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Force Feedback Transfer for Haptic Implementation in Surgical Robots

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Abstract—*Medical robots are designed to be employed in execution of surgical procedures, collectively form the branch of medical robotics called 'Micro-robotics'. Micro-robots aim to attain synergy between capabilities of the robot and the human surgeon. Minimally invasive surgery provides many benefits over open surgery, such as minimum intervention; less scarring, lesser blood loss, pain etc. as compared to normal surgery. However the lack of haptic feedback makes the area of application for surgical robots limited. Because of absence of force feedback, the surgeon has only limited perception of the operating site compared to the perception he would have had in case of open surgery. This paper discusses the basic haptic implementation and all the techniques that have been used so far to facilitate force feedback at the surgeon handle. The facilitation of haptic feedback will allow the surgeon to operate using the surgical robot without the burden of attaining cues only from visual feedback.*

Keywords*: CASR, tissue deformation, vibrotactile palpation*

1. INTRODUCTION

Micro robotics is the branch of medical robotics which deals with development of robotic tools and robotic systems to facilitate surgical procedures. Various surgical procedures that can be facilitated by micro robotics include, image guided surgery, stereotactic guidance, minimally invasive surgery etc. [1]. Tele-operation facilitates the surgeon to operate the patient by surgical robot. In this case, input device is controlled by human surgeon; the patient end robot follows the input. The pre-eminent aim of this partnership is to attain synergy between capabilities of the robot and human surgeon.

Minimally invasive surgery is essentially a surgical procedure which can be conducted without need of large incisions. Surgical robots are capable of performing same surgical task within a volume of small incision, which would otherwise require a larger incision to be made. A typical MIS robotic system includes specially designed instruments and a endoscopic camera [2]. It is favorable to employ a MIS system than performing open surgical operation. This is because robotic devices offer much higher accuracy than attained by human operators. The advantages of minimally invasive surgery include,

- Shorter hospitalization stays for patients
- Minimally invasive surgical procedures
- Reduction in pain experienced by the convalescent
- Reduction in tissue trauma
- Cost of hospital stay is lowered
- Lower risk of developing infection
- Lesser blood loss
- Higher accuracy is attained

Generally, these systems constitute of three major subsystems, viz. surgeon console and patient side cart and the vision assistance system. The former constitutes of sophisticated display system, interface panels and various surgeon's control handles. The patient side cart houses the actual robotic device with two or three electro-mechanical arms which move in response to the controls at the surgeon's end (such as grip, orientation etc.). The vision assistance aids the surgeon to get an idea to make judgment about the movement of the surgical tool attached as the end-effector.

These robotic surgical systems provide high accuracy; this capability can prove to be of great advantage if complex operations are required to be carried out in limited space. They also provide a large range of motions and rotations of the tool. Moreover, the commanded operations can be scaled to accurate small movements to be performed inside the patient.

However, a couple of limitations have been encountered in these systems, such as, high cost for initial set up and maintenance, incapability to utilize qualitative information and absence of haptic feedback.

Many solutions have been proposed for incorporating haptic feedback in the systems used for Minimally Invasive Surgical Robots. However, they are able to provide only measured values for forces at tool tip and tissue interaction site [3]. Such systems lack the capability to provide the haptic feedback at the surgeon handle, which could facilitate the surgeon to sense the movements of surgical tools.

There have been many attempts to give solution to this problem. Some of these have been successful, and are being employed commercially and also for further development of such devices. However, due to partial fulfillment of the requirement of haptic feedback, minimally invasive surgery can be used for a limited range of surgical applications. Overcoming the insufficiency of intuitiveness in the implementation of MIS robots, caused by absence of proper haptic feedback, will allow application of these systems in broader spectrum of surgical procedures.

