure 20: A variation design of parallel mechanism platform as a master controller

(52) A scissor handle attached on single platform of parallel manipulator was used to control the slave robot for laparoscopic instrument manipulation. (161) a laparoscopic telesurgical workstation was developed to has a stylus on top of parallel platform. (162) A radial wire driven system was developed to use as the master controller. An operator hand is pull by wire in specific direction to move in the space. radial wire mechanism attached to the stylus(163) and to handle(164) to perform in spine surgery. The hybrid design development was reported in (54, 165) added the wrist mechanism on top of the Stewart platform.

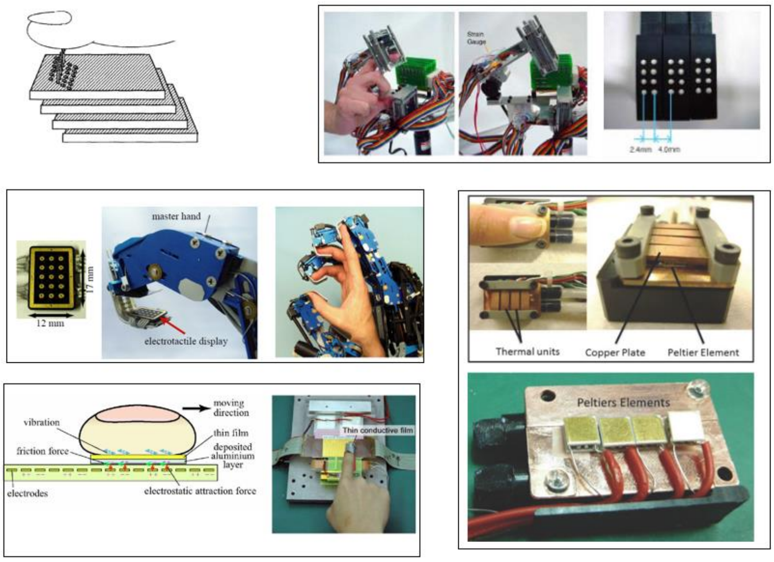

Figure 21: A Variation of tactile feedback on the fingertip

Tactile feedback is also necessary for the teleoperation in some applications. (166, 167)A vibrotactile is activated at the fingertip to notice the contact motion as a sensory substitution. (168-170) the array of miniprobe was used to display and sensing the tactile feedback. electrostatic tactile(171) and thermal tactile(172) can be used as the tactile feedback to the fingertip. Figure 21 shown examples of tactile feedback.

2.2.5 Design Consideration

Dynamic controller for teleoperation

Kazerooni presented and proved the controller framework to achieve desired relationships between the master robot and slave robot. The telerobotic system has been specified into three methods for desired performance. Force scaling is used to magnify or attenuate the applied force to force at the slave robot. high-frequency vibration filtering is used to filter out the small vibration from the operator hand vibration. Normally, the low-pass filter is applied to the force that applied from the master. Position scaling is applied to master position to be scale. For the micromanipulation, the position scale factor is valued from zero to one. For the control architecture, He classified the dynamic behaviours to 3 class, dynamic behaviour of master robot and slave robot, dynamic behaviour of human arm, and dynamic behaviour of environment. These behaviours were added in the standard H_∞ control is used to assure that the system behaviour followed the desired dynamic behaviour.

Passivity Condition & Stability

Passivity condition proposed by J.Jansen(173) is a tool to study the stability and performance of the teleoperation robot system. The energy inputted by the user to the teleoperation robot system must be positive all the rime. Following equation show passivity condition

$$\int_0^t f(\tau)\dot{x}(\tau)d\tau \geq 0, \quad \forall t \geq 0$$

In the other meaning, the teleoperation system does not generate the energy which mean the system act as a pseudo passive controller. The system in passivity condition provides stability to the operator.

Manipulability

Manipulator has workspace limitations due to its kinematics. The workspace of the robot represented the space that end-effector of the robot can be reach. It can be separated into two types of workspace, reachable workspace and dexterous workspace. A master device should provide high dexterous workspace to cover the slave robot. The space with low dexterity means the operator has movement constrain. The dexterity can be measure as a manipulability which introduced in (8). The manipulability can be calculated with the following equation

$$M = \sqrt{|J(q)J(q)^T|}$$

Where J is the Jacobian matrix with respect to joint configuration. If the Jacobian matrix equal to zero refers to the singularities. High manipulability means the manipulator able to changing arbitrary kinematics. The manipulability can be separated into two type velocity manipulability ellipsoid and force manipulability ellipsoid. Velocity manipulability ellipsoid presented the change arbitrary of the velocities direction the workspace, while the force manipulability ellipsoid presents the changing arbitrary of force in particular direction at the end.

2.2.6 Continuum Robot

A continuum robot can be categorized based on its structure. The manipulator with more DOF than execute task require is called redundant robot. whereas, the numerous DOF robot is called hyper-redundant robot. for the infinite joint robot, the robot which structure define by the infinite joint is called continuum robot. The first continuum robot was developed by Hirose, then Chirikjian and Burdick's contribute in theoretical of hyper-redundant robot. there are various designed of continuum robot, snake-like robot, hyper-redundant robot, soft robotics, constant curve continuum robot, and concentric tube. A full review is reported by (174).