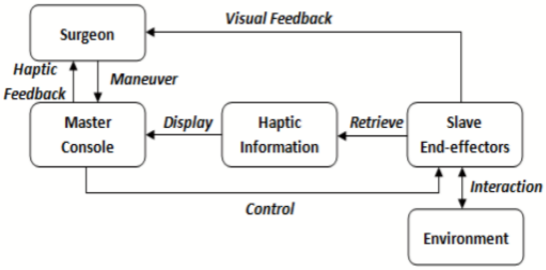

Fig. 1: Master-slave configuration for haptic feedback [4]

Most of the commercially available MIS robotic systems, such as Da Vinci Surgical System, ZEUS Surgical System, are based on master-slave configuration [2]. The architecture of a typical master-slave configuration based MIS system is shown in Fig. 1.

The existing surgical robots do not provide force feedback to the surgeon. The proposed project work is intended to provide the surgeon console with the haptic feedback of the force exerted by the tool being used by the surgical robot. This development in the interface between the robot and surgeon console would give the surgeon a sensation operated. The purpose of this project is to provide a haptic feedback to the surgeon, so that he can assess how much force should be exerted by the tool, so as to accomplish the task accurately, without any undesired movement of the surgical tool. Facilitation of force feedback to the surgeon will give him a better idea of the surgical tool's movement. This project work has been initiated to fulfill the need of providing force feedback at the surgeon's handle.

2. ARCHITECTURE OF HAPTIC DEVICES

Most commercially available haptic feedback mechanism has either serial or parallel architecture. Both serial and parallel haptic mechanisms have peculiar characteristics which are tabulated as given in Table 1 [3].

Table 1: Comparison between serial and parallel mechanisms

S. no	Characteristic	Serial mechanism	Parallel mechanism
1.	Workspace	Large workspace	Compact footprint
2.	Stiffness	Low	High
3.	Force feedback	Lack of sufficient force feedback capability	High force output
4.	Grasping interface	Do not have grasping interface	Lack of grasping interface
5.	Degrees of Freedom	Offers more DOFs	Offers relatively less number of DOFs

Many other haptic devices have been developed with distinct architecture such as a glove or exoskeleton architecture. These configurations offer various advantages such as larger workspace and increased degrees of freedom. However, like serial mechanisms, glove type devices also suffer from insufficiency of force feedback [3]. Thus there arises a need of developing haptic devices which provide force feedback with greater efficiency.

A very popular haptic device which has been used commercially is PHANToM. It has a serial mechanism with verticality multi joint structure [5]. It constitutes of a five bar parallel mechanism and offers either three or six degrees of freedom [6]. The implementation of gimbals mechanism in this system, it becomes difficult to employ this haptic device in some surgical applications such as bellybutton surgery [5].

A trainer based on simulations for detection of prostate cancer is based on this haptic device. A complete minimally invasive surgical robotic system has been designed by taking modified PHANToM as the master and cable driven tele-operator Black Falcon as the slave, in [2]. The slave manipulator provides eight degrees of freedom, while the master manipulator (modified PHANToM) provides seven degrees of freedom.

3. FORCE FEEDBACK MECHANISMS

The most foreseeable approach towards providing a haptic feedback mechanism would constitute of implementing force sensors at the tool tip. The force sensor that is commonly used for this purpose is strain guage. However, this approach will provide force feedback with a few drawbacks [7] and [5], which can potentially deteriorate the performance of the system. These factors, which may downside the performance of the haptic feedback mechanism based on employment of force sensors at tool tip, are listed below,

- Downsizing becomes a difficult task
- Intricacy in sterilizing of tools
- It will lead to considerable increase in the cost
- Narrow bandwidth of the force sensor affects force transmission
- Stability is also affected by the narrow bandwidth of the force sensor

Moreover, not all types of surgical tools can support implementation of force sensors on their tip. These factors collectively make this approach non-viable for most of the MIS surgical applications. There is no generally classification of haptic feedback devices, however they can categorized based on various parameters such as architecture, according to the force sensing mechanisms and according to the degree of freedom provided by the devices.

The sensory information attained by human operators, constitutes of two pieces of information. They are called Kinesthetic information and tactile information. The former constitutes of the information regarding position, orientation, velocity of joints and force data of limbs. On the other hand, the latter constitutes of pressure and indentation distributions. The kinesthetic information is transferred by sensory receptors which are in the muscles, tendons etc. While the tactile information is transferred mechanoreceptors in the finger pads, these are between the derma and epidermis. The tactile information constitutes of cutaneous and sub-cutaneous information. Moreover, other information may also be attained by human touch [1].

Most of the haptic feedback systems that have been developed, have taken only the kinesthetic part of the haptic feedback into consideration while designing of those systems. This is because realization of cutaneous information is extremely difficult [1].

A typical remote haptic system can be represented as given in Fig. 2. It essentially includes, sensors and actuators for acquisition and reflection of the force feedback (Kinesthetic and cutaneous), respectively. It is not mandatory to implement different hardware for Kinestheic and cutaneous haptic information [1]. A highly efficient haptic feedback system should constitute of complete sensing of both kinesthetic and tactile information, and provide the same at the other end, without any errors. However, mostly this is not the case, there is only some amount of haptic information that could be sensed and provided at the other end. And the accuracy and performance specifications are also crucial, as the information being sent through the feedback is not completely error free

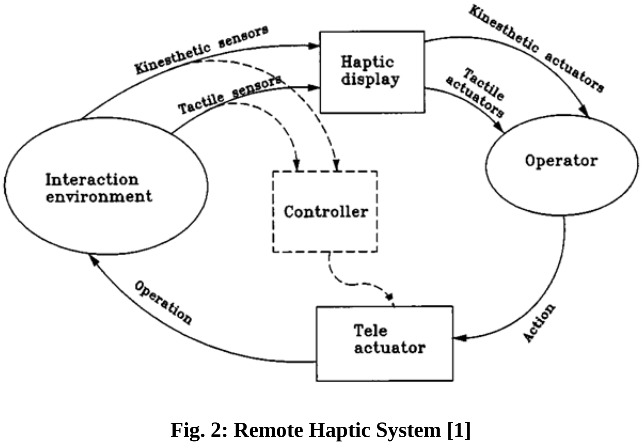

Fig. 2: Remote Haptic System [1]

There are various strategies to design the haptic feedback using force sensors, as discussed before. Although, it is not considered to be one of the most efficient ways to provide haptic feedback, but some design strategies using the force sensors can prove to be very effective. One of such strategies is employed in [8], where bilateral algorithm has been employed for providing force feedback in a typical master-slave configuration, whenever the tool-tissue interaction occurs. Moreover, a control algorithm has been developed using optimization theories to assure a fixed point maneuvering of the surgical tool within the workspace.

Along with the development of better and efficient force feedback haptic devices, an effort to develop better identification and recognition techniques has also been considered for development of intelligent haptic systems. Such a system has been designed in [9], where the refined recognition of small-size objects is facilitated by an array of force sensing resistors. The amalgamation of the sensing instrumentation and neural networks developed in [9], is established so as to achieve high resolution of small objects or complicated structures. The system is intended to be more intelligent by enabling switching between laser sensing and integrated tactile sensing. The various sensing mechanisms that have been employed for force feedback are discussed in following sections.

A. CASR

This approach of providing force feedback as given in [1], is based on the principle that establishes a relationship between the area of contact and the net contact force. Essentially, the CASR is Contact Area Spread Rate, which implies the rate with which contact area spreads with increase in force exerted by the finger. This approach does not rule out the presence of other crucial design parameters that could be considered for an efficient haptic feedback design. However, in case of insufficiency of relevant resources, this approach can efficiently fulfill the need of the haptic feedback which is required to discriminate between compliance of different areas.