From the reviews, continuum robot can be categorized by actuation and main structure. The categorized group can be divided into four sub-domains by structure and actuation axes. By the structure, it can be considered as discrete and continuous structure. The discrete structure robot is modelled as the rigid-body link robot which can analysis by kinematics. In contrast, constant-curvature kinematic type of robot is modelled as a function of the arc parameter and arc length along the main backbone. Unlike structure, it can be separated into two style of actuation, extrinsic and intrinsic actuation. The actuator of continuum robot has a constrain in mechanical design includes footprint, friction, dynamic output, backdrivability, speed, and bandwidth. An intrinsic actuation has actuators in the linkage which require large manipulator size. While, an extrinsic actuation is applied to the structure to change kinematic. this type of actuation has many features, increase range of motion, flexibility to change the shape, and small size design. However, this type of actuation has to confront the problems such as large-external transmission system, hysteresis, high friction, and elastic instability.

The continuum robot is widely applied in minimally invasive surgery. The main surgery with using continuum robot is single-port access surgery, ophthalmic surgery, colonoscopy, neurosurgery, cardiovascular surgery, ENT surgery, abdominal surgery, and urology. The figure 22 shown various continuum in medical application.

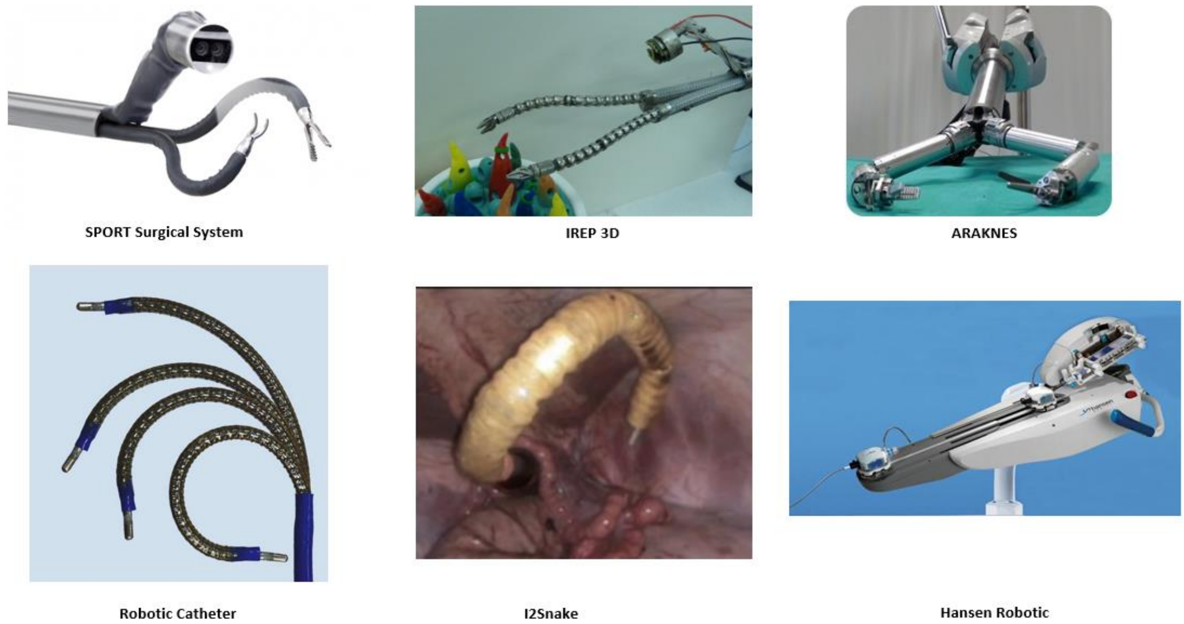

Figure 22: surgical applications of continuum robot.

To increase efficiency of the master controller for a continuum robot. The master controller should not only control the pose of the end-effector of the robot, but it should provide intermediate joint control for all structure. Another major challenge in master controller is to get the information from the slave robot such as shape and force sensing.

METHOD

3.1 Overview Proposed Method

The master controller for a snake-like surgical robot in this study is designed to provide more intuitive, force feedback, ergonomics, and transparency. Due to the kinematic of the continuum robot, the master controller is separated into two parts, instrument main base controller and dual-arm instrument controller. A base instrument controller is designed to couple the position of the controller mapped with velocity of the instrument main base. The instrument controller is designed as 6 DOF master manipulator with the non-singularities wrist. Both controller is used to provide force and torque feedback to the user hand. these are designed to have a low inertia, low friction, and good Backdrivability. Transmission system includes capstan, cable, gear to increase torque output while keep low inertia. To achieve high manipulability as a cooperation robot, the mutual manipulability is used to measure how good the robot and human hand can manipulability the object together. An auxiliary algorithm to smooth motion and high directional force exert which based on the force manipulability ellipsoid. A translational movement for the master controller is based on pantograph mechanism, while the orientation movement is frictional driven on the spherical wrist to avoid the singularities of the motion. After developed the bot controller, it will be integrated and use to control the highly articulated robot and snake-like continuum with dual arm. The validation for the system will cover both system properties and tasks performance.