Certain sensors and actuators can be employed to design a CASR based haptic feedback system. The sensors and actuators which fulfill the criteria for efficiently transferring the haptic information acquired by CASR philosophy can be used as CASR sensors and actuators. The information acquired by CASR approach constitutes of two main components, firstly, time signal corresponding to force and secondly, time signal corresponding to area of contact. Both of these signals are analog signals. On drawing comparison between CASR data acquisition and conventional approach to acquire data for haptic feedback, it can be easily concluded that CASR approach is much easier and faster than the latter. This is because in conventional approach sampling of time varying spatially distributed pressures needs to be done, in time and space domain.

The sensors that can be used for CASR based haptic feedback system includes sensors based on piezoelectric or piezoresistive materials. Such CASR sensors are built be sandwiching a thin layer of piezoresistive/piezoelectric material between two layers of conductive material. Suitable instrumentation can be employed to measure electric signals. Another alternative for CASR sensing constitutes an optoelectronic unit which can measure the fluctuations in intensity of light because of changes in area of contact. The schematic of these sensors is shown in Fig. 3.

It has been experimentally proven in [1] that the optoelectronic sensing is much more accurate than sensing accomplished by piezoresistive or piezoelectric sensing devices. However, it is also noteworthy that the miniaturization of optoelectronic unit for sensing is a complex task. It is important to consider whether the effort in miniaturizing the optoelectronic unit is resulting in a considerable amount of superiority in accuracy or not.

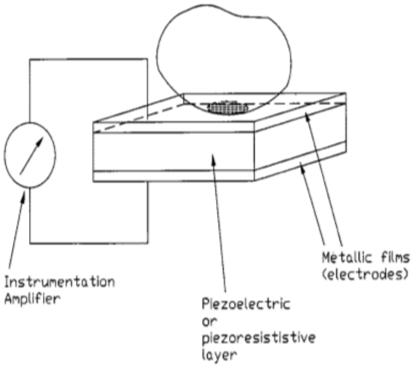

Fig. 3(a): Piezoelectric or piezoresistive CASR sensor [1]

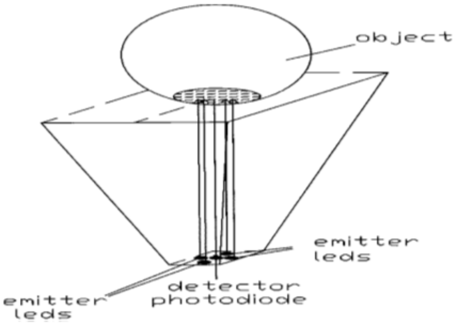

Fig. 3(b): Optoelectronic CASR sensor [1]

B. Tool Contact Acceleration:

One of the most popular commercially available surgical robotic system is da Vinci surgical robot. Although, this surgical robot has been in use across the world but it also suffers from lack of haptic feedback. The Verro Touch System presented in [10] is designed so as to provide da Vinci robotic system with haptic feedback, in the form of tool contact acceleration. This is accomplished by inclusion of five elementary modules, which are listed as follows:

- Vibration sensor unit: aids measurement of tool accelerations
- Receiving unit: conditions the signal obtained from the vibration sensor unit
- Gain control unit: facilitates variation in the magnitude of actuator signals
- Voice coil actuator unit: replicates tool accelerations physically
- Stereo speakers unit: replicates the signal audibly

High frequency accelerations produced by da Vinci surgical system's tools can be measured using MEMS based micro-accelerometers. The actuators for the haptic feedback at the surgeon handle can be obtained by conventional actuation modules for generation of vibrotactile feedback.

The micro-accelerometer attains the acceleration reading for x,y,z directions, and converts them into voltage signals. These signals are passed through low pass filter to attain the bandwidth comparable to human vibration detection. A first order HPF is used to rectify DC component in these signals. A summing amplifier is then used to sum the three signals so as to attain the vibrations in the three directions. The output signal of the summing amplifier is directly sent to the speaker and to the surgeon handle through main receiving unit. The signal flow of accelerations in x,y,z directions to the surgeon handle and speaker console is shown in the Fig. 4.

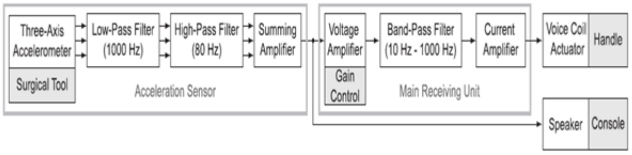

Fig. 4: VerroTouch System [10]

C. Sensors:

Various conventional sensing techniques can be employed for generating haptic feedback in minimally invasive surgical robots. Although these techniques are conventionally used in robotic systems and other electronic systems, but for their utilization in minimally invasive surgery, they need to be miniaturised. This purpose can be solved by using equivalent MEMS based sensors. Some of these techniques as discussed in [2] are given below.

a. Displacement based sensing

It is one of the fundamental methods of measuring force. The principle behind this technique is the force and displacement relationship observed in a mass spring system. The various displacement sensors include potentiometer, LVDT, digital encoders etc. Amongst all these devices LVDT transducer is most commonly used.

b. Current based sensing

Another approach to sense force is by measuring current of the motors actuating the joints. However, this technique lacks accuracy because of errors generated because of backlash, variation in the conductivity of brush, over-estimation due to unintended supply of motor current to accelerate moving joints etc. However, these errors can be compensated by appropriate techniques such as use of extended Kalman filer.

c. Resistive based sensing

An array of force sensing resistors can be used for obtaining the feedback, as given in [9][2]. It is beneficial to use collection of these sensing elements rather than using a single axis force sensor. This setup will certainly provide richer information than obtained by the single axis force sensor. This is because the array of force sensing resistors provides the distribution of the forces perpendicular to the surface of the array [2].

d. Capacitive based sensing

This technique of sensing force provides results with high sensitivity and thus it is suitable choice for the applications where small forces and deflections have to be measured [2].

Other advantages of using these sensors include, low cost, compact geometry, high reliability etc. However, they can be used only in those applications that need measurements to be done within a small range.

e. Optical based sensing

This sensing strategy can be used as a comprehensive strategy for force sensing and force transfer. Any optoelectronic equipment which possesses the ability to sense force comes under this category. Force transfer can be done through optical fibres. Photodiodes, light emitting diodes are examples of optical based sensing technique.

D. Pneumatic Artificial Muscle:

As it was stated earlier, implementing conventional force sensor such as strain gauge, results in difficulty in downsizing and sterilizing and several other problems. However, if conventional pneumatic actuators are employed for force measurement then these problems can be rectified [7]. The conventional pneumatic actuators used for translational motion are pneumatic cylinders while for rotational motion, rotary vane motors can be utilized.

The basic principle behind using pneumatic actuator is the high back-drivability of these actuators. This characteristic of pneumatic actuators is exploited to attain force sensing without employing any force sensor [7]. It has been shown in [7] that pneumatic artificial muscle (PAM) give a better performance and high sensitivity, as compared to other pneumatic actuator based haptic devices.

The advantages of using Pneumatic Artificial Muscles in human machine interfaces are listed below:

- High force to weight ratio
- Human operators can share functional characteristics of PAM
- Operation on safe energy
- Effect of inertia and gravity can be reduced

The haptic feedback mechanism developed in [7] uses PAMs and pneumatic actuators (pneumatic cylinders and vane motors) for the design of the slave console hardware. Slave console hardware essentially two modules, which are, supporting manipulator and forceps' manipulator. The supporting manipulator offer four degrees of freedom while forceps' manipulator offers two degrees of freedom.