3.2 Environment in this study

Colorectal cancer is a malignance cancer mortality. Transanal Endoscopic Micro-surgery (TEMS) is one of the minimally-invasive surgery procedure for effective excision. This microsurgery approaches via a single-port laparoscopic port. There are many challenges for this technique, ergonomic, limited external workspace, instrument triangulation restriction. Other limitation is the fulcrum effects that reverse the motion relative to the surgeon. The micro-IGES robotic system has a lightweight designed (3 Kg). the footprint of the robot is 0.35 m in width x 0.5 m in height, and 0.5 m in depth. This robotic platform is mounted on the support arm that can hold the load at 5 Kg. The surgical port is 36 mm in diameter in the various length. This port is optimistically designed to avoid the injuries.

Articulated instrument has 7 DOFs as mention earlier. It driven by antagonist tendon driven. The extensible tendon is 0.45 mm in diameter which able to bare tensile stress at 110

N. The lateral force at the tip is 3.5 N with the maximum tendon tension at 65N. Articulated instrument shaft is 5 mm in diameter. The elbow joint is ±45^o. The wrist joint is ±90^o. the gripper is widely open with range from ±180^o. While instrument shaft can rotate ±180^o and translation range is 80 mm. The workspace of the instrument is shown in fig. 23. The workspace of the entire rectum has a cylindrical shape with a dimension 40 mm in diameter and the length of 200 mm. the volume size is 2513 mm^3.

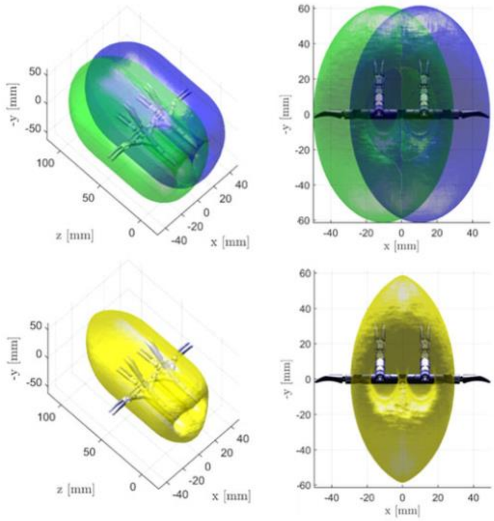

Figure 23: Workspace of Micro-IGES robot from Hamlyn Centre

For the I^{2}Snake robot, it is a hyper redundant robot with 26 DOFs. This robot is designed to operate for the ENT surgery. At this version, the robot has been used for the transoral surgery. The different between micro-IGES and I^{2}Snake robot is the kinematics. The I2Snake robot separated into two parts, main body and articulated instrument, while the micro-IGES has only the articulated instrument. The master controller for the I^{2}Snake need to control whole/separated robot.

The working space dimension of the master console is 600 mm x 400 mm x 300 mm in WxDxH respectively. A position scale factor between master controller and slave robot is 3:1. For the microsurgery, requirement of the maximum force feedback for master controller in lateral force is 2 N. The proposed master controller requires low backdrive friction with lower than 0.20 N. The master controller need to be designed as low inertia as possible to increase the high bandwidth. The wrist motion requires high range of motion. The master controller required no clutching for the smooth control. The master handle is recommended to has a grasper with/without actuator on pen-based handle. Arm support for the arm weight is considered to improve more ergonomics. The operator controls the robot via the 3D display that receive the video signal from the 3D camera in the third channel of the surgical port. The extra controller for the I^2Snake main body could be used admittance control to traverse in the confined space. the extra controller aim to designed as the spherical joint with lateral bar for the body-elbow based control.

The shared control is used as control architecture. The master-slave system shared the information including kinematic, dynamic, visualization, and support command. The virtual stiffness could be used to limit the movement in both master controller or slave robot.

The trajectories path way of the slave robot required the smooth movement. The redundant robot should adapt the kinematic with minimum movement. the control algorithm which could provide the small movement in every joint configuration is the method that control the manipulator to move smoothly. The example is the rotation at fixed point.

One research challenge in the continuum robot is that to increase the high force in particular direction. The fore manipulability ellipsoid can be used as the quantitative measurement. To increase the force at the fixed point, one example is the adjustment of the arm to apply force at particular direction. Although the force control can be applied, the manipulator in the confined shape has specific posture that can exert force in some level. The manipulator should adjust the whole body to be able to transfer the maximum force. A Wrench control is also used to estimate the force/torque that applied by the manipulator.

Micro-IGES robot and I^2Snake robot dual articulated instrument are aimed to be controlled by the proposed master controller. The master-slave system will be test the task performance and system properties.

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