The supporting manipulator offers four degrees of freedom of which three are of rotational nature, centred at entry point through a trocar cannula. The remaining one degree of freedom facilitates translation along the direction of forceps' insertion. The advantages of using this configuration as given in [7] are listed as follows:

- Minimization of load on patient's body
- Elimination of requirement of coordinates of the port position, which are otherwise needed for kinematical calculations

The forceps' manipulator constitutes of a thin translational insert and a gripper at the tip of the forcep. Also, the actuator housing is present at the other end of the forceps' manipulator. The actuation of gripper is facilitated by embedded pneumatic cylinder. This leads to larger gripping force and also interference with other joints is avoided. The pitch and yaw movements are actuated by two PAMs. These are installed at the driving end of the antagonistic tendon drive as given in [7]. Stainless steel wires are employed for the force transmission. The forceps' manipulator is flexible in the sense that it can be detached or attached to the supporting module for quick change. The pneumatic surgical manipulator developed in [7] is shown in Fig. 4 and tendon drive mechanism of forceps' manipulator module is shown in Fig. 5.

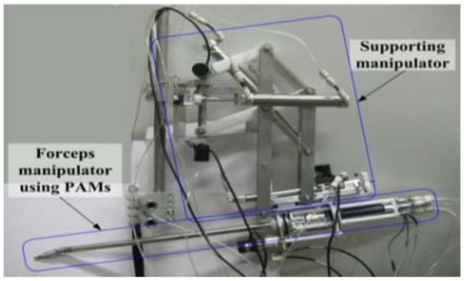

Fig. 5: Slave side surgical manipulator [7]

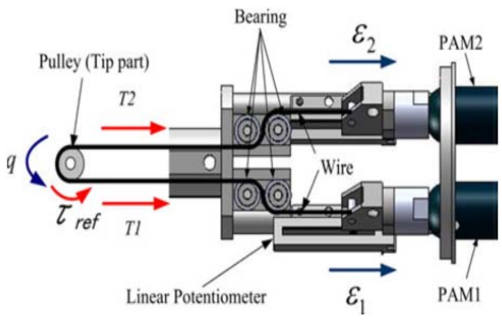

Fig. 6: Antagonistic tendon drive mechanism [7]

E. Tissue Deformation

A more efficient approach for developing a haptic feedback mechanism is to develop a haptic model for the organ that has to be operated. These models can be utilized for replicating the force at the tool-tissue interaction site. A typical representation of haptic feedback mechanism using haptic modeling is shown in Fig. 6.

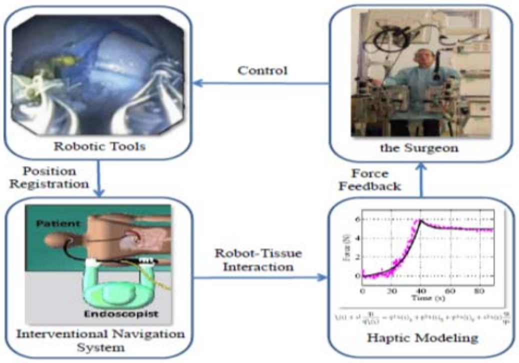

Fig. 7: Implementation of haptic modeling approach [24]

A similar approach has been used in [8], where force exerted by the tool of endoscopic surgical robot is estimated. For haptic modeling of an organ, its main characteristics which affect the force at the tool-tissue interaction site. The characteristic which is crucial in case of gastrointestinal organ/tissue is its viscoelasticity. This type of approach is also used in [3], where morphological deformation and arterial stress is measured by developing a model of the artery segment. The measurement of these characteristics is facilitated by image processing and photoelasticity.

Various properties that are based on deformations and linear elasticity can also be derived, once deformation, elasticity etc. are attained. In [11], medical images are utilized to get the geometry of the organs. The geometry of the organ is then utilized to attain deformations, linear elasticity and other physical properties are attained by computation using finite elements.

F. Vibrotactile Palpation

When vibrations are induced in a tissue its behavior is similar to a damped harmonic oscillator, at lower frequencies. According to this principle, it can be derived that there is a relationship between the characteristics of damped harmonic oscillator such as mass, spring and damping coefficient and the properties of tissue like shear viscosity, density, shear elasticity etc. [3].

On the basis of these concepts a vibrotactile sensor has been developed in [3], for use in MIS to facilitate haptic feedback. This system is capable of detecting a timorous knot within a soft matrix. This is accomplished by measuring mechanical frequency of tissue after excitation. The given system is capable of exciting the tissue as well as measures its dynamic response.

G. Tendon Sheath Actuation

Tendon sheath actuation can be employed for force sensingand transmission. A haptic feedback mechanism for minimally invasive surgery in NOTES application is presented in [4]. This system uses tendon sheath actuation for force sensing and force transmission.

The driving mechanism used at the MASTER system is tendon sheath actuation. In the slave manipulator every joint is driven by a tendon pair. If pulling force is applied to one of the tendons and the other tendon is released then the joint will rotate.

The force exerted at each joint is related to the tension in the corresponding driven tendon. This force can be attained at the end through force transmission mechanism. Thus, force sensing elements can be placed at any location outside the patient.

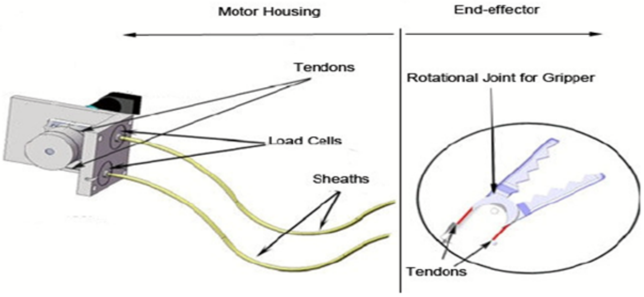

Fig. 8: Haptic Information Acquisition [4]

This technique suffers from some limitation when addressing certain problems like NOTES. These include inaccessible configuration of tendon-sheath and it can also be time varying. The method for acquisition of haptic information used in [4] is shown in Fig. 7.

The addition of the haptic feedback mechanism in surgical robotic system provides some extra information which would not be available to the surgeon by direct touch. It may also facilitate complex tasks like knot tying.

4. APPLICATION ORIENTED HAPTIC IMPLEMENTATION

The implementation of haptic feedback for various types of minimally invasive surgery and tasks associated with those operations is desirable to augment best capabilities out of both, surgeons and robots. The information that needs to be acquired for haptic feedback depends on the task that has to be performed. Certainly some piece of information which is needed for Laproscopic surgery will be different from the feedback which will be needed to detect prostate cancer. Thus it is desired to design robotic systems with haptic feedback dedicated to a specific area of medical. Some of these application oriented haptic implementations are discussed here.

A. Laproscopic Surgical Robot

A laproscopic surgery is carried out by making a few small incisions in the abdominal cavity. Carbon dioxide is pumped into the cavity to open the workspace. A laproscopic unit is inserted through one of the incisions. The laproscopic unit constitutes of a chain of lens optics; it transmits the visual feedback of the operation side to the camera at outer end [12].

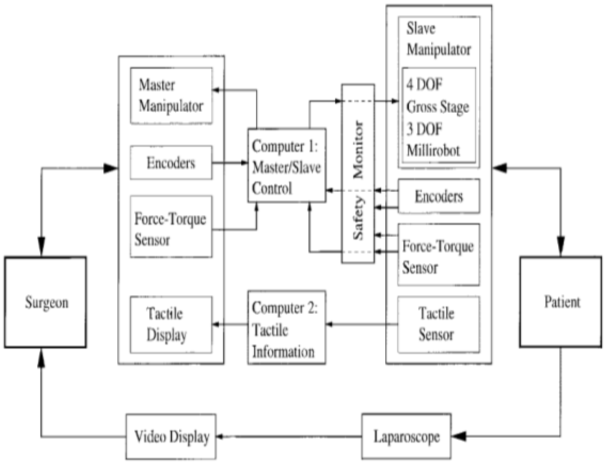

Fig. 9: Conceptual representation of haptic feedback in Laproscopic surgical robot [12]

Various other feedbacks can be included in this system to make the perception of the surgeon even better. This will facilitate the surgeon to perform more complex task using this type of surgical robot. Such a haptic feedback mechanism has been presented in [12]. The conceptual representation of this system is shown in Fig. 8.

B. Trainer Robotic Systems

Virtual reality is one of the most crucial aspect derived from marriage of surgery and robotics. Robotic systems which create a virtual environment, which is replication of the real surgical scenarios, are of great significance as they are employed in providing training to the surgeons. There are many advantages of such surgical robotic systems, as they provide training to the surgeons without causing any damage to real patients. This means health or medical condition of real patients is not risked in the hands of interns or students. This is also useful because surgeons can enhance their skills on every kind of case without the case being practically present.

Although there are many advantages of using surgical trainer robots, but it is also important that haptic feedback mechanism should be present in these systems to give the user a perception that is similar to the real time scenarios of these operations. The various modules that must be incorporated to achieve a realistic haptic feedback are given in [13]. It also includes the modeling of organic tissues which is also helpful in haptic mechanism, as it can be used to determine deformation and stress etc.

Implementation of haptic mechanism for a trainer robotic system which is employed for urological operations is accomplished in [6]. The given mechanism provides five degrees of freedom. It basically constitutes of a two degree of freedom five bar linkage and a spherical joint. This configuration is designed so as to be statistically stable and offer low friction, low mass and inertia. The actuators used in this system are dc servomotors. And the force transmission is accomplished by capstan drives, pulleys and tendons. A Haptic Training System (HTS) based on multiulateral control is realized in [5]. This system employs three robots to and multilateral control is attained by modal decomposition and thereafter the control can be designed like bilateral control.

C. Cannulation and Needle Insertion

Surgical procedures involve many complex tasks such as dissecting, injecting, suturing etc. These tasks require precise positioning and orientation to perform the operation successfully. Although through training surgeons can develop the skill to attain depth cues in three dimensional space to carry out these tasks. However, if additional information is provided to them in the form of force feedback, the performance in minimally invasive tasks will certainly improve.

A two handed endoscopically guided robotic system has been developed in [14]. This system offers six degrees of freedom and constitutes of a two handed architecture. The function of this robotic system is to perform cannulation task by attaining feedback. Cannulation refers to the task of inserting one tube into another. A detailed insertion model and choice of materials and instrumentation is given in [14].

The most common task that is required during surgical procedures is needle insertion. The depth perception of the surgeon in three dimensional space is not perfect and the surgeon depends on certain depth cues. If the needle insertion task is supported by a robotic system which has enhanced force feedback, then the operator will perform this task more efficiently. Such an approach has been used in [15] to perform coaxial needle insertion. The system developed in [15] provides one degree of freedom and the force transmission is executed by cable. This system provides the operator with the scaled version of force applied at the tissue by the needle tip. It also compensates for shaft frictional force.

In large scale surgical robotic systems which have different modules of surgical procedures that can be executed modules through that system are integrated altogether, then their respective haptic feedback also need to be integrated. For this purpose a multi lateral design for integration of several haptic modules or probes, is given in [16]. This can be done by integrating these probes through audio communication between these modules. This is represented in Fig. 9.

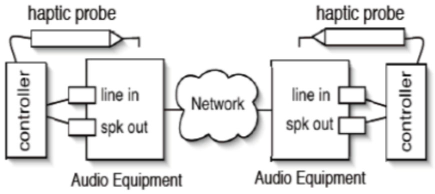

Fig. 10: Integration of haptic probes via audio [16]

5. CONCLUSION

Various techniques that have been used to attain force feedback in surgical robots have been discussed in this paper. The area of application where the surgical robots can be used will broaden to a great extent if the force feedback realization is merged to the existing surgical robotic systems. Certain approaches such as CASR approach and vibrotactile palpation can work very efficiently if the issues associated to them are dealt with. For this purpose, different haptic approaches should be used for different surgical robots according to the suitability.CASR can prove to be more suitable for cannulation and needle insertion robots rather than vibrotactile palptation, which could be better in case of laproscopic surgical robots.

